APPENDIX 2- CONSIDERATIONS ON ADAPTING TUNNEL FORMWORK

Proposal 6 considered a fixed casting station and the subsequent launching of the freshly cast rings as construction progresses. Now a different family of solutions will be introduced. In these proposals, the working principle is quite the opposite. It is the concrete pouring station that advances as it casts the tower. The casting front will therefore be mobile thanks to a specifically designed formwork technology.

Previously, an overview of formwork technologies introduced the so called travelling formwork. The following proposals -Proposal 7 & Proposal 8- will develop this concept of travelling formwork whilst combining it with the requirements of Windcrete, in terms of geometry and construction constraints (high quality, systematic processes and monolithic pouring of the structure). Both of these proposals are partially inspired by the tunnel industry and will face similar problems with regard to the use of current tunnel technology. As these problems will have to be dealt with by all the proposals involving tunnel technology, this part serves as a brief overview of the main impediments that they must overcome and potential solutions to bypass the undesired features of regular tunnelling methods.

Requirements

Existing technology will serve as a source of inspiration but most undergo an adaptation process to fit the needs of the project. In other words, Windcrete cannot be constructed satisfyingly by directly applying classic tunnel lining travelling formwork. There are three main aspects that underline the need for a certain adaptation of the process, two major issues and presumably a minor problem. These issues that the adapted method must address are:

- Requirement 1: Achieving a circular cross section rather than an arched tube.
- Requirement 2: Continuous placement of concrete rather than casting in discrete steps.
- Requirement 3: Outer mold face.

Broadly speaking, these issues are common to all tunnel construction methods. So, independently on the tunnelling method that will serve as primary source of inspiration all these issues will have to be addressed. These three requirements will be addressed by suitably modifying classic tunnelling procedures to satisfy the needs of the project.

Requirement 1-Achieving the desired cross-section

Travelling formwork for tunnelling usually results in a semi-circular cross section, normally varying from 300° to 340° rather than a full circle. This is in part due to the fact that tunnels in operation require a flat base slab to support the lanes for cars or to embed the rails in the case of a railway tunnel. This geometry is also closely related to the construction process. The bottom slab will indeed support the permanent traffic lanes when the tunnel is finished, but also during the casting of the tunnel lining, the bottom slab serves as working platform for the travelling formwork. This flat surface is quite indispensable for the heavy travelling formwork to roll smoothly within the cross section. The resulting cross section will be in the shape of a horse-shoe.
Figure 1. Typical cross-section achieved by current construction methods. Peri formwork.

Solutions to Requirement 1
The first element that an adapted method must include is therefore a way to correct current practices to obtain a perfectly circular cross-section. Three alternatives will be discussed, the first directly replaces the use of a traveller by including hydraulic struts, the second involves the design of a special type of carriage, and the third considers a modified structural design for the tower that allows an inner-travelling formwork.

HYDRAULIC STRUTS
Perhaps the simplest of all, replace the travelling formwork all together by using a series of diametric hydraulic struts. Travelling formwork usually covers three basic functions, it carries the concreting equipment, it transports the forms and it holds the forms in place while the concrete is still fresh. Logically, hydraulic struts can only cover the last function of the form traveller. Therefore, hydraulic struts may be used, but will necessarily have to be combined with a mechanism to place and fill the forms. In turn, this mechanism is due to be mounted on rails too if it must be able to transport heavy forms so altogether hydraulic struts are not a solution on their own.

‘CANTILEVER CARRIAGE’
If one wants to avoid the need for a flat concrete slab at the bottom of the cross-section during construction while still employing a travelling formwork, it is clear that the rails used by the carriage should not interfere with the structure being constructed. A way to achieve this is by not placing the rails inside the cross section, but rather outside of the soon-to-be structure. A rather straight-forward way of achieving this is by designing a cantilever-like travelling system that is still mounted on rails but has a suspended steel frame that extends several meters in front of the actual wheels and thus in front of the rails. The traveller will move backwards as construction progresses.

Put simply, the front of the carriage is a truss-like steel frame that is suspended like a cantilever beam, while the rear part of the steel frame rests on wheels. Of course, this traveller would require some heavy counterweight at the rear end to counteract the pressure exerted on the front.
A rather simple representation of what this cantilever carriage would look like is presented below.

This could potentially allow the front of the steel frame to support forms and fresh concrete from the inside of the structure while the remainder of the carriage, including the wheels, is located outside of the concreting zone.

As construction advances, rails can be left in place. New forms could simply be placed on top of the previously used rails as this special carriage would only require rails further ahead. In other words, the rails would indeed be located on the concreting path, but just not used at the same time pouring of concrete takes place, causing no interference.

The main advantage of this carriage design is that it is able to provide the desired shape, while maintaining the ability to move on tracks without the tracks obstructing the casting of a circular cross-section.

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Figure 2. Simplified representation of cantilever carriage.

Figure 3. Simplified representation of cantilever carriage holding the forms from the outside.
If it may be that using conventional travelling system formwork (mounted on rails passing through the inside of the structure) is the best way forward.

If this was the case and it was found that using an internal travelling form is a cost-effective solution, it would be clearly advantageous to modify the interior of the tower to accommodate a series of rails for the self-propelled formwork system. This would mean including several reinforced cross-sections in the structural design of Windcrete that would serve as supports during construction. The rails used for construction could be embedded and left in place in the final structure or removed.

Anticipating construction loads into the final design is common practice in civil engineering. By integrating into the design elements that would aid the construction process, more possibilities can be considered.

This solution is in fact quite reasonable given that Windcrete’s design already includes several reinforced cross-sections where the mooring lines will be fixed. Windcrete’s design also considers the placement of an elevator, which will certainly need a guide wall and additional reinforced sections. All of these could serve a double purpose by assisting the construction.

The recommendation is then to assess these reinforced sections planned in the design of Windcrete and see if they could also be used as temporary supports aiding the activities during construction.

**Requirement 2—Achieving continuous placing and avoiding joints**

Tunnel technology typically presents a number of joints. As described in previous chapters, classic tunnelling equipment casts the tunnel linings in discrete steps. First pouring the concrete, providing support until it hardens, then the mold retracts and moves to cast the next ring, clearly leaving circumferential construction joint after each cycle. Circumferential joints are not the only joints that will result from current tunnel practices. To show this, an overview of tunnel construction solutions provided by Peri, a German company. Peri is a world leader in advanced engineered formwork.
As can be seen, most of the solutions include at least 2 cross-sectional construction joints. These joints are a direct consequence of tunnelling methods, that usually prefer to cast the several linings in-situ separately, and then properly seal the joints.

So, what can be seen is that, besides circumferential constructions joint every 12-20 m (approximately equal to the length of the travelling formwork), longitudinal joints can also be expected by conventional tunnelling methods.

As the construction process of Windcrete aims at providing a joint-less structure, the current state of tunnelling practices needs some re-thinking and some modifications undertaken. These modifications should allow continuous concrete placement to avoid both of these types of joints.

**Solutions to Requirement 1**

**ROBOTIC ARM TO PLACE FORMS**

To achieve the second requirement regarding continuous placement of concrete, it is clear that the travelling machine be able to place new forms before previous forms are full. A modified approach will thus consider a traveller capable of realizing both the function of filling forms with concrete (and supporting them) and placing new forms so it can pour concrete uninterruptedly.
To comply with this additional feature that the travelling formwork must be equipped with a mechanism capable of placing new forms, an interesting technology also inspired from the tunnel industry could very well hold the key to the solution. Tunnel Boring machines are equipped with a segment erector. The erector is a rotating system which picks up precast concrete segments and places them in the desired position a mechanic arm that lifts and places the ring segments. This erector is basically a mechanical arm that is able to handle the heavy concrete segments.

This idea proposes to make use of this technology whilst slightly modifying its function. Whereas inside the TBM the erector serves the purpose of placing the ring segments, in this adaption it could be used to place the new forms in a similar way. The circular panels and sheathing could be divided in pre-assembled segments, which the erector places in the desired position.

This erector can be mounted on the very same travelling formwork supporting the concreting equipment, or placed on an independent carriage. Regardless of the preferred configuration, counterweights will have to be provided so the erector remains balanced while lifting forms. By including this technology, the casting front could progress whilst continuously pouring concrete. Proposal 10 & Proposal 11 will make use of this technology.

**TRAVELLER OVERLAP**

The supporting frame of the form traveller is slightly longer than required, so as to always present a free gap to place the new set of forms and allow continuous movement.

To clarify what is meant here a mechanized formwork is shown which was used to construct the Portal of the Rokski Tunnel. The equipment used was designed and built by Russian company Stalform.

In this image, the mechanized traveller (in yellow) is supporting two sections of forms (in blue) which were being assembled at the time of the photograph.

If one looks closely, what can be seen is that the circular frame of the traveller is slightly longer than the total length of the two consecutive forms, thus leaving a small gap at the front of the machine, where no forms are present. This area has been shown in green for clarity.

*Figure 5. Modified image of Rokski Tunnel construction. Formwork System Engineered by Stalform.*

As concrete inside the forms dries, these can be stripped, cleaned and placed on this extra gap. Then, the traveller moves backwards leaving the exact same gap all over again, once more forms from the back of the construction can be stripped and taken to the front of the construction and re-placed on this empty gap. Therefore, after each movement cycle of the traveller, there will always be an available gap at the front of the construction.

By arranging a slightly longer frame like the one in the photograph, after the traveller moves backwards, it will always provide free empty gap for a new set of forms. The traveller moves in discrete steps covering a distance equal to the empty gap, which in turn should correspond to the length of a set of forms.

By imagining such a system, an exciting new feature is made possible which is the continuous placing of concrete. Indeed, even though forms will be added to the front of the traveller in discrete steps one section at a time, the filling of the forms does no longer need to stop. The only real requirement is that before the section of forms closest to the front of the traveller is completely filled, the new set of forms placed on the gap must already be in place so concreting can move from one section of forms to the next uninterruptedly.

Subsequently, where concrete is hard (at the rear-end of the traveller) forms can be stripped and transported to the front of the traveller where they can be placed again.

Of course, it will be required that the forms in contact with the surface of the traveller (the inner forms) can enable the sliding movement of the traveller beneath them. Yet, this requirement seems quite feasible by incorporating small wheels in this contact surface allowing the frame to slide underneath the forms while still carrying their weight. Using such a traveller will raise awareness on the importance of travelling speed. Speed must be sufficiently low to provide a quality pouring of forms but also slow enough so that forms where concrete is still fresh are not left hanging but instead have time to harden before the traveller moves on.

Please note that it is highly unlikely that the traveller in the photograph was designed for this purpose.

What can be drawn from this part is that travelling systems offering a slight overlap may be suitable for constant concrete pouring of monolithic structures but further research will be required.

Note that this traveller with an overlap for constant placement of new forms could be combined with the cantilever-carriage described earlier satisfying both REQUIREMENT 1 & 2. By combining both, one can design a traveller with the ability to continuously accommodate new forms, and the ability to move on rails that do not pass through the structure.

**Requirement 3- Outer mold**

The nature of tunnel construction itself usually implies that concrete is injected in the free space between the rock and the panels, making no-use of exterior panels. While this difference may appear significant, and it does indeed involve additional costs, it can be easily corrected from a
technical point of view. With little additional complexity, an outer mold surrounding the structure to be built can be provided. This is in fact actively done throughout the tunnel industry for open-sky tunnel construction. This tunnelling practice is called open cut and it is believed it can be successfully adapted to build the towers.

Figure 6. Open-cut tunnelling method. Formwork by Peri.