Immersed tunnel design in subarctic rivers

Bergsma, J.G.; Bakker, Klaas Jan; 't Hart, CMP

DOI
10.1016/j.tust.2017.04.010

Publication date
2017

Document Version
Accepted author manuscript

Published in
Tunnelling and Underground Space Technology

Citation (APA)
Bergsma, J. G., Bakker, K. J., & 't Hart, CMP. (2017). Immersed tunnel design in subarctic rivers. *Tunnelling and Underground Space Technology*, *67*, 158–166. https://doi.org/10.1016/j.tust.2017.04.010

Postprint of Tunnelling and Underground Space Technology
Volume 67, August 2017, Pages 158–166
Link to formal publication (Elsevierhttps://doi.org/10.1016/j.tust.2017.04.010

Author: J.G. Bergsma [a,b,c]
Co-author: K.J. Bakker [b,d]
Co-author: C.M.P 't Hart [a,c]

[a]Tunnel Engineering Consultants (TEC), Laan 1914 35, 3818 EX, Amersfoort, The Netherlands.
[b]Delft University of Technology, Faculty of Civil Engineering, Department of Hydraulic Engineering, Stevinweg 1, 2628 CN, Delft, The Netherlands
[c]Royal HaskoningDHV, George Hintzenweg 85, Postbus 8520, 3009 AM, Rotterdam, The Netherlands
[d]WAD43 bv, Prins Willem Alexanderdijk 43, 3402 PJ, Ijsselstein, The Netherlands

Immersed Tunnel Design in Subarctic Rivers

1 INTRODUCTION

The demand for tunnels crossing waterways in urban areas is expanding into colder regions, with immersed tunnels an increasingly competitive alternative for waterway crossings. Recent examples of new immersed tunnels affected by cold weather include the Bjørvika, Söderstrum, and Marieholm tunnels in Norway and Sweden. This article aims to describe the practical and technical issues related to applying the immersed tunnel construction method to colder regions for them to stay competitive.

An initial distinction can be made between tunnels crossing large water bodies and tunnels crossing rivers based on the differences in their ice regimes. For example, one of the main ice related issues for immersed tunnels crossing seas and lakes is ice pile-up, which results in heavy loading of the approaches and mechanical scour of the seabed. This is an issue which is relatively well documented and has been taken into account in projects like the Øresund tunnel. The ice regime of a river is quite different, where issues for immersed tunnels have thus far gone undocumented. Subarctic issues typical in river ice regimes may include ice jams, anchor ice, surges, water level drops, and thermal expansion of ice, as well as unfavorable material behavior.

2 THE ORLOVSKY TUNNEL

Since every project is defined by its local conditions, the Orlovsky Tunnel in St. Petersburg, located at the edge of the subarctic, served as a case study for research on this topic. The Orlovsky tunnel was proposed to be the first permanent link between the North and South parts of St. Petersburg, but the chosen bored tunnel variant was subsequently scrapped and the project has since been dormant. The Orlovsky Tunnel is meant to cross the Neva River in a 600 m wide and 16 m deep river bend, in soft soil, and with limited space on either riverbank, which plays into the advantages of an immersed tunnel over other options. The Neva River is a fast flowing river with a steady hydroregime due to the regulating influence of Lake Ladoga at its source and is frozen for about 3-5 months per year. The river has an average discharge of 2510 m^3/s and flow average velocities vary along the between 0.43 and 1.03 m/s. Its highest flow velocities (up to 1.37 m/s) occur in spring when snow and ice melt, which can double its discharge compared to its average.

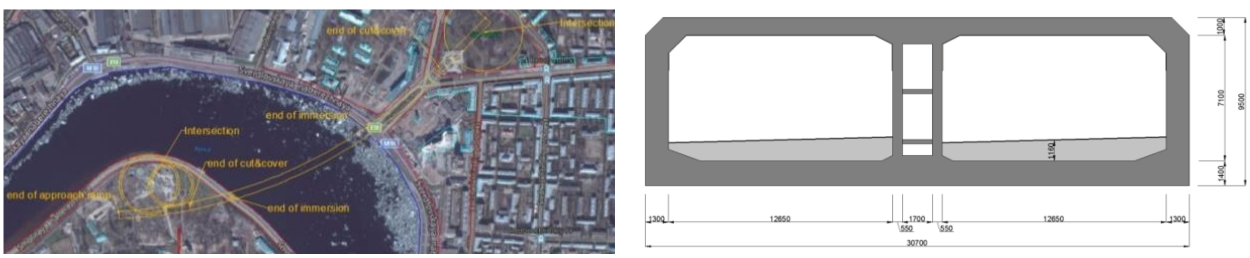


Figure 1 Preliminary design of the Orlovsky Tunnel

A preliminary design of an immersed tunnel resulted in the general cross-section seen in Figure 1, which was used for evaluation of subarctic issues. In order to meet the traffic requirements, the tunnel consists of 2 tubes with 3 lanes each and a central service gallery. The maximum depth of the tunnel floor is around 27 meters due erosion at the outer riverbank.

Average monthly temperatures in St. Petersburg are between -7.7°C and +17.8°C, and maximum and minimum temperatures are +33°C and -36°C respectively. Figure 2 shows the average daily temperatures in St. Petersburg over the period of 1960-1995.

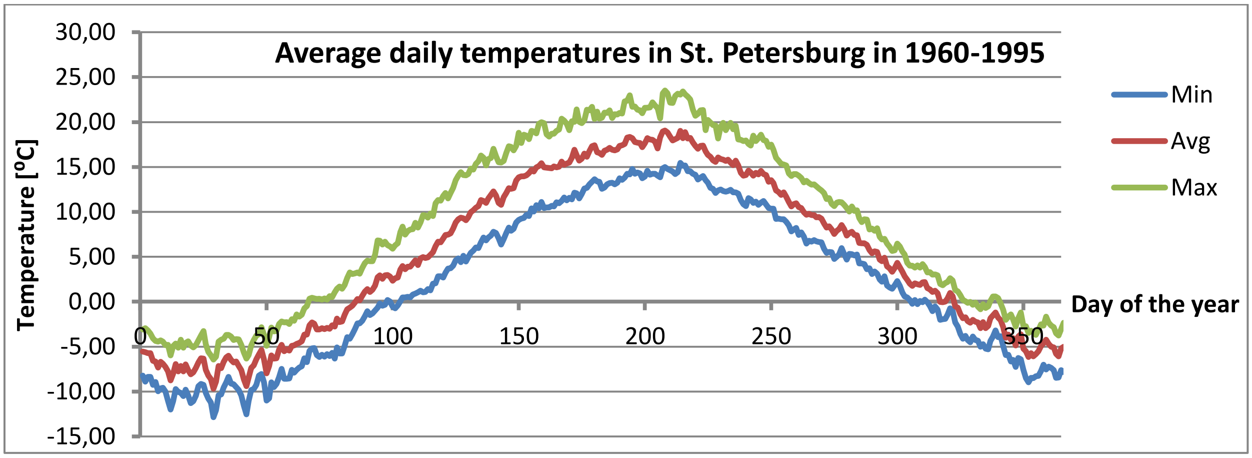


Figure 2 Temperatures in St. Petersburg

In a strong winter the surface ice cover is around 70 cm thick, while there may also be 100 cm of anchor ice on the riverbed. The only data point, however, was obtained in 1914, which showed that the entire Neva bottom in St. Petersburg was covered by a 1 meter thick layer of porous anchor ice (Altberg 1936).

3 IMMERSED TUNNELING IN THE SUBARCTIC

Some of the main challenges for immersed tunneling in the subarctic are the result of low temperatures and ice formation. The workable period for immersion and waterway activities will be reduced by the climate, reducing it to the ice free period. Tunnel element transport, mooring, immersion, dredging, and placing of a foundation may not be favorable, or even possible, in the winter months.

For wintertime construction one must also take into consideration the working conditions, reduced efficiency of working in the cold, regulations, safety, depreciation of equipment, hours of daylight, and so forth. The tunnel elements may be constructed on the inner bank of the river bend, close to their final location, which would reduce transport time in the ice-free period. By constructing the tunnel elements in the winter prior to immersion, the construction time can be reduced.

Winter construction activities will have to take freezing temperatures into consideration. For example, while concrete immersed tunnel sections are generally cooled with pipes to prevent thermal cracking, in the subarctic, concrete may have to be pre-heated and insulated to prevent freezing (and possibly post-cooled when hardening as well).

4 ICE REGIME OF RIVERS

The ice regime of a river is determined by several factors, of which the two main ones are cooling rate and turbulence of the water. The type of ice that will form in rivers is dependent on the flow velocity (v), which largely determines the turbulence in the river, and the rate of cooling ($\dot{\phi}$) as shown in research by (Ashton 1988) summarized in Figure 3. The main mechanisms of ice formation in the Neva River involve frazil ice, drifting ice floes, and large ice accumulations (Eranti en Lee 1986), due to its fast flow regime.

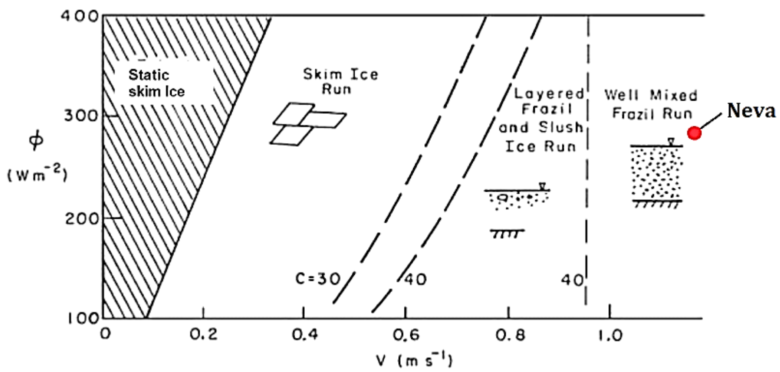


Figure 3 Initial ice formation (Ashton 1988)

4.1 *FRAZIL ICE*

Frazil ice is formed in turbulent water bodies, usually caused by wind in lakes and seas or high flow rates in rivers. The turbulence causes the water body to mix as it is cooled, resulting in a uniformly supercooled water body. Frazil ice crystal will start to form once the frazil ice nucleation point, T_{min}, is reached, which is only just below 0°C.

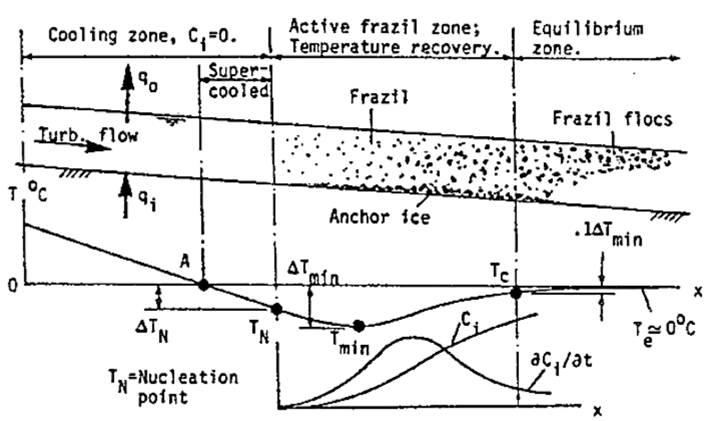


Figure 4 Development of frazil ice and ice anchors (Tsang, 1988)

When flow velocity decreases in a river, this point, T_{min} increases, which is why frazil ice is often found in mildly sloped river sections. Once ice crystals form, the supercooled water will have an attachment point for more crystals to form, resulting in a process known as secondary nucleation. The crystals agglomerate to form frazil ice pans or ice disks, which accumulate until a solid ice cover is formed. The ice cover will continue to grow by frazil ice sticking underneath. The ice cover begins formation at the river mouth and expands upstream.

The high flow velocities and rapid cooling present in the Neva result in strong frazil flows with large-scale deposition in the Neva Delta. Frazil crystals are buoyant, but turbulence generally keeps them submerged in the water body (Tsang 1988). At the end of the Neva, in the Neva Delta, the slope decreases and frazil ice builds up on the river bottom to form anchor ice.

Like many rivers, quantitative data on frazil production and the formation of sludge in the Neva is scarce. Measurements have seldom been carried out and are difficult to come by. Numerical methods can calculate the maximum possible buildup of frazil, though the range of the results is large (in the Neva: 0.7 - 7.0 kg/m^3s). Thermal pollution and climate change are shown to cause longer periods of frazil production in the Neva, and higher recurrence and larger volume anchor ice and ice jams. Local monitoring would be required to get reliable figures on frazil ice production to account for the maximum size of ice jams and anchor ice accumulation for tunnel design.

4.2 *ANCHOR ICE*

Frazil ice has a strong adhesion to objects. Objects with a higher roughness will have more frazil accumulation, and any cables or nets in the river can expect to experience a heavy buildup of ice. Frazil ice that nucleates and sticks to the bottom of a river is known as anchor ice. Anchor ice has been shown to form in rivers with a Froude number smaller than 0.2 (Bisaillon en Bergeron 2007). Anchor ice is buoyant and will exert a lift force capable of lifting large clumps of soil and in some cases large boulder.

The buoyant force may pose a risk to an insufficiently ballasted tunnel element. Thick anchor ice in a river may also create blockage that raise water levels upstream, increasing the risk of flooding.

4.3 *ICE JAMS*

Ice jams are obstructions to the flow of water due to ice accumulation. They are likely to occur at sharp bends, decreases in channel slope, constrictions, obstacles, and confluences. The Neva Delta satisfies all these conditions, which is why ice jams occur almost yearly. The following figures show two discernible types of ice jams: freeze-up and break-up.

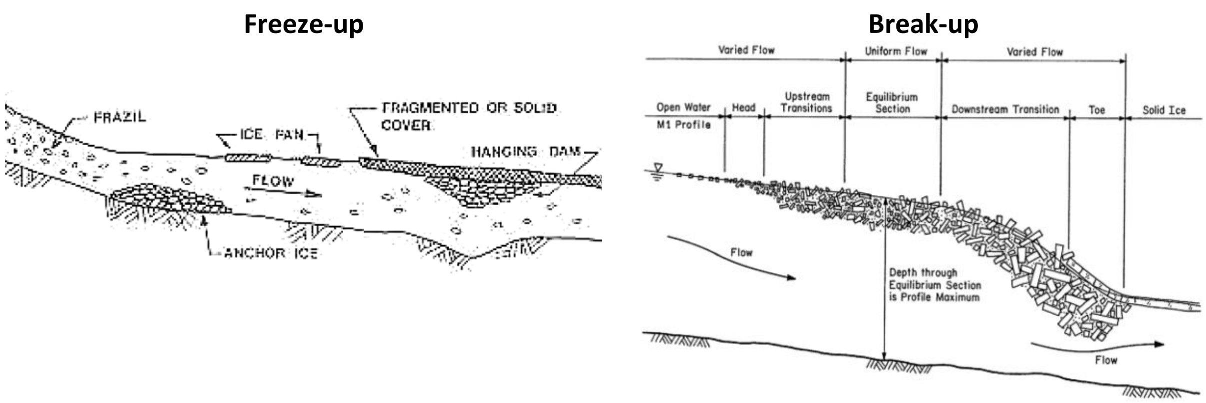


Figure 5 Ice jam types (The New Brunswick Subcommittee on River Ice 2011) (US Army Corps of Engineers 2002)

Freeze-up jams occur at the start of the cold season when freezing starts. In the Neva, border ice is formed on the banks and in Lake Ladoga. Frazil particles, formed by the still high flow velocity, adhere together to form clusters and travel downstream in the form of ice pans. These ice pans tend to get stuck at river sections where the velocity is less than 0.6 m/s or where the Froude number is lower than 0.08. These then form a solid layer of soft ice on the river and frazil ice will attach itself underneath, forming a hanging ice dam.

A hanging ice dam will cause an obstruction of flow, causing more and more frazil ice to accumulate and forming the ice jam. Upstream of the ice jam the flow velocity decreases and the water level increases. The decrease of flow velocity upstream causes the formation of anchor ice, which ice further slows down the flow velocity, contributing to the ice jam and moving the obstruction farther upstream.

Breakup jams occur at the end of the cold season. Though temperatures are generally still near freezing during the breakup, the higher temperatures cause a strength reduction in the ice. The water velocity must generally be larger than 0.6 m/s for breakup to occur in rivers (Debolskaya 2009). This can happen, for example, when there is a surge in the discharge or a flood wave. Breakup ice jams form and progress quickly. They are highly unstable due to unsteady flow and will often break and reform downstream. The roughness of a breakup jam is high, making large-scale scour underneath the ice jam likely. A midwinter jam caused by shifting of ice cover may freeze again, resulting in flooding behind the jam and scour underneath. This is a relatively common occurrence in the Neva River.

4.3.1 ICE JAM GROUNDING

Ice jams may grow to the point where they are grounded and moving along the riverbed. Grounding of ice jams usually occurs near channel banks, the jam toe, and at shallow river sections. Extensive grounding may occur when discharge, and thus water level, drop and cause the ice jam to drop with it. Residual flow underneath ice jams will move it by friction, which means a grounded ice jam will exert both vertical and horizontal forces on the riverbed and tunnel.

4.3.2 FLOODING UPSTREAM

In the upper reaches of the Neva, flooding occurs often. The riverbanks should be designed to an acceptably low risk of flooding of the tunnel, and the tunnel itself should be designed against the accidental case of flooding. At the Orlovsky tunnel the maximum water level is +1.95 m BS with a return period of 100 years (Shiklomanov 2010), which is 1.65 m above the average water level. The riverbanks within the city limits have a height of about +4 m to +6m BS. Thus, the tunnel’s level of safety against flooding due to ice jams is good.

4.4 *DRIFT ICE*

Drift ice flows down rivers during ice cover formation in autumn and break-up in spring. The properties of ice in these periods strongly differ in density. Frazil ice in autumn consists of much softer slush ice pancakes than in spring, when border ice breaks loose and floats downstream in large, hard chunks. Field measurements have stated the maximum ice floe length in spring as 18 m (Russian State Hydrometeorological University 2010). A collision with a floating tunnel element's wall or bulkhead could potentially cause structural damage and leakage.

In spring, ice floes may be controlled in a manner that prevents collisions in order to increase the workable period in the river. In autumn, collision loads will be much smaller, but the frazil ice will attach to anything exposed in the river. Immersion of tunnel elements may be possible, though in the Neva frazil ice will hinder immersion. Ice sticking to the bottom of the tunnel element would disturb the sand flow operation and would impair its vertical position regardless of the chosen foundation type.

4.5 *WINTER FLOW PROFILE*

When ice forms in a river, the wetted perimeter of the river essentially increases. This decreases the hydraulic radius of the river and increases the total roughness, which can be expressed as a combined Chézy-coefficient. The maximum velocity will no longer be near the surface of the river as it is in open channel flow, but closer to the center. Research on flow under ice in shallow rivers of 2 to 5 meters deep in the USA showed that the location of the maximum velocity was an average of 0.37 d below the ice in shallow rivers (varying from 0.19 to 0.52). The maximum velocity was approximately 1.2 times the average velocity (Barrows en Horton 1907).

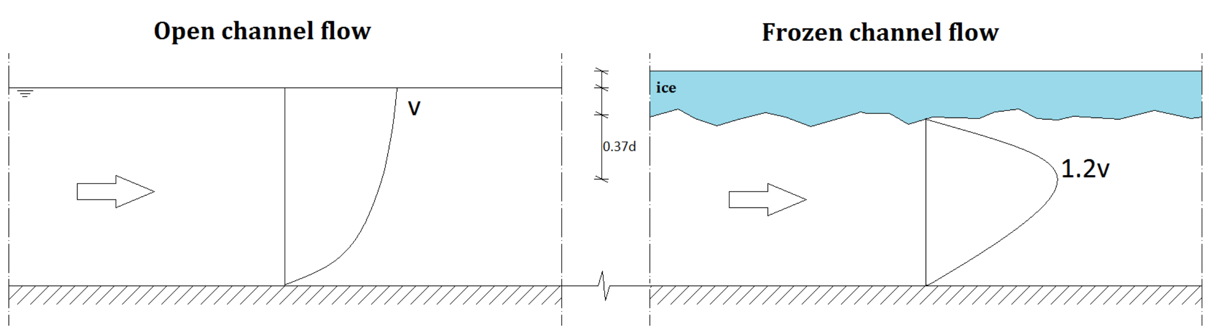
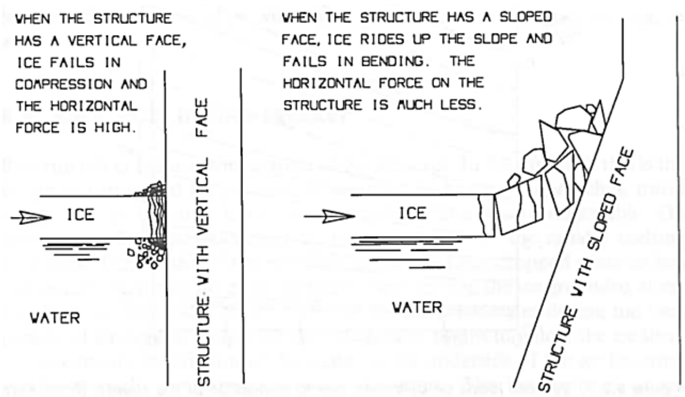


Figure 6 Flow velocity profile when ice-free (left) and under an ice cover (right)

Due to the presence of frazil ice in the Neva River, the bottom of the ice cover starts rough, but smooths out over time, such that the position of the maximum flow velocity changes over time. The Neva riverbed's roughness coefficient is approximately equal to that of frazil ice. By using Chézy's formula for flow velocity, the discharge capacity of the Neva River can be calculated as 72% of the open channel velocity, which close to the 60% figure for discharge capacity and flow velocity measured by (Shiklomanov 2010).

4.6 *LOADS ON EMBANKMENTS*

Horizontal ice loads on the embankments can be significant to the point where a sloped embankment may be preferable to reduce this load. The ice load on the structure is typically limited by failure of the ice by crushing or flexure. Crushing failure is typically much larger in magnitude than flexural failure. Flexural failure can be induced at a smaller force by applying a sloped embankment as shown in Figure 7.



Inclination	Force magnitude
$0° - 15°$	100%
$15° - 30°$	75%
$30° - 45°$	50%

Table 1 Reduction of horizontal load depending on inclination (Freitag and McFadden 1997)

Figure 7 Shear forces on ice structures (McFadden and Bennett 1991)

The consequence of such a design choice is that the inclination will induce vertical forces on the embankment, and hence, the tunnel. Main causes of these surcharges are thermal expansion, ice sheet drag, water level fluctuations, and ice ride-up.

4.6.1 THERMAL EXPANSION

When a river freezes over, the ice thickness will increase without an increase in surface area, due to the geometrical constraints. This will continue with hardly any lateral forces. When the temperatures rise again, the ice cover will expand, resulting in pressures on the riverbanks. The magnitude of the thermal expansion load will depend on the condition of the ice, loading rate, geometry of the embankment, and friction factor between the ice and the embankment.

The large width of the Neva means that there will be failures in the ice at other locations than the embankment, known as multi-zonal ice failure. The loading on the embankment will thus be minimal.

4.6.2 ICE SHEET DRAG

The ice sheet will move as a whole under the influence of wind and water flow. Rubble will mount in front of longer embankments, which will spread the load. The rubble in front of the moving ice sheet will also likely have an angle to the horizontal, which will induce flexural failure of the ice such that this load will not govern design.

4.6.3 WATER LEVEL FLUCTUATIONS

Ice sheets will move up and down due to water level fluctuations. These water level changes may drop quickly due to an ice jam upstream, or rise suddenly from a flood wave. Depending on the adhesion of the ice sheet to the embankment, this will induce vertical forces. A rapid rate of water level change will increase the magnitude of the vertical force. In wide channels (width > 5 times the maximum drift ice length) ice will fail flexurally, causing cracks and reducing vertical forces. The maximum force is limited by ice strength, calculated under strip loading (Eranti en Lee 1986). In the Neva, a water level change larger than 0.23 m will cause cracking and will not induce larger vertical forces on the embankment.

4.6.4 ICE RIDE-UP

The downward force, however, is governed by a mechanism other than water fluctuation. Ice will ride up and rest the embankment. When ice is pushed up a sloped embankment, it fails flexurally and rests on the ice cover. The total ice force on the embankment is a combination of the weight of the ice blocks and the force from flexural failure of the ice on the slope.

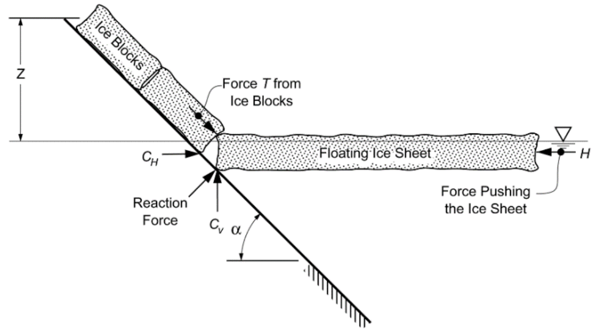


Figure 8 Vertical ice forces on inclined embankments (US Army Corps of Engineers 2002)

Ice slabs broken by flexure typically have a length of 4 to 8 times the ice thickness (US Army Corps of Engineers 2002). Assuming two blocks with a thickness of 0.7 m stacked on the embankment at an angle of 20^{o} the stacking height is 5.3 m, resulting in a vertical force in the order of 40 kN/m. A steeper slope will have a smaller vertical load. The worst case scenario for the shear keys would be a large buildup of ice in combination with a low water level.

5 DESIGN & EXECUTION

The design of an immersed tunnel in subarctic conditions is largely the same as in other scenarios, with the addition of thermal and ice load cases on the tunnel and its surroundings. These loads are particularly prominent in the design of the tunnel protection layer and the shear keys. Additional measures may be necessary to protect the tunnel from ice jams as well.

Execution is considerably affected by cold temperatures and workable periods.

5.1 *DESIGN OF TUNNEL AND SCOUR PROTECTION*

The tunnel and scour protection placed on top of the immersed tunnel should be robust in order to account for ice jams, anchor ice, winter flow velocities and surges. To this end, the design should consider prevention or reduction of these phenomena at the tunnel location, design for accidental load cases, and contingency measures in the case of extreme loading. The tunnel protection design must account for the high flow velocities and lift from anchor ice resulting from the river’s ice regime.

The optimal tunnel protection designed for anchor ice is smooth and heavy. Typically applied riprap would attract more anchor ice for several reasons. More turbulence due to a higher roughness of the rock will encourage frazil ice production, while the larger exposed surface area will accommodate more frazil ice to adhere to it. Rock is also supercooled faster as it is less influenced by heat from the riverbed than finer soils, meaning that it initiates ice crystallization quicker (Bisaillon en Bergeron 2007).

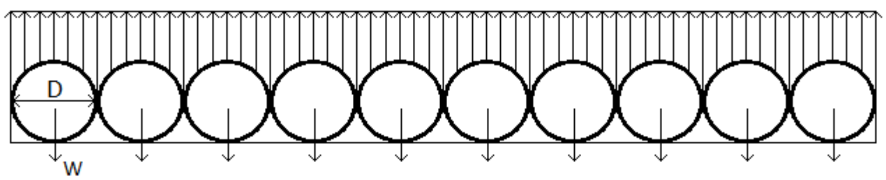


Figure 9 Anchor ice acting uniformly on a layer of riprap

In order to calculate the rock size of the protection layer, a simplified model can be conceived where a volume of anchor ice acts on a row of spherical rocks. The upwards force on the riprap should balance with the downwards immersed weight of the rock. Anchor ice occurs on a yearly basis, so it should be considered as a variable load rather than an accidental load. By this method the minimum rock size for a 1.3 m column of anchor ice and a safety factor of 1.5 is approximately 220 mm, which is larger than the typical rock protection applied on top of immersed tunnels in wide rivers. It must be noted, however, that while flow velocity can still be governing to design, in the Neva River this is not the case.

Calculation of the required median stone size to resist the flow velocity can be done be choosing a threshold of motion. The drawback of using this method, however, is that the associated formulae assume an open-channel (CIRIA, CUR, CETMEF 2007). More research is required to design rock protection in a frozen channel, though by underestimating the hydraulic radius a first estimate of rock size can be calculated. In the Neva, the maximum average flow velocity of 1.37 m/s, resulting in a surface velocity of approximately 2.1 m/s, was shown not to lead to excessive rock protections.

A damaged tunnel protection will increase the effect of loads from sunken ships or falling anchors on the tunnel. The tunnel's factor of safety against uplift is lower with less soil weighing the tunnel down, and if anchor ice is able to attach to the tunnel, the Gina gaskets may be at risk of cracking if they are left unprotected.

5.2 *SHEAR KEYS*

A subarctic river will typically have a summer and winter bed. An ice cover will not have the same thickness or depth in the river's cross-section. Instead, it will vary in thickness and roughness and will cause concentrated flow on sections of the riverbed, causing local scour. Turbulence inside a scour hole, or behind soil deposits, will encourage the nucleation of frazil ice in the water and on the soil surface. An ice cover begins formation at the riverbanks, thereby increasing flow velocity in deeper sections of the channel. More scour can thus be expected in the main channel, while sedimentation increases at the banks. This can cause steep riverbanks, which will lead to a highly variable surcharge over the longitudinal alignment of the tunnel. The steeper banks will result in very large forces in the shear keys. In combination with freeze-thaw in the soil, the riverbank may also become unstable. On top of this may be the surcharge on the embankments as a result of ice loading.

A mitigating effect exists in river bends, where the effect of the ice's friction causes the secondary flow to split into two weaker spirals as shown in Figure 10. This reduces deposition on the inner bank and as a consequence reduces erosion at the outer bank.

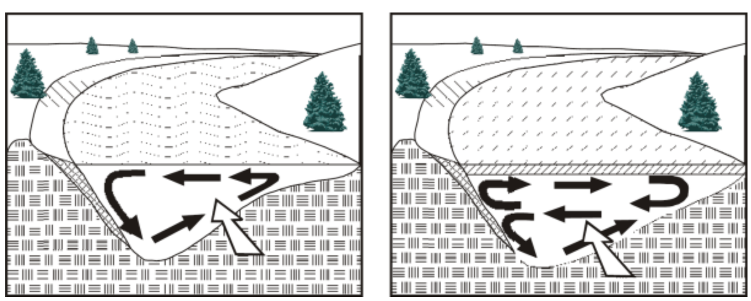


Figure 10 Secondary flow in an ice-covered river bend (US Army Corps of Engineers 2002)

The long-term effect of the Neva's variable river morphology must also be taken into account.

5.3 *ICE JAMS AT THE ORLOVSKY TUNNEL*

Freeze-up Ice jams occur with a likelihood of about 90% in St. Petersburg. Their location is highly dependent on the discharge at freeze-up. Since the discharge in the Neva is fairly constant on a yearly basis, ice jams are most likely to occur in 3 locations. The first place where they occur is at the Bolsheokhtinsky Bridge (see Figure 11), due to the piers of the bridge and the narrowing of the channel. The longest ice jam recorded here was 22 km long, starting just 1.5 km upstream of the Orlovsky tunnel. These ice jams can reach a thickness of 6 m (Russian State Hydrometeorological University 2010) in the 10 m deep river (its hydraulic radius at this location). The other 2 locations are at the Big Obukhovsky Bridge and just upstream of the river bend at Ust-Izhora (Shabanov 2009).

Though these are the most common locations of ice jams, they can occur anywhere. The location of an ice jam has shown to be highly dependent on the water level of Lake Ladoga at the start of winter. The most probably ice jam location can thus be predicted at the start of the winter (NPK Proektvodstroy sd).

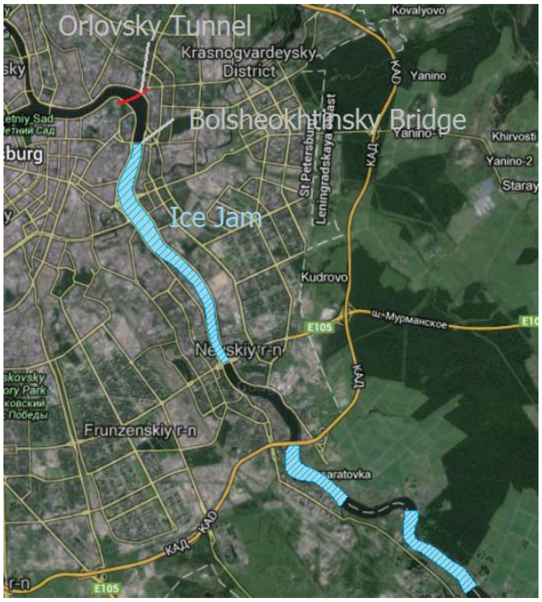


Figure 11 Most probable ice jam locations on the Neva (Google Maps)

The Bolsheokhtinsky Bridge was constructed in 1911 and has had major overhauls over the years. It was last renovated in 1997. Considering the typical functional life of an immersed tunnel of 100-120 years it is possible that this bridge will not remain for the entire lifespan of the Orlovsky tunnel. If the bridge is removed, the next probable location for the ice jam is at the Orlovsky tunnel in the river bend. This is an undesirable situation as it would result in large vertical loads of the stacked ice and horizontal loads caused by the scraping motion of the grounded ice jam.

While breakup ice jams in the Neva are relatively uncommon, the river has a marked increase in discharge, typically in April. Flood waves at this time are common, though small in amplitude. The river is wide enough in the delta region such that spring breakup jams are uncommon. Ice runs do occur, but have little direct effect on an immersed tunnel in its operation phase. Due to the shallow slope and the steady water level in the Gulf of Finland, the water levels in the Neva Delta are not sensitive to discharge fluctuations and the risk of ice jam grounding will be minimal at the tunnel.

5.4 *ICE JAM CONTROL*

Grounding of ice jams, in any case should be avoided by forcing ice jams to form elsewhere. Ice jams can be controlled by structural and non-structural measures. Structural measures will affect the morphology of the river as a whole and non-structural measures will have only a short term effect on the river. Generally, it is easier to prevent ice jams than to remove them.

5.4.1 STRUCTURAL MEASURES

In rivers with frazil ice it is possible to encourage ice sheet formation in order to minimize or fix the location anchor ice and hanging ice jam formation. The Froude number should be between 0.08 and 0.15 to promote stable ice cover growth. Below 0.08 frazil ice is deposited, creating hanging ice jams. Above 0.15, ice floes will slide under the existing ice cover to form an ice jam (Freitag and McFadden 1997).

Altering the Froude number of a river would involve substantial adaptation of the river, such as changing the roughness or slope of the river. In St. Petersburg, extensive river works like these may be an option if flooding in the upstream sections of the Neva is to be tackled. However, for the Orlovsky tunnel, a simpler option is to place piers upstream of the tunnel to fix the location of the yearly ice jam. This is essentially what the piers of the Bolsheokhtinsky Bridge are currently doing. If this 105 year old bridge is ever removed, the piers could remain in the absence of another solution. A weir may be a solution as well, though this will change the hydraulic conditions of the river.

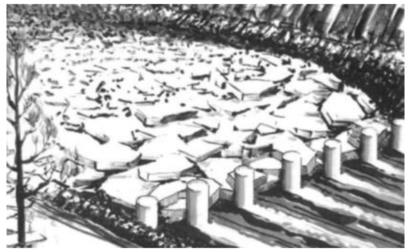


Figure 12 Cylindrical piers encourage ice jam formation (White, Ice Jam Mitigation 2005)

5.4.2 TEMPORARY MEASURES

Alternatively, ice booms can be used, which block ice at the water surface. These can be effective for stopping slow drift ice and slush traveling up to 0.6-1.4 m/s (Foltyn en Tuthill 1996). The booms encourage rapid ice growth by collecting frazil ice and prevent ice from moving downstream. During breakup, booms can be used to redirect ice around an area. The downside is that the booms would have to be placed yearly at the end of the navigable season in order to allow ships to pass.

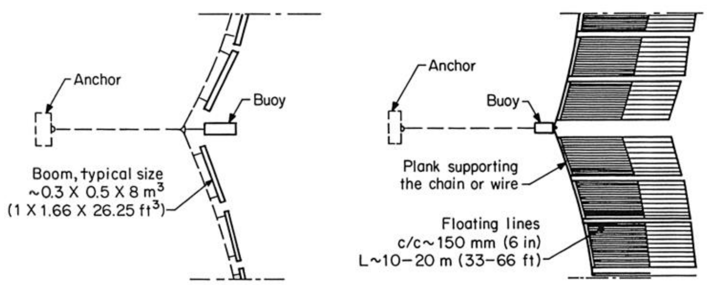


Figure 13 Ice boom (left) and frazil collector (right) (Eranti en Lee 1986)

Ice jams can be weakened by cutting, drilling, blasting, breaking, and thermal measures. Measures can be prepared at an early stage, since the lead time for the prediction of a hanging ice dam is about 1.5 months (Russian State Hydrometeorological University 2010).

5.5 *MATERIALS AND INSTALLATIONS*

Research on materials applied in immersed tunnels showed that the permanent phase of the tunnel should not suffer to greatly from the cold environment. Attention should be paid to the rubber profiles in the immersed tunnel, which can have a safe operational temperature until about -30^{o}C. For colder environments, additives may be used to reduce the glass temperature of rubber. The steel support frames will require a protective coating and sacrificial anodes to deal with de-icing salts, which is already common practice. Similarly, the deterioration effects of cold weather environments on movable parts will increase costs for maintenance and adaptation of equipment and installations for the tunnel, though will not cause any major challenges to construction and operation of the tunnel.

5.6 *CONSTRUCTION OF THE IMMERSED TUNNEL*

Often the most cost-effective solution for dealing with subarctic phenomena is to avoid them. Planning such that critical construction stages endure mild conditions will lead to improved safety, better efficiency, and higher quality. Though construction processes may be adapted (such as applying methods of cold weather concreting) or protected (by, for example, a construction hall), waterway construction such as TE transport, immersion, foundation, and backfill will benefit greatly from being performed in the ice-free period.

By analyzing past weather data, one can determine the likelihood of ice formation and breakup. In St. Petersburg, analysis of weather data between 1950 and 1995 showed the yearly number of days below $0^{o}C$ is best modelled by a Weibull distribution (Figure 14). The number of days with a temperature below $0^{o}C$ is roughly equal to the number of days that the river is frozen, though with a phase difference. This will give the contractor a window for waterway construction with an acceptable probability of exceedance. By analyzing the likely dates of ice breakup, one can reduce work preparation time (see Figure 15).

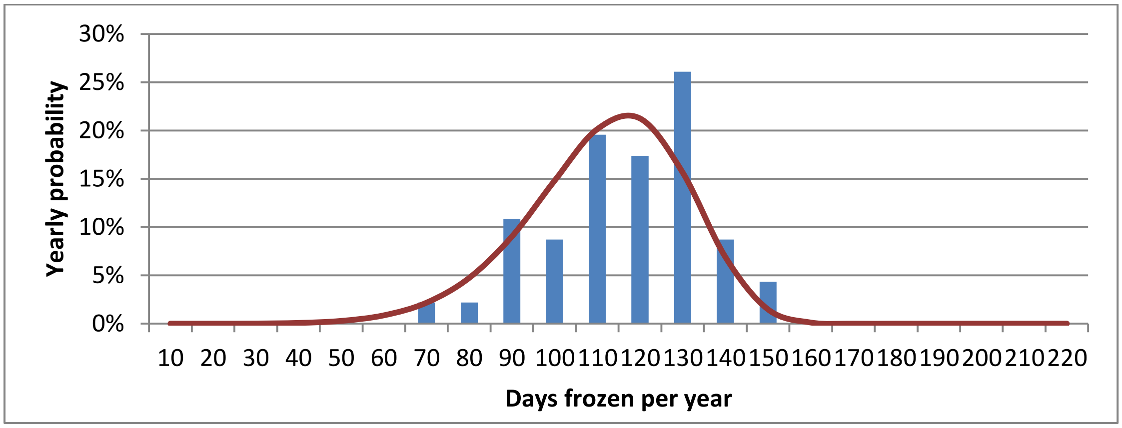


Figure 14 Weibull distribution plotted against the yearly number of frozen days of the Neva

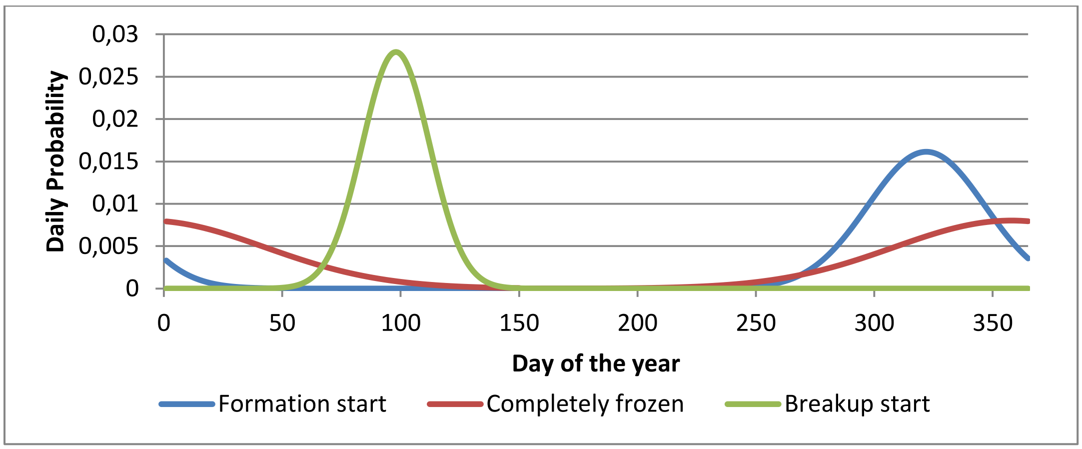


Figure 15 Example of ice cover formation and breakup daily probabilities

Execution choices should be based on an acceptable level of risk taken in during construction. The consequence of non-completion before the onset of ice must be evaluated in order to determine its risk. Contingency measures are available that can reduce this risk include ice booms and frazil collectors that will extend the workable period. External risks can be further mitigated by monitoring and predicting weather.

6 EVALUATION OF SUBARCTIC IMMERSED TUNNELLING

As a whole, immersed tunneling is an achievable and feasible option for subarctic locations. Most of the challenges brought on by the adverse climate can be summarized as additional loads on the structure, as is summarized in Figure 16.

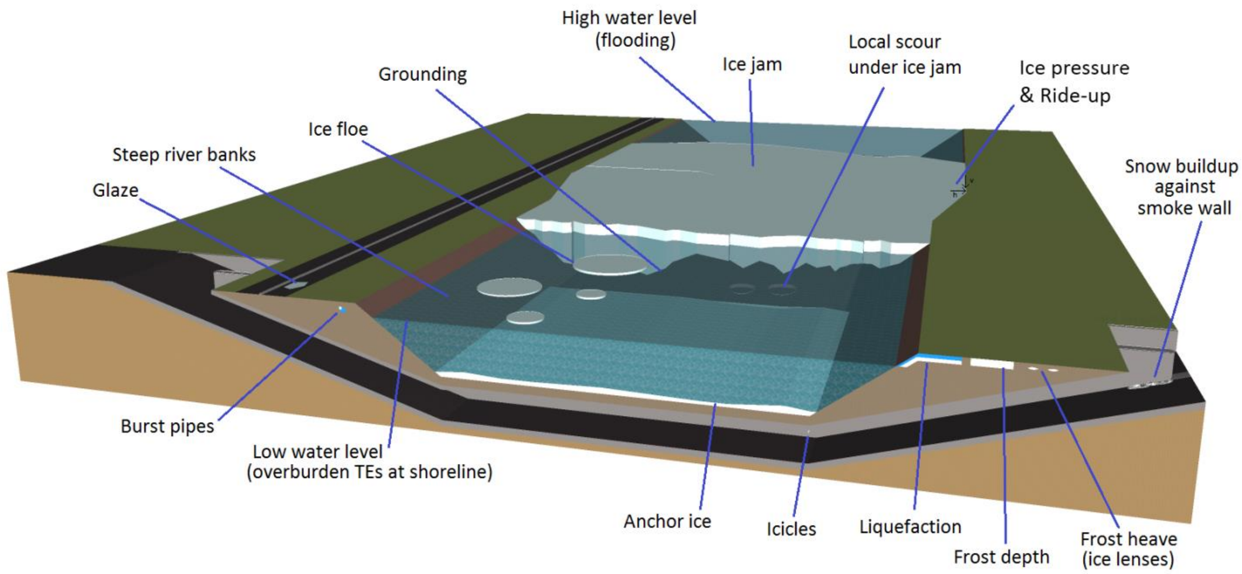


Figure 16 Ice regime of the Neva River (J. Bergsma)

The construction phase comes with larger, but manageable risks compared to tunnel execution in milder climates, though it should be noted that subarctic aspects may not be the main concern for contractors. The severity of the subarctic climate varies per location, and the closer one gets to an arctic environment, the more difficult construction becomes. Therefore, as always, projects should be evaluated on a case-to-case basis.

7 CONCLUSION

Many of the lessons learnt on subarctic issues related to rivers can also be applied to immersed tunnels in seas and lakes. As described in this article, ice formation will have far reached consequences on the construction of an immersed tunnel. While ice is a big part of subarctic engineering, one must also keep in mind temperature related aspects such as rubber gasket performance, cold-weather concreting, thermal strains, and geotechnical issues may also occur. Despite the challenges brought on by the subarctic weather, immersed tunnels remain a viable construction method in these regions.

8 ACKNOWLEDGEMENTS

This article was made possible with the support of Delft Technical University, Royal HaskoningDHV, and Tunnel Engineering Consultants (TEC).

9 WORKS CITED

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

Ashton, G.D. "Intake design for ice conditions." *Elsevier Applied Sc.*, 1988: 107-138.

Barrows, H. K., and Robert E. Horton. *Determination of Stream Flow During the Frozen Season.* Washington: Government Printing Office, 1907.

Bisaillon, J.F., and N. E. Bergeron. "Modelling anchor ice presence-absence in gravel bed streams." Edited by CGU HS Committee on River ice Processes and the Environment. *14th Workshop on the Hydraulics of ice Covered Rivers.* Quebec City, Quebec: CRIPE, 2007.

CIRIA, CUR, CETMEF. *The Rock Manual.* London: C683, CIRIA, London, 2007.

Daly, Steven F. *Report on Frazil Ice.* Working Group on Thermal Regimes, Philadelphia: International Association for Hydraulic Research, 1994.

Debolskaya, E.I. *Numerical Modeling of Ice Regimes in Rivers.* Vol. 1, in *Hydrological Systems Modeling*, edited by Lev S. Kuchment, & Vijay P. Sigh. Singaport: EOLSS Publishers/UNESCO, 2009.

Eranti, Esa M., and George C. Lee. *Cold Region Structural Engineering.* McGraw-Hill, 1986.

Foltyn, Edward P., and Andrew M. Tuthill. "Design of Ice Booms." *Cold Regions Technical Digest*, April 1996: 1-31.

Freitag, Dean R., and Terry McFadden. *Introduction to Cold Regions Engineering.* American Society of Civil Engineers, 1997.

McFadden, Terry T., and F. Lawrence Bennett. *Construction in Cold Regions.* Fairbanks, Alaska: John Wilet & Sons, Inc., 1991.

NPK Proektvodstroy. *Technical Report "Engineering and hydrological surveys, calculation of turbulent diffusion.* St. Petersburg: NPK Proektvodstroy, n.d.

Russian State Hydrometeorological University. *Proceedings of the Russian State Hydrometeorological University, number 14.* St. Petersburg: State Hydrometeorological University, 2010.

Shabanov, Olga. *Ice jams on the Neva.* December 18, 2009. http://www.meteo.nw.ru/articles/index.php?id=507 (accessed July 8, 2013).

Shen, Hung Tao. *River Ice Research: Progress and Missing Links.* Department of Civil and Environmen, Clarkson University, Potsdam, NY, USA: CRIPE, 2003.

Shiklomanov, I.A. *General characteristics of the river basin of the river Neva. Book 1.* St. Petersburg: MINISTRY OF NATURAL RESOURCES OF THE RUSSIAN FEDERATION, 2010.

The New Brunswick Subcommittee on River Ice. *New Brunswick River Ice Manual.* Department of Environment, Environment Canada NB, Fredericton, NB, Canada: Environment Canada NB, 2011.

Tsang, Gee. *Development of Mathematical modelling for Prediction of River Cooling and Frazil and Anchor Ice Formation.* Rivers Research Branch, National Water Research Institute, Burlington, Ontario, Canada: National Water Research Institute, 1988, 393-404.

US Army Corps of Engineers. *Engineering and Design: Ice Engineering.* Washington, D.C.: Department of the Army, 2002.

White, Kathleen D. *Ice Jam Mitigation.* Presentation, Engineer Research and Development Center, USA Army Corps of Engineers, Hanover, NH, USA: USA Army Corps of Engineers, 2005.