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Immersed Tunnel: A Viable Option for The Orlovsky Crossing

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Immersed and Floating Tunnelling

The Orlovsky crossing in St. Petersburg has been a hot topic over the past years. St. Petersburg faces a constant balancing act between river navigation and road traffic. In the ice-free period, the bridges over the Neva River open nightly for an extended period of time to allow ships to pass, stopping road traffic for several hours. A tunnel would provide the first uninterrupted road link between the two parts of the city, which may allow the city's bridges to be open for longer, effectively increasing the capacity of both road and waterway.

The latest design for the link was a two-tier bored tunnel with a TBM diameter of 19.2 m, the largest ever to be constructed. Since the required cover on a TBM tunnel relates directly to its diameter, the depth of the tunnel is significant and the resulting approaches will be long, diminishing the advantages of the bored tunnel.

At first glance, an immersed tunnel seems like a more practical solution due to its efficient shape and short approaches. However, several location-specific issues have been brought up that must be addressed and solved in order for this solution to be viable, including:

- Water quality in the Neva
- Sub-zero temperatures
- Ice regime of the Neva
- Flow velocity
- Unexploded ordnance

This article covers the generic IMT design as well as the issues that are specific to such a tunnel at the proposed location.

***Keywords**:* *St. Petersburg, Orlovsky, Neva, Ice, Subarctic, Temperature*

1. The Orlovsky Tunnel

The Orlovsky Tunnel is a proposed road link in St. Petersburg between the two parts of the city split by the Neva River. St. Petersburg faces a balancing act between navigation and road traffic, where the many bridges across the Neva River open nightly, effectively splitting the city in two for several hours.

The proposed Orlovsky Tunnel would create the first permanent connection between north and south and would increase the capacity of both road and waterway. The tunnel has been subject to much debate due to costs and construction challenges.

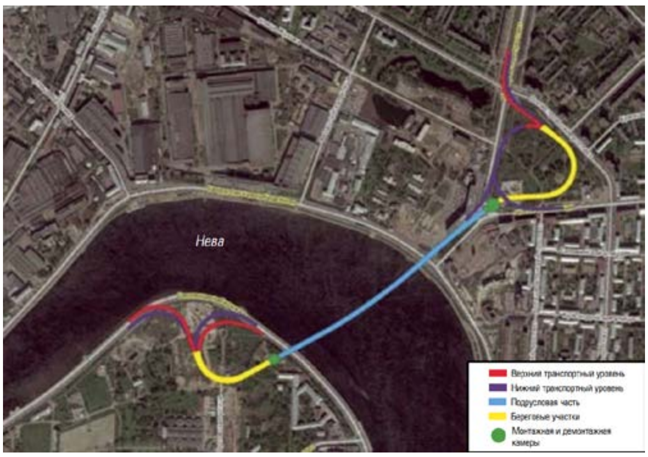

Fig. 1 *The Orlovsky Tunnel runs under the Neva River in St. Petersburg (Ryzhevsky, 2014)*

The projected maximum capacity of the crossing is 90 thousand vehicles per day, which requires a road with 2x3 lanes. The latest design consisted of a two-tier bored tunnel with a TBM diameter of 19.2 m. A typical soil cover of one times the diameter means the maximum depth of the bottom of the bore is -51.1 m BS. At any feasible slope the intersections on the banks have significant depth and are thus considerable structures in an urban environment that has limited space. The project has been put on hold due to rising costs stemming from a range of issues including poor soil conditions and the consequences of the application of a single tunnel bore.

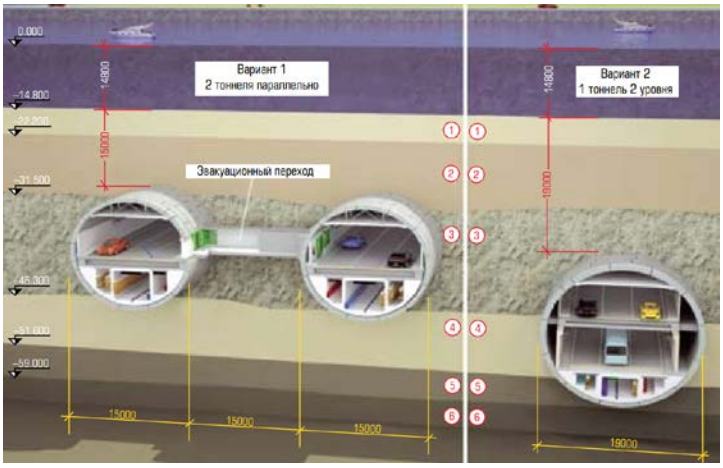

Fig. 2 *Bored alternatives for the Orlovsky Tunnel (Ryzhevsky, 2014)*

Several alternate solutions for the crossing of the Neva have been devised, including a bored alternative with two tubes, an immersed tunnel and recently even a bridge.

2. An Immersed Crossing

An immersed tunnel was proposed and designed by Tunnel Engineering Consultants (TEC) in the preliminary design stage. The immersed tunnel was rejected early on, in part due to environmental concerns and the belief that the immersion process would cause significant navigation and road blockage. However, an immersed tunnel offers numerous advantages while mitigation of drawbacks is achievable as described further on in this article.

Fig. 3 *A preliminary design of the Orlovsky Tunnel cross-section*

An immersed tunnel offers a significant shape advantage. Its shape can be optimized to fit the traffic envelope, thereby minimizing space lost. A service bore can easily be included to provide easy access for maintenance and tunnel operation, while also providing safe passage in case of an emergency. The service bore can be sized as desired, and will improve the serviceability and user safety of the tunnel.

A preliminary design of an immersed tunnel in the Neva resulted in the cross-section seen in Fig. 3. In this design there are 2 tubes with 3 lanes and a single service tube in between. This creates a wide but low tunnel that will require the least amount of dredging. The soil cover on the tunnel roof is generally around 1.5 m thick, resulting in a maximum depth of the bottom of the tunnel of -27.0 m BS.

The low height of the tunnel and the shallow ground cover results in a shallower tunnel than the bored alternative, resulting in significantly shallower onramps. This will lead to a significant reduction in costs of connecting infrastructure. Approaches will be shorter and less deep, and will be easier to place in the limited space available.

The deepest section of the tunnel is located in the outer bend of the Neva, where the river is deepest. A 600 m approach will be necessary on the north shore under an existing avenue and will surface in the Sad Neva Park. As a result, traffic congestion on the north shore during construction is an area of concern.

3. Traffic Congestion

Roads run along the river banks of the Neva at the location of the tunnel. Traffic flow on these roads can expect a degree of disruption during construction of the approaches.

A proven method that has been successful worldwide in reducing traffic hindrance is the cut & cover method, where deep walls are placed with a roof slab such that excavation can be done while traffic flows above. The building pit of the ramps may serve as a staging area for easy access to the cut & cover tunnel.

On the north shore, a cut & cover tunnel would cause traffic blockage for a period of time, after which construction may continue via the access way at the Sad Neva Park. This park will serve as a staging area for construction and will be the location of the intersection to the tunnel, as it would for a bored tunnel.

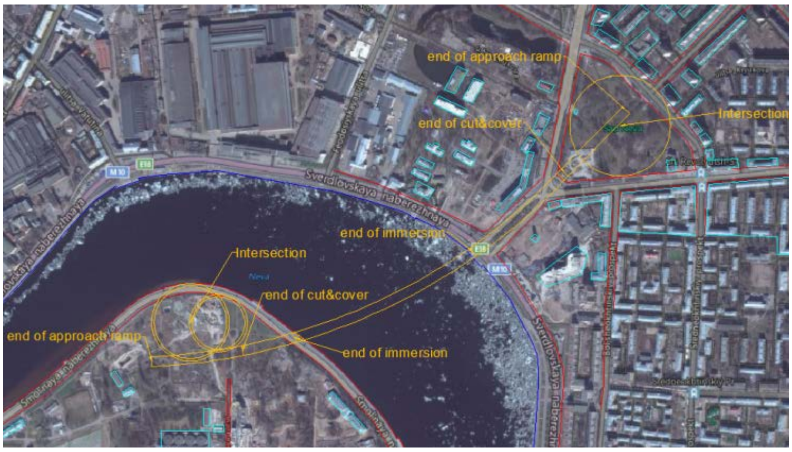

Fig. 4 *Location of the intersections of the Orlovsky Tunnel*

On the south shore several alternatives exist. A cut & cover tunnel may be considered or, alternatively, the road may be rerouted in order to allow for an open building pit or cofferdam. The area along the Neva can then also be used for construction of the tunnel elements and, later, of the ramps of the intersection. This way, land will be optimally used in every stage of construction and traffic hindrance will be mitigated by rerouting of the existing road.

A point of attention is that the operation of the nearby Main Water Station (MWS) may not be shut down, as it would interrupt the water supply of St. Petersburg’s Central District. Construction on the river banks will require temporary rerouting of pipelines in order for the cut & cover method to be permitted.

4. Water Quality

An immersed tunnel is typically placed in a dredged trench, which offers the advantage of an unobstructed flow in the final state. A concern in St. Petersburg is that the dredging process will unearth silt and contaminated soil and pollute the Neva, which supplies the city with 98% of its potable water (Vodokanal St. Petersburg, 2014). In order to protect the clean water source of 5 million people, measures must be taken to avoid contamination of the river.

For the dredging to be possible it must comply with local water quality regulations that state that there is a 200 m contamination-control area around the intake pipes. Within this sanitation area, all activities other than operation works of the water intake are prohibited. The intake pipe nearest to the tunnel and is approximately 500 m downstream. This places waterway activities just outside of the contamination-control area. However, since dredging activities would be performed upstream of the intake, any stirred-up contaminants would flow towards it. Contamination levels must not exceed specified thresholds in order for water to stay safe for consumption. Therefore, it is important to choose the right dredging equipment to minimize stirring up of sediment. Silt curtains can be applied to contain suspended solids to further reduce contamination. Additionally, the large discharge of the Neva (≈2500 m^3/s) will aid in reducing the concentration of suspended soils in the water. While, controlled dredging will reduce contamination, additional water treatment may be applied to remove residual contaminants, if required.

The presence of unexploded ordnance poses a challenge for dredging. A side-scan sonar Survey was done that located 8 objects directly on the tunnel route. These pose a hazard to dredging activities as well as the water intake. The key to productive and cost-effective dredging is to locate and remove ordnance prior to dredging. This has been done successfully in the past at the Øresund and Medway tunnels.

5. Cold Region Immersed Tunneling

Immersed tunneling is not a new technology - many immersed tunnels have been constructed around the globe; the bulk of them in The Netherlands, USA, and Japan. As of yet, none exist in Russia. A wealth of experience has been gained in Europe, Asia, and Australia with concrete immersed tunnels, which can be tapped to achieve a safe, efficient, and effective tunnel. As is the case with every construction project, immersed tunnels require a custom design that is specific to its location. One of the challenges for immersed tunneling in Russia is the cold temperatures that the structure and the construction process will face. Adaptations to design, construction, and maintenance of the tunnel are required to deal with the adverse weather conditions.

6. Ice Regime of The Neva

The Neva can be frozen anywhere between 2 to 6 months per year. In terms of ice formation the Neva River is classified as having a fast flow regime (Freitag & McFadden, 1997). The main mechanisms of ice formation in rivers with a fast flow regime involve frazil ice, drifting ice floes, and ice accumulations (Eranti & Lee, 1986). There is significant mixing that causes the river to cool more or less evenly in its vertical profile.

The ice regime of the Neva is characterized by frazil ice, which is a result of the high flow velocities in the Neva. Turbulence prevents the water from freezing and results in a uniformly supercooled water body. Eventually frazil ice crystals will form when the maximum supercooling is reached. In the Neva Delta, where the tunnel is located, the river bed has a shallower slope and hence a lower flow velocity than upstream, meaning much more frazil ice is formed. Frazil ice tends to attach itself to the rough river bed or underneath an existing solid ice cover. These phenomena are known as anchor ice and hanging ice jams respectively, which are both prevalent at the site of the proposed tunnel. The bulk of engineering aspects can be attributed directly or indirectly to this phenomenon. Fig. 5 summarizes the main aspects of the Neva’s ice regime on the tunnel.

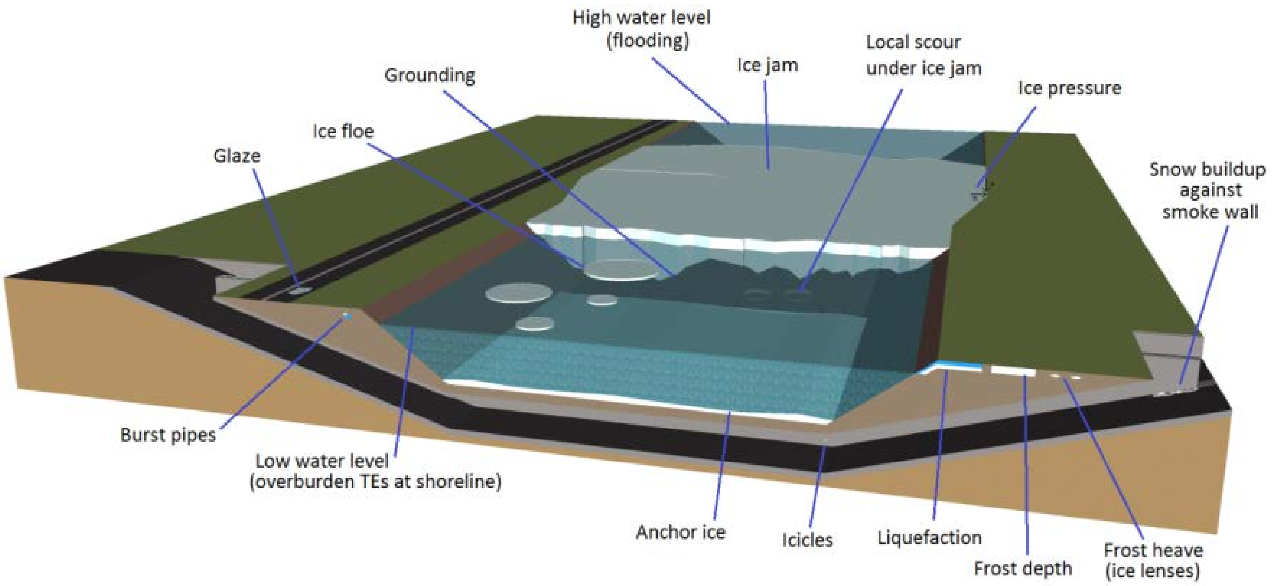

Fig. 5 *Ice regime of the Neva River*

6.1 Effect of Anchor ice and Flow velocity on Tunnel Protection

One point of attention is the backfill and tunnel protection. Anchor ice is common in the Neva Delta and, if attached to the tunnel or tunnel protection, will exert an upward force due to the buoyancy of the ice. While measurements are scarce, a 1m thick ice layer has been reported in the Neva Delta (Altberg, 1936). Calculation models are sensitive to input, resulting in a large range of estimated anchor ice volumes between 0.7 - 7.0 kg/m^3 (Russian State Hydrometeorological University, 2010). Thus, more research on the ice regime in the Neva is required. Without this, a high safety factor should be used on the expected thickness of anchor ice.

The optimal tunnel protection against anchor ice is smooth and heavy. This will reduce accumulation of ice and counter the buoyancy. The commonly applied rock protection layer would attract more anchor ice for several reasons. The gravel will increase turbulence as well as provide more surface area for frazil ice to adhere to. Gravel is also supercooled faster as it is less influenced by the temperature of the river bed than finer soils (Bisaillon & Bergeron, 2007). A rock protection is therefore less suitable at this location.

The tunnel protection must also resist the flow velocities in the open-channel season as well as flow under ice. The flow velocity under a stable ice cover at the Orlovsky tunnel was calculated to be around 0.72 times the flow velocity of the open-channel velocity. However, due to the friction of the ice cover, the maximum flow velocity is closer to the bed and more likely to cause scour. An extreme case can be imagined where a surge of water caused by fast melting snow and ice rushes under a thick ice cover.

A relatively standard rock tunnel protection for tunnels in wide rivers (Fig. 6) was shown to be sufficiently resilient to the effects of both flow velocity and uplift. As such, the influence of ice and flow velocity was not governing to design. Rather, the size of the tunnel cover is governed by the requirements for falling or dragging anchors.

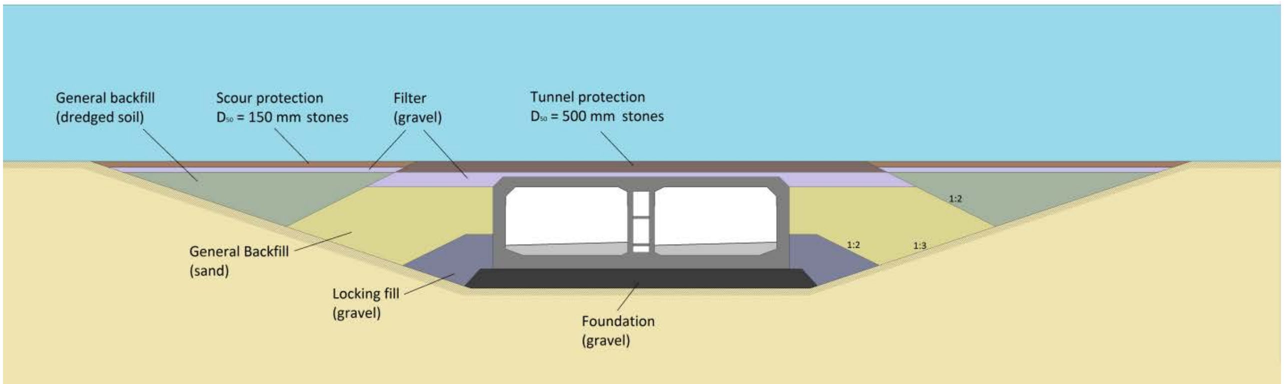

Fig. 6 *Backfill and tunnel protection (inspired by Lunniss & Baber, 2013)*

6.2 Drift Ice

Forces on the embankments caused by drift ice or a moving ice cover can be significant in the case of a vertical face. Field measurements state the maximum ice floe length as 18 m in the Neva River (Russian State Hydrometeorological University, 2010). The resulting shear force on the outer bend of the river is in the range of 2000 kN/m.

The embankments can be designed with a slope in order to force ice to fail by flexure rather than crushing. The buckling strength of ice is much lower than the compressive strength, thus the wall will experience lower forces. An embankment slope steeper than 30° will reduce this load by 50%. However, the embankment would then be susceptible to ice ride-up, which will incur a large surcharge. Ice slabs broken by flexure typically have a length of 4 to 8 times the ice thickness (US Army Corps of Engineers, 2002). With an ice thickness of 0.7 m, the resulting surcharge will be in the range of 30-40 kN/m^2, depending on the applied slope.

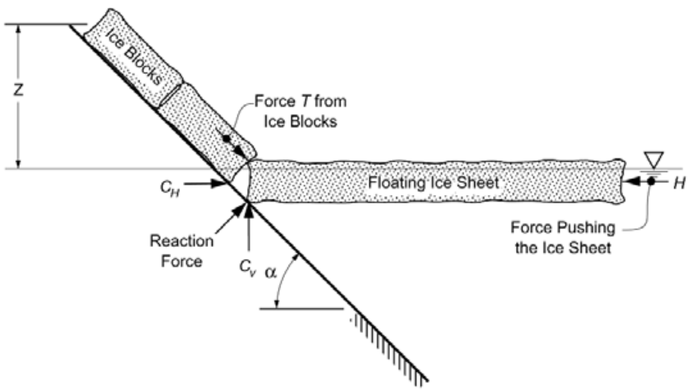

Fig. 7 *Vertical ice loads on sloped embankment (US Army Corps of Engineers, 2002)*

Drift ice impact with tunnel elements should be avoided. This means that elements moored in the river when there is ice must be protected. Consideration must be taken with thermal expansion of ice in the melting season that can cause significant loads on the tunnel elements. Immersion of the tunnel elements will take place when drift ice stops flowing at the immersion site, in lieu of protection measures.

6.3 Ice Jams

Ice jams are likely to occur at sharp bends, constrictions, obstacles, confluences, and reductions in channel slope. The Neva River satisfies all these conditions, which is why ice jams are prevalent. Hanging ice Jams are formed an estimated 9 out of 10 years in the Neva at the Bolsheokhtinsky Bridge, just 1.5 km upstream of the Orlovsky Tunnel. These ice jams are formed during the freeze-up period when ice amasses at the convergence of the bridge and frazil ice flows stick to the underside of the ice cover. These ice jams are found to grow up to 6m thick in the 10m deep river, causing significant blockage. This can result in flooding upstream and low water levels downstream, though the mild slope of the Neva and the tunnel’s proximity to the Neva Bay dampens the latter effect.

Hanging ice jams tend to form in river sections with a Froude number less than 0.08 and a flow velocity less than 0.6 m/s, as is the case just upstream of the Bolsheokhtinsky Bridge. If the more than 100 year old bridge is to be removed the next probable ice jam location is at the tunnel, where the Froude number is 0.06. This would have a very negative impact on the tunnel as scraping forces from moving ice jams will remove the tunnel cover and cause abrasion of concrete. High loads will be found on the tunnel and embankments.

An ice jam will not have an even thickness over the width of the river and will laterally redistribute the river's discharge over its cross-section. This will increase the depth at the outer bend of the river, potentially causing bank instability. In shallower sections, roughness of the ice jam may lead to local scour holes.

Thus, location of the ice jam is crucial in order to take into account the probability of flooding, low water levels, scour, and grounding. If the Bolsheokhtinsky Bridge were to be removed or significantly altered over the design life of the Orlovsky tunnel, measures must be in place to protect the tunnel from ice jams. This can be done by way of permanent piers, ice booms, breakers, or thermal input.

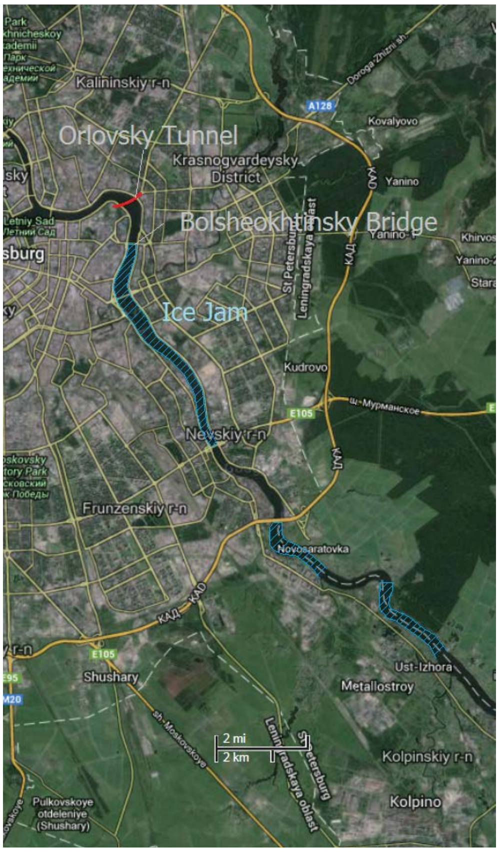

Fig. 8 *Location of freeze-up ice jams*

When temperatures rise, ice will become weaker. For breakup to occur, water velocity must generally be larger than 0.6 m/s (Debolskaya, 2009). This can happen when there is a surge in discharge or a flood wave, often caused by rapid thawing. Flood waves in the Neva are common, though small in amplitude. The river is wide enough in the Neva Delta such that breakup ice jams are uncommon. However, ice runs occur more commonly, which will load the embankments as previously described.

7. Gaskets

Special attention must be placed on the performance of gaskets in freezing temperatures. Gina and Omega gaskets are commonly applied as water seals at immersion joints. They are typically made of styrene-butadiene rubber (SBR), which the most economical and feasible choice for the Orlovsky Tunnel. However, SBR may only be loaded until -30°C. Beyond this, additives are required to prevent cracking. The watertightness of the gaskets is sufficient as long as there are no cracks or other damage to the gasket.

The properties of the rubber need to be specially engineered for the gaskets to reliably perform in the freezing temperatures in St. Petersburg, which can be as low as -36°C. For example, plasticizers will lower the rubber's glass temperature, allowing it to perform at temperatures below -30°C. However, this will also lower the modulus and tensile strength.

Before application, the gaskets may be stored at any temperature as long as the gaskets are not loaded. Even if the elastomer is frozen temporarily it will regain its rubber properties as soon as it warms up. During transport, the gaskets are folded in containers and some sections will be strained. Thus, transport should not be done at extremely low temperatures and gaskets should be stored unfolded.

8. Temperature Loads

The temperature loads in subarctic regions are more extreme. The large temperature difference between the inside and outside of the tunnel will cause steep temperature gradients in the walls and slabs of the tunnel. These gradients will cause a differential in expansion and/or contraction, causing bending moments and shear forces in the sections and in the walls or slabs that restrain these sections. The maximum temperature gradient that is typically considered is in the order of ±10℃. In the case of the Orlovsky Tunnel this can be up to 30°C due to the assumed longitudinal ventilation. The effects and magnitudes of following thermal loading aspects were analyzed for Orlovsky Tunnel:

- Temperature differentials in the walls.
- Differences in average temperatures of the outer sections and the inner walls.
- Temperature fluctuations and expansion joints.

The first two effects are illustrated in Fig. 9. The temperature distribution can be split into an average temperature and a differential. The mean temperature will cause the structural element to expand or contract, while the temperature differential will cause a bending moment. In the preliminary stage a linear temperature distribution is assumed, which means that eigen temperatures are neglected.

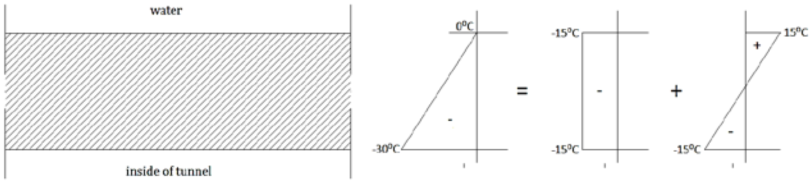

Fig. 9 *Temperature distribution in tunnel sections*

The temperature differentials will cause bending. A plastic analysis in the ultimate limit state (ULS) determined that the rotational capacity of the plastic hinges is sufficient to handle these moments, due to the sheer size and stiffness of the tunnel cross-section (see Fig.). This means that the load factor for the temperature differential load can be set at γ=0 in all limit states, because of the differentiation between load and deformation.

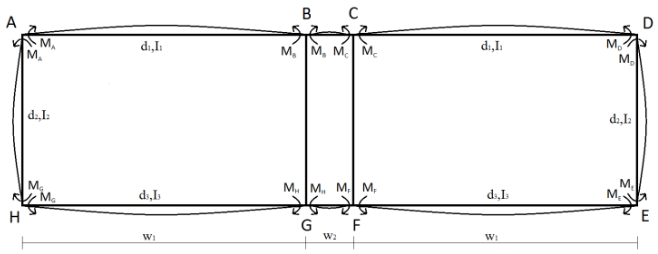

Fig. 10 *Tunnel deformation due to thermal distribution in tunnel sections*

The inner walls of the tunnel element will be exposed to cold temperatures on both sides of the walls, meaning its average temperature can be up to 15℃ cooler than the outer sections. This means that the inner walls will contract more than the outer sections. The inner walls will also shrink more due to drying shrinkage.

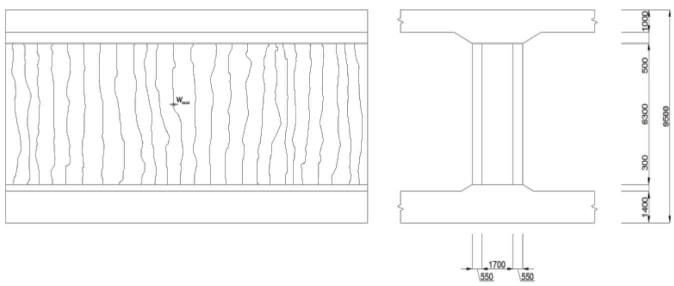

Fig. 9 *Cracking due to difference in average temperatures of slabs and edge restraint*

The edges of the inner walls are restrained at the top and bottom slabs. The difference in total shrinkage may thus result in cracking of the inner walls. This crack width must be limited due to the presence of de-icing salts. This was shown to be possible in the Orlovsky Tunnel by applying extra horizontal reinforcement in the inner walls (Fig. 9).

The large temperature range in St. Petersburg will cause large expansions and contractions of the tunnel elements, which may then require exceptionally large expansion joints. In order to reduce the size of the expansion joint, shorter tunnel elements may be considered. However, this will increase the number of immersions, which should be limited in order to be able to perform all immersion activities in a single open-channel period.

9. Execution

Often the most cost-effective solution to dealing with subarctic phenomena is to avoid them. Planning such that critical construction stages endure mild conditions will lead to improved safety, higher efficiency, and higher quality. In order to have a shorter construction time it may not always be possible to avoid subarctic circumstances. Construction processes can be adapted (such as applying methods of cold weather concreting) or protected (such as a construction hall over the tunnel elements). Cold weather construction aspects such as accessibility, efficiency, hours of daylight, depreciation of equipment, and labor regulations will affect both cost and construction time and should be considered. Overall planning and methodology will ultimately depend on the results of a cost-benefit analysis.

In order to quantify costs and risks of the construction process a risk analysis should be done. A Monte Carlo simulation was done for the Orlovsky Tunnel. The critical construction activities in the ice-free period are dredging, foundation, immersion, and backfill. Probabilistic distributions were defined for the construction activities, defined as the internal risks, and for external risks such as ice cover duration, flood waves, poor weather, high flow velocity, shipping traffic, and so forth. Fig. 10 shows the probability of ice formation on the Neva River in St. Petersburg. It was found that construction is possible in a single ice-free period.

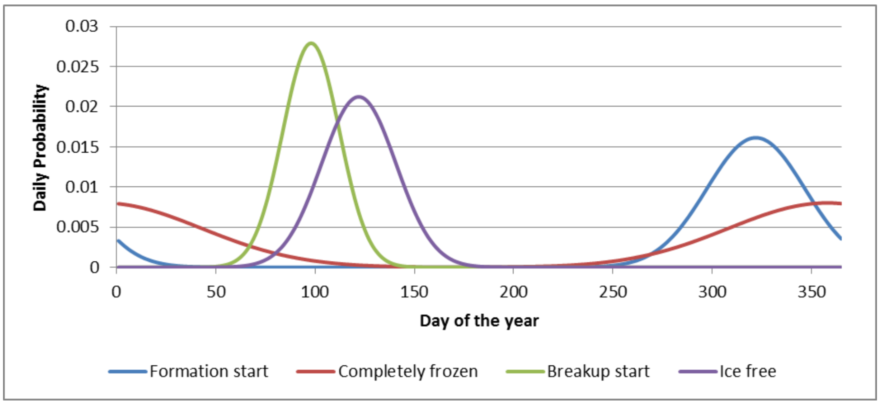

Fig. 10 *Ice cover formation and breakup: daily probabilities*

The outcome of the simulation was the valuation of risk of non-completion before ice formation and allows one to observe which processes are governing. It showed that waterway construction activities can fit in one summer with an acceptable risk. External risks during construction can be mitigated by forecasting, while monitoring of the construction process will reduce internal risks. Risk of non-completion is reduced by reducing the number of tunnel elements. Ice booms and frazil collectors are feasible emergency measures if construction extends into the freezing season. Frazil collectors and ice booms can increase construction time by up to 10 days if needed. Monitoring and predicting weather will aid in predicting the date of onset of frost, which will reduce external risk.

Dredging has the largest standard deviation, because of ordnance and contaminated soil. Ordnance detection with a magnetometer is recommended in order to account for bombs or for early removal. Multiple or high capacity dredgers would reduce the dredging time and further reduce the probability of non-completion.

Obstruction to shipping can be mitigated, though not completely avoided. Waterway works like dredging, placing the foundation, and backfilling can be done while the bridges are closed and no large ships are expected at the tunnel. When the bridges open, the construction vessels can be anchored at the existing anchoring point on the inner bend of the Neva at the tunnel. During immersion, the waterway should be closed to traffic. Choosing a gravel foundation will allow ships to pass over the tunnel sooner while it is also beneficial to construction time.

10. Conclusion

The urgency and added value of the Orlovsky crossing as a tunnel is evident and an immersed tunnel would provide a functional and economical solution. An immersed tunnel would offer a high level of safety, functional intersections, and good integration into the urban environment, while technical and practical solutions exist to mitigate challenges posed. All in all, this article has shown that an immersed tunnel is a suitable and effective solution for the development of St. Petersburg, or any other subarctic urban environment.

11. References

[1] Altberg, W. *Twenty years of work in the domain of underwater ice formation*. International Union of Geodesy and Geophysics. International Association of Scientific Hydrology, 1936.

[2] Bisaillon, J., & Bergeron, N. E. *Modelling anchor ice presence-absence in gravel bed streams*. In C. H. Environment (Ed.). 14th Workshop on the Hydraulics of ice Covered Rivers, 2007.

[3] Debolskaya, E. *Numerical Modeling of Ice Regimes in Rivers*. Hydrological Systems Modeling (Vol. 1). EOLSS Publishers/UNESCO, 2009.

[4] Eranti, E. M., & Lee, G. C. *Cold Region Structural Engineering*. McGraw-Hill, 1986.

[5] Freitag, D. R., & McFadden, T. *Introduction to Cold Regions Engineering*. American Society of Civil Engineers, 1997.

[6] Lunniss, R., & Baber, J. *Immersed Tunnels* . (1 ed.). CRC Press, 2013.

[7] Russian State Hydrometeorological University. *Proceedings of the Russian State Hydrometeorological University, number 14.* (L. Carlin, Ed.), 2010.

[8] Ryzhevsky, M.E. *And again to the question of the Orlovsky Tunnel. Afterword*. Innovation in Construction No. 35, 2014.

[9] US Army Corps of Engineers. *Engineering and Design: Ice Engineering.* Department of the Army, 2002.

[10] Vodokanal St. Petersburg. *Water supply system*. http://www.vodokanal.spb.ru/en/vodosnabzhenie/struktura_vodosnabzheniya/, 2014.