



YAMAL LNG TANKS

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1 INTRODUCTION

In spring 2013, the Joint Venture VINCI Construction Grands Projets and Entrepouse Projets got the EPC (Engineering, Procurement and Construction) Contract for four LNG (Liquefied Natural Gas) tanks in Yamal peninsula (Siberia) northern the Polar Circle.

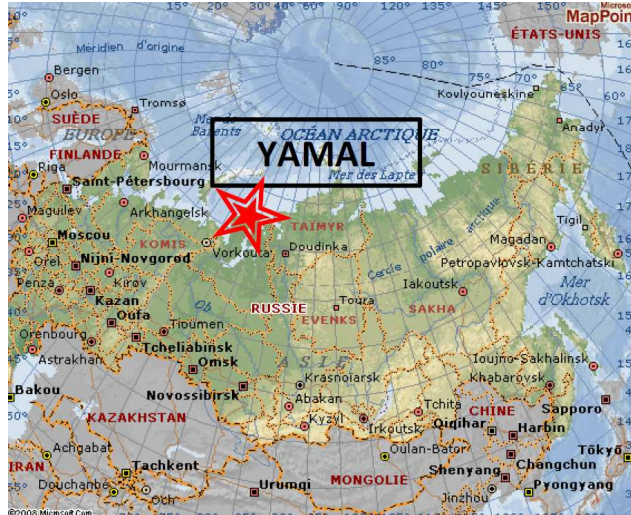


Figure 1: Yamal site

The initial Contract was around 1 165 MUS\$; it has been officially signed on the 16th of October 2013.

This award has been mainly got thanks to an alternate solution for the foundation which resulted in a cost saving of around 100 M\$ for the Client (the Russian Company JSC YAMAL LNG). Furthermore, this alternate solution did not impact the construction schedule: delivering of Tanks 1 & 2 in November and December 2016, Tank 3 in November 2017 and Tank 4 in November 2018.

Every LNG Tank has a net capacity of 170 000 m³. Similar to a kind of huge “thermos”, it is composed of an outer concrete Tank including a base slab, a circular wall (78,8 m internal diameter and 43 m high) and a spherical domed roof (top level at 53 m), a steel inner Tank which contain the LNG at a temperature of -163°C, several insulating materials placed in between the concrete outer tank and the steel inner tank. Pumps, piping and other mechanical equipment are also part of the Contract.

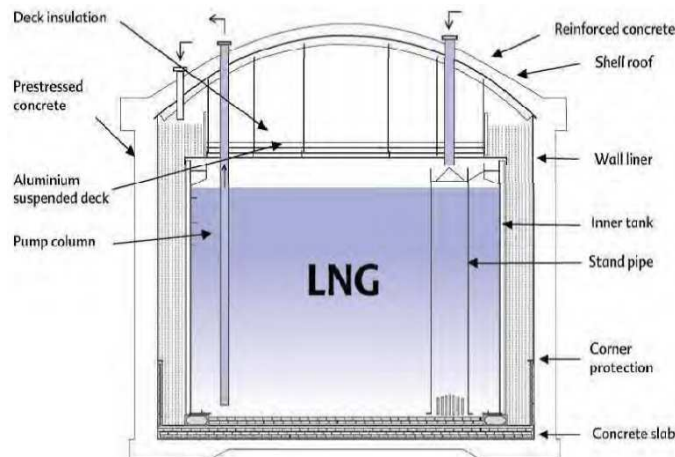


Figure 2: typical scheme of a full containment LNG Tank

The 140,000 tons (total weight in service) Tank is elevated 1.90 m above ground level and 948 steel piles support it, 24 m long, founded in the Permafrost (soil being permanently frozen during 2 years at least).

The challenge consisted in designing and implementing such alternate solution in a very short time à la satisfaction du Client despite very extreme climatic conditions. Indeed, in winter the temperature can be around -50°C and the polar night lasts from mid-November to mid-February.



Figures 3: site pictures, February 2015

2 CONCEPT OF THE ALTERNATE SOLUTION

2.1 INITIAL CLIENT'S SOLUTION

The foundation proposed by the Client at Tender Stage included:

- 1365 steel piles, 37 m long, with a diameter of 530 mm and a thickness of 20 mm (resulting in a total length of 202 km for the 4 tanks)
- 1365 pendulum bearings, placed at top of piles (5460 bearings for the 4 tanks)
- A very dense network of steel struts connecting the top of piles placed in the free gap between ground level and the tank base slab as shown on figure 4. Total of such steel structure was 550 tons for the 4 tanks.

It is important to note that changing the type of pile (material, diameter, thickness) was not allowed because the Client had already order several thousand of piles, 16 m long each. The only possibility was to change the pile length.

SOLUTION CLIENT

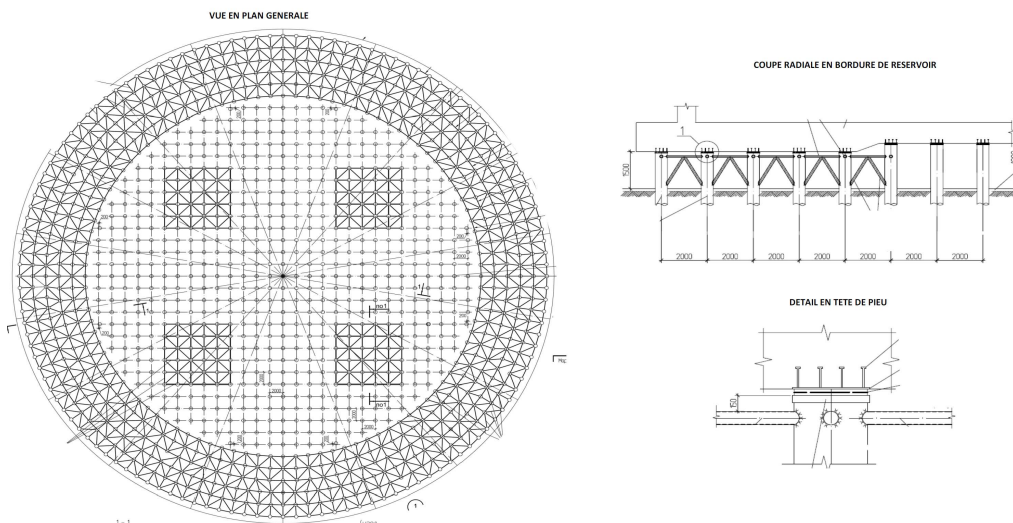


Figure 4: Foundation – Client's solution

2.2 JV'S ALTERNATE SOLUTION

At Tender Stage, VINCI Construction Grands Projets and Entrepouse Projets proposed the following solution for the foundations:

- Thanks to a fine tuned structural and geotechnical analysis, numbers of piles and pile length have been significantly reduced: 948 piles per tank (instead of 1365 for Client's solution) with a length of 24 m. (instead of 37 m for Client's solution). Total piles length is reduced by 111 km for the 4 tanks, resulting in a saving of 55% in comparison with Client's quantities.
- The pendulum bearings included in Client's solution are quite suitable for such structure within a seismic area but this is not the case for Yamal Peninsula, which has a very low seismicity. So, we proposed to use typical spherical bearings, less expensive than pendulum bearings.



- Furthermore, thanks to the change of bearings type, the tops of piles do not need to be connected by the steel frame included in Client's solution: indeed, with spherical bearings, all tops of piles are connected by the tank concrete base slab. The cancellation of the Client's steel frame resulted in a saving of 550 tons of steel and the construction schedule was also significantly improved. In addition, it also permitted a better air circulation below the tank, improving the functioning of the thermos-stabilization device (a permanent soil freezing system which guaranties that the temperature of the permafrost remains always below -5°C , in accordance with the geotechnical design, all along the 50 years design life).

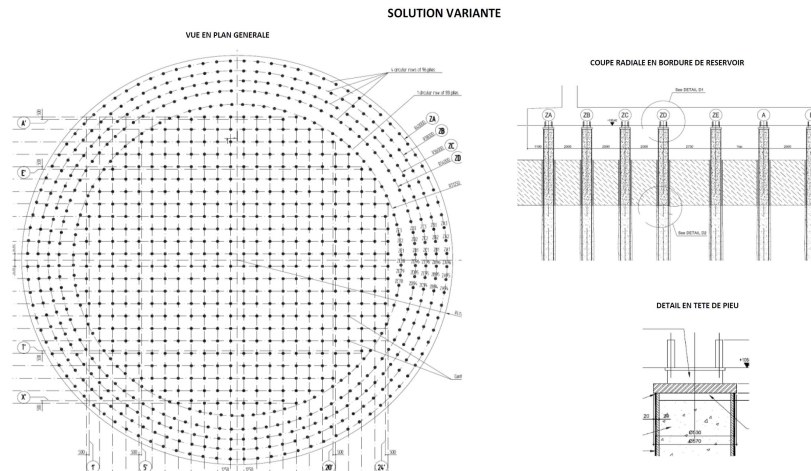


Figure 5: principle of the Joint Venture foundation solution

3 DESIGN

3.1 CONTEXT

The design of the LNG tanks had to be compliant not only with Russian Standards (as every structure built in Russia) but also with Eurocodes Standards (It was a requirement from French Company TOTAL which was part of the Client).

Practically, the Design Offices from VINCI Construction Grands Projets and Entrepose Projets developed their design following the Eurocodes Standards and a Russian Design was appointed to check the compliance with Russian Standards, providing some modifications when required (such as, for instance, adjustment of the reinforcement design).

3.2 FOUNDATION DESIGN

The top part, around 55 m deep, of the Permafrost is extremely heterogeneous. Furthermore, there are specific settlement criteria to be checked for a LNG tank (for instance the relative deflection of the base slab along a radius should not exceed $1/300$). The above considerations convinced the Designers to perform a rigorous soil-structure interaction, using a dedicated 3D Model (using MIDAS Software) including:

- The concrete outer tank, modelled with shell type elements for the base slab, the wall and the roof, and beam type elements for the piles
- The Permafrost soil, modelled with solid type elements. Around 44 different types of soil have been used, with specific strain Moduli and Poisson's coefficients estimated from numerous Laboratory tests)

The overall dimensions of the Model have been taken as 160 m vertically (corresponding to twice the tank diameter) and 400 m horizontally (in order to get negligible settlements at the lateral ends of the model). The soil heterogeneity required building a specific Model for every tank. Figure 6 shows a general view of the MIDAS Model for tank 3.

The design considered four situations all tanks life cycle long:

- End of construction
- Hydro test: the steel inner tank is filled with water with a total weight corresponding to 125% of the maximum LNG weight (the purpose of such loading is to test the foundations)
- After soil consolidation
- Under service condition (with the maximum LNG weight)

Figure 7 shows an example of results outputs.

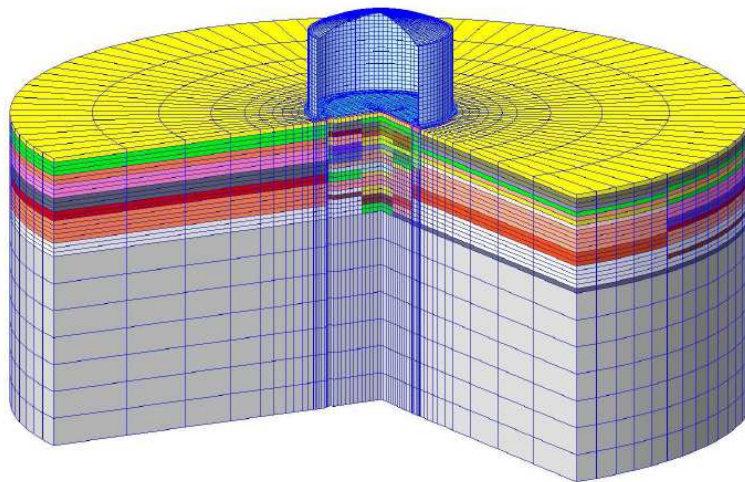


Figure 6: general view of MIDAS Model for tank 3

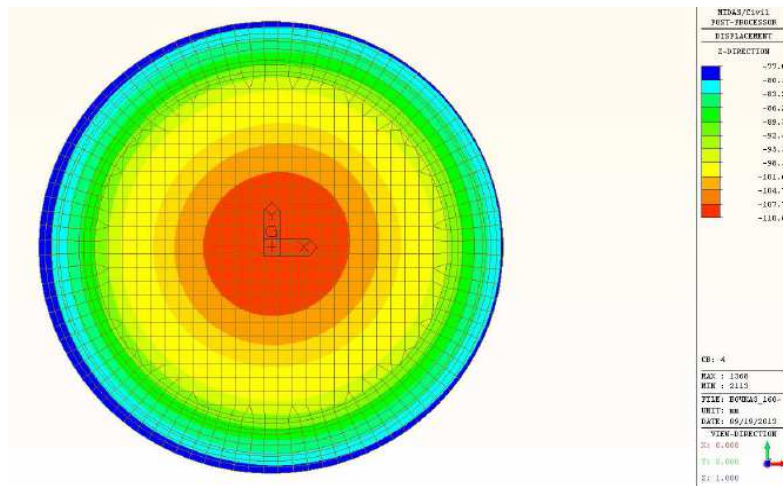


Figure 7: map deflections for the base slab of tank 3

3.3 CONCRETE OUTER TANK DESIGN

The structural design of the concrete outer tank includes three main steps:

- Seismic design
- Design under normal situations
- Design under abnormal situations

3.3.1. Seismic design

Seismic action is very low within the LNG tanks area since the peak ground acceleration is only $0,185 \text{ m/s}^2$ when considering the 2500 years return period earthquake.

The analysis which is carried out is a dynamic response spectra and modal analysis using Seismic Response Spectra. The calculations are based on finite element lump mass models of the structure using computer program HERCULE which takes into account the various components of the storage tank (including impulsive and convective LNG liquid masses for the horizontal earthquake and total LNG mass for the vertical earthquake).

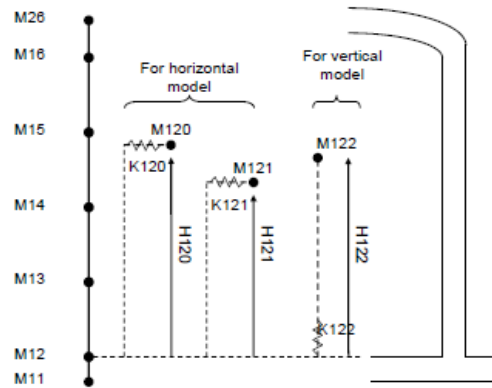


Figure 8: principle of the lump mass model for seismic design

3.3.2. Design under normal situations

Normal situations include:

- The main construction steps
- The test loads (hydro test and pneumatic test)
- The service loads

The design is based on a static linear analysis, using a 3D finite element model with shell elements using computer program HERCULE.

One full half of the tank is modelled as typically shown on Figure 9. The thicknesses of the shell elements are adjusted according to the actual thicknesses of the structure whereas beam type elements are used for the piles.

The soil-structure interaction is modelled using elastic springs whose values are determined in order to get, for every situation, the same settlements as the ones calculated with MIDAS Model as presented in above section 3.2.

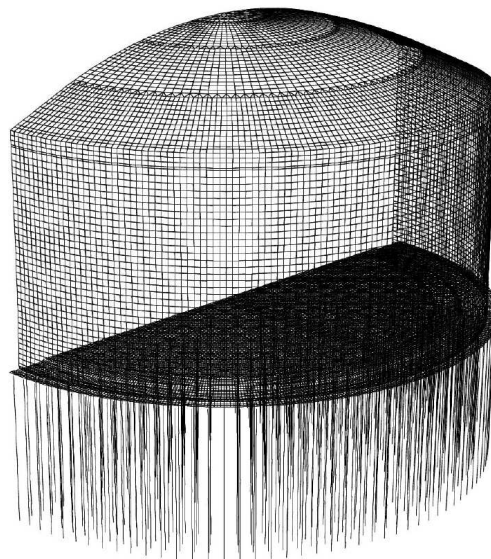


Figure 9: 3D HERCULE Model for static linear analysis

Reinforcement maps, automatically calculated by HERCULE software, were used to finalize the reinforcement drawings.

3.3.3. Design under abnormal situations

The LNG tanks are systematically designed for two abnormal (or accidental) specific situations:

- LNG spillage: in service condition, the LNG is contained in the steel inner tank, the LNG load being directly applied to the base slab and to the foundations. Spillage situation consists in considering a failure of the steel inner tank, the LNG being only contained in the concrete outer tank, the hydrostatic LNG pressure being directly

applied to the circular concrete wall. This is why the concrete wall is post tensioned with horizontal and vertical tendons. In such situation, the internal wall face, in direct contact with LNG, is at the temperature of -163°C.

- **External fire:** The concrete wall and roof must withstand heat radiation resulting from pressure safety valve fires and from adjacent facility fires. The incident heat flux is taken as 32 kW/m² and the fire duration is 2 hours, data resulting from a risk analysis performed by the Client.

Due to the high thermal gradients, which arise in the concrete structure in case of either a LNG spillage or a fire due to heat radiation, it is not possible to undertake a linear elastic analysis (using the elastic model presented in the preceding section 3.3.2) as this would give unrealistic results. This is due to the fact that, under high thermal gradients, the concrete sections will crack, thus inducing a redistribution of the stresses. Consequently, a non-linear thermo-mechanical analysis is required. It is done in two successive steps:

- The first step is dedicated to a transient thermal analysis to calculate the temperature distribution in the concrete and the insulation materials under LNG spillage and fire conditions. The model, using ANSYS software, is a 1° sector of the LNG tank with symmetry boundary conditions on the vertical lateral faces. The model includes 3D thermal elements for all the relevant components of the structure (the concrete structure itself and the various insulation materials). Design thermal boundary conditions consist in the contained LNG temperature and in the external atmospheric temperatures (both maximum “summer” and minimum “winter” external atmospheric temperatures are considered).

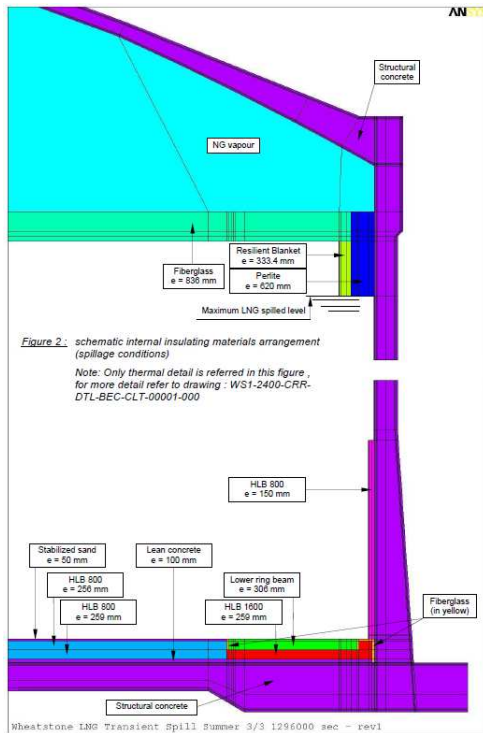


Figure 10: ANSYS model for thermal analysis

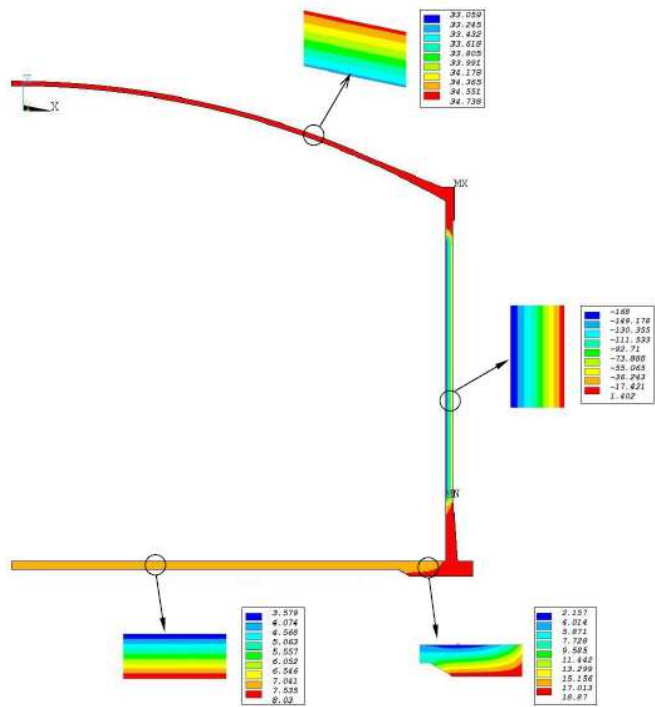


Figure 11: ANSYS model – example of temperature maps under spillage situation

The results are the temperatures within the concrete structural elements as shown on figure 11.

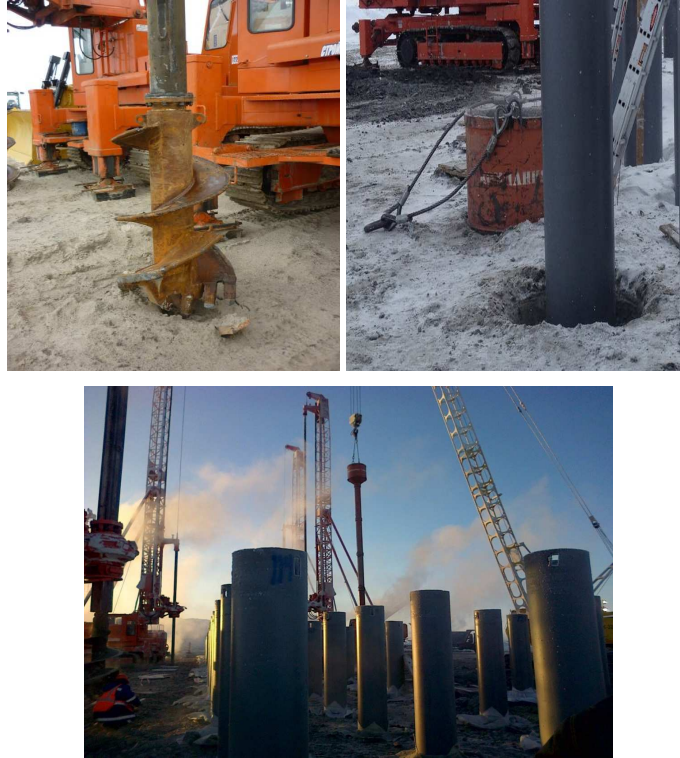
- The second step is dedicated to the thermal stress analysis, using a non-linear 2D axisymmetric layered thin shell finite elements model taking into account cracking of the concrete and the elastic-plastic behaviour of the concrete, steel reinforcement and post tensioning tendons as well as the variations of these characteristics with temperature. The used computer program is ICW (software developed by the Structural Design Department of VINCI Construction Grands Projets) based on incremental and iterative calculation of the equilibrium of the structure. The temperatures issued from the thermal analysis (calculated with the ANSYS Model previously presented) are automatically transferred to the ICW model. Obviously, the ICW Model includes also the other loads to be considered simultaneously with the spillage or the fire situations (permanent and pre-stressing loads, LNG pressure, etc.). ICW results are the stains and stresses in any part of the tank, for all the structural materials (concrete, reinforcement and post tensioning tendons) in order to check the specific criterion of either spillage or fire situations.



4. CONSTRUCTION

4.1 PILES FOUNDATIONS IN PERMAFROST

This is to set up 950 piles 24 m long for each tank:



Figures 12: Piles foundations

For each pile, a hole is drilled into the permafrost, the auger of 70 cm diameter for a drill of 20 m deep. Then, we install a steel casing on the drill top part and we re-fill the hole with a mixture of sand / cement, we drive in it, by vibrating hammer, a steel pile of 53 cm in diameter and 24 m long. For permanently frozen soils, we generally opt for steel pile foundations, where we pour a water-sand-cement equivalent around the piles that we allow to freeze and harden. This mix acts as a binder with permafrost soil, whose temperature, ranges from -9°C to -7°C , do not allow normal cement mortar to harden before it freezes.

The tank is placed 2 m above the ground, the soil itself being formed by an embankment of 2 m above the permafrost. This backfill is to protect and not disturb the thermal equilibrium of permafrost, but we kept a certain movement freedom between pile/backfill.

On top of that, we put between each pile a heat-stabilizer (thermo stab), containing a phase-changing liquid-gas, responsive to temperature variations (from -50°C to -15°C).

The principle is to install in the ground a thermos-syphon made of a 21m long cryogenic pipe, diameter 38mm, on the top of which there is a simple radiator. The radiator is located in the free space below the tank, in the vein of "cold" (arctic!) air.

The thermos-syphon is hermetically sealed and filled with a 'changing phase' gas at the factory. In Russia, the gas that is commonly used, and at present still legally authorized, is the halocarbon R22.

The gas has a liquefaction temperature around -15°C . Therefore, in winter (which last about nine month during the year), the arctic cold air blowing below the tank cools down the radiator (the external temperature can reach -50°C) and the gas condenses. By gravity the R22 liquid falls down the bottom of the cryogenic pipe. There, there is exchange of heat between the ground (initial nominal temperature of the permafrost around -6°C to -7°C) and the cold R22 liquid. The temperature of the ground is decreased while the R22 liquid is heated then vaporized, and the gas is going back up to the radiator where it is cooled down and the cycle starts again.

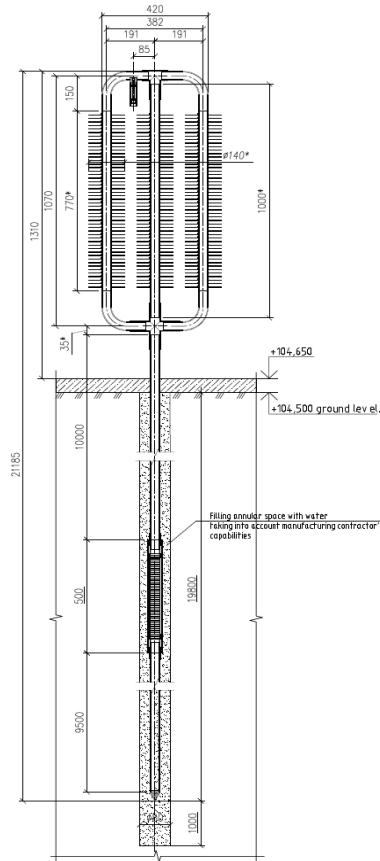


Figure 13: scheme of the heat-stabilizer or thermo stab

This system does not need any external energy as it is based on the physical characteristic of the gas, and as the pipe and radiator are sealed, the liquid-gas remains in the thermos-syphon and the system is perpetual.

In fact, the system is only working in winter, as in the "summer period" the temperature of the external air is above the temperature of liquefaction of the gas. Therefore, the gas remains in the radiator.

The system will also stop working when the temperature of the whole ground below the tank will reach the liquefaction temperature of the gas, as there will not be any more exchange of heat. Calculations show that it will take in the range of ten years to have the full ground below each tank, around all the pile length frozen at about -15 to -17°C.

4.2 ELEVATED RAFT



Figures 14: heat-stabilizers, the slab and the elevated raft

Once thermo stabs and piles have been installed, we placed "kneecap bearing" fixed on top of the piles, and poured a slab on grade for installation of the horizontal formwork required for the elevated raft.

We had, during the pouring of the 1 M thick raft, to solve the problem of differential settlements, between the raft formwork level supported by the unfreezing backfill/permafrost underneath, and the bearing level set on top of the pile.

Reinforced slab on grade, and also further to trials, installation of the horizontal raft formwork, 8mm above design level were implemented and we succeed to achieve construction at design.



4.3 OUTER WALL SLIPFORMING

Basic principles

- *Argument for use of slipform, for the 40M high tank's walls:*

The specific meteorological conditions at 700 km north to Artic Circle, let only a "window" of 4 month per year, compatible with acceptable external concreting conditions. Only a slipform tool make it possible, to pour the 40 m high wall in less than 24 days.

- *Mandatory action to be taken, when slipforming choice have been done:*
 - o *Mock-Up construction and training:*

When the slipform equipment's is delivered, 5 weeks are necessary to pre-assemble the tool, just beside the tank construction.

In parallel, one month before tank slipforming begin; a specific "mock up" wall of 12 lm long and 10 m high will be built on the yard area. This mock up wall will be the slipforming physical training and formation to this specific tool. This training & formation is applicable to all concerned trades (formwork team, reinforcement team and concrete pouring team), as well for workers/ foreman/general foreman and staff.

The slipform construction staff and operatives shall be fully inducted and trained as an integrated team. There will be performed a Slipform training course directed by the leader of the slipform operating team. Every person working as part of the slipform operation will attend this training before start-up of the slipform operation.

- o *Planning*

As the slipform operation is a continuous process, planning should be made for supply and distribution of concrete, reinforcement, ducts and embedment goods to ensure that the slipform operation can continue 24 hours per day without any hindrance.

Planning shall also include labour supply for ensuring an adequate workforce for the tasks involved.

Planning shall also include the supply of the correct equipment, spare parts and consumable goods.

An Embedment list is produced prior to slipforming start-up. This list contains information on all embedment's to be installed in the wall during the slipform operation. The Embedment list describes the exact position of all embedment's horizontally with reference to the Yokes, and the level for embedment's referred to top of the base slab.

A separate list is produced regarding installation of the Liner strips

Slipform operations

- *Start-up:*
 - o *Installation/setting of the form on the raft*
 - o *Fixing of Reinforcement, embedment's and post tensioning ducts*
 - o *Placing and compacting of concrete in the form*

After completing a pour of approximately 1m high (5 to 6 layers) and the concrete has achieved enough strength the lifting of the formwork can commence.



Figure 15: raising of the formwork

– *Running the slipform operation*

When the start-up phase is completed, the slipform operation continues at a certain speed and lifting height. A slipforming rate of 2 to 2.5 m per 24 hours is normal. The lifting speed will be adjusted to current strength and setting conditions.

To determine the level of setting of the concrete a bar; $\varnothing 12$ mm, is pushed down into the concrete until it meets the hardening front. Based on this information lifting of the formwork is decided.



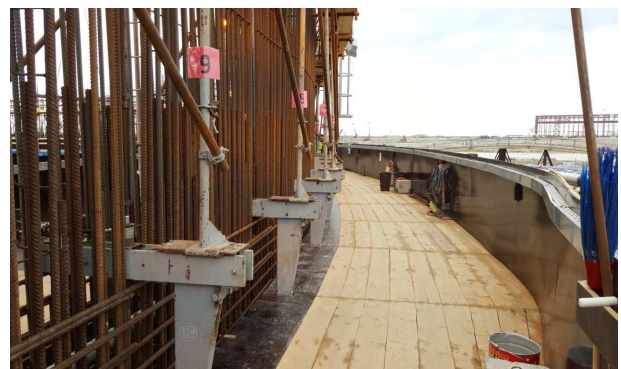
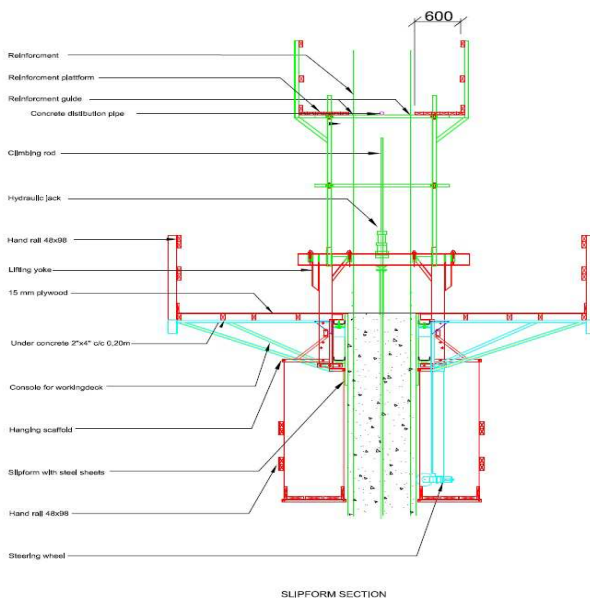
Figure 16: slipform operations

The verticality of the form is continuously checked at least every 2nd hour and documented every 0.75 m. For this slipform 16 lasers will be installed. The lasers will be installed on the Base slab, sending the laser beam vertically through an opening in the platform, pointing at a fixed point where it can be monitored. Deviation from the verticality is corrected with the jacks, the steering wheel or by placing weight accordingly on the platform.

A horizontal laser spotting each yoke jack continuously checks the horizontal level of the form.

The speed of the slipform will be reduced during time-consuming operations such as installation of:

- Horizontal embedment's at levels +2,5 m and +5m above top of base slab
- Approaching top level of slipforming operation
- A curing compound will be applied to all concrete surfaces. This compound shall be applied to the walls from the hanging deck at least once per shift. Areas presenting surface deficiencies are marked for repair prior to placing curing compound



Figures 17: formwork scheme and formwork platform

Thermally insulated canvas of 4m high will be suspended below the hanging scaffolds, alongside each wall face. Including the protected hanging scaffolding high, this will provide 2 to 3 days thermal protection to the green concrete, in order to mature properly.



Nota:

A 24 hours stop in slipforming followed by a restart of the operation without causing a permanent construction joint is possible if it is carefully planned. In this situation, the form will be lifted at a speed of about 2.5 cm/hour. A stop lasting for up to 4 hours needs no specific precautions.

Any construction joint will, after a required stop, be treated with surface retarder and high-pressure water washing equipment further on. The waste will be removed by operatives and by using suction pumps for removing water and small particles.

Cleaning of formwork panels during slipforming is one of the most important tasks to check in order to avoid quality issues on the wall. Our strategy was to systematically change a panel as soon as a problem was detected or if we had suspicion of a problem. A dedicated team trained and led by specialist, was in charge of changing these panels.

- Slipform dismantling, and steel roof temporary support

Wall slipforming process will be ended 1.30 to 1.8 m below the level of the steel roof compression ring. Steel columns inserts; have been embedded within the top of wall, in order to be the temporary support of the steel roof liner.



Figure 18: pouring of the wall top part

Then the slipform tool will be dismantled/modified on working platforms. Prefabricated roof sectors will be assembled in place, supported temporary on the centre by a mast and outside, by the “haunch 1 embedded steel columns”.

Then the inner tank area is accessible for fitting out, protected against weather conditions.



Figure 19: the steel roof liner before pouring

4.4 CONCRETE DOME ROOF

Pouring of end of wall and roof beginning

The top part of the wall, above the steel roof liner, includes the vertical post-tensioning anchors. This wall part is the structural interface with the roof, and it will be poured in one vertical phase. Using the outer wall platform we will support the external wall formwork, and the inner face will be cold joint preparation located on top of the roof steel liner.



Figures 20: pouring of end of wall and roof beginning

Pouring of the roof outer ring phase

This 5 m wide transition part of the roof, with a thickness variation from 1.4 m wall side to the 0.4 m roof side, is poured on one horizontal staggered phase.



Figure 21: pouring of the roof outer ring phase

Pouring of the dome roof

The concrete roof is casted staging and will be poured in 2 separated layers.

The steel roof liner still supported by the temporary central mast, we will cast the standard roof dome (0.4m thick) by stages to control shrinkage, and in two layers to not overload the temporary central mast support.



Figures 22: pouring of the dome roof