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A big full-round tunnel formwork designed for the Ingula Pumped Storage Scheme in South Africa

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ABSTRACT: At the end of September 2012, a big full-round formwork of self-launching type, designed and fabricated by CIFA S.p.A. Italy, has been assembled in South Africa. The diameter of this formwork is of 9.4m and the block to be cast is 13,5m long. So, the total length of the equipment is approximately 33m. The self-launching system for tunnel formwork has been used several times in the past, but rarely with this kind of dimensions. Moreover, this formwork, which will mainly be used on a flat track, shall also be employed along a final 12.5% upgrading tunnel track approximately 135m long. For this reason, the formwork has been carefully designed for the two a.m. conditions, as well as for the transition area between the flat and the sloped tracks, which will be performed in three casting steps. The formwork, equipped with a proper double concrete distribution system, has been calculated for a max concreting rate of 55m³/h (the volume of each concrete block is of approx. 400/500 m³). Proper anti-floatation props have been located at both ends of the formwork and the maximum upward reaction against the ceiling has been estimated in 2000kN each side. During the design, particular care has also been paid to the erection of the formwork, which has to be carried out inside the tunnel.

1 Introduction

We are in the central-eastern part of the Republic of South Africa, about 250 km far from Durban and 350 km far from Johannesburg, straddling the provinces of Free State and KwaZulu Natal; here, inside the magnificent South African landscape rich of a wide variety of flora and fauna, the "Ingula Pumped Storage Scheme" is under construction.

The Ingula Pumped Storage Scheme, previously named Braamhoek, is being implemented by Eskom Enterprises, the South African electricity public utility which is the largest producer of electricity in Africa and among the top seven utilities in the world, in terms of generation capacity.

This project consists of an upper dam, named Bedford Dam, and a lower dam, named Bramhoek Dam, both of approximately 22 million cubic meters water capacity. The two dams are located at a distance of 4.6 km each other and are connected by underground waterways, through an underground powerhouse which house no. 4 pump turbines having a total capacity of approximately 1332 MW.

The scheme, scheduled to come into operation during 2014, is a “pumped-storage hydroelectricity plant” (PSH) with an energy storage capacity of 21,000 MWh; during times of peak energy consumption, water will be released from the upper dam through the pump turbines to the lower dam to generate electricity. During times of low energy demand, the pump turbines are used to pump the water from the lower dam back up to the upper reservoir.

Both reservoirs, Bedford Dam and Bramhoek Dam, are complete. The collection of water in Bramhoek Dam commenced on 4 November 2010 and the dam is already 100% full (March 2011).

The underground civil works (including the powerhouse and the transformer caverns, ventilation and surge shafts, two headrace tunnels and a tailrace tunnel, the intake and outlet structures) were awarded to CMI JV, a consortium of South African and Italian companies between the local PG Mavundla and two important Italian companies: CMC di Ravenna and Impregilo S.p.A.

Currently the main access tunnel, the outlet works, the Intake works and all the underground excavations are completed; the concrete works are progressing in the waterways and caverns.

Figure 1. Location Map (left), the upper dam (right top) and the lower dam (right bottom)

2 The Tailrace Tunnel

The final part of the underground waterways (the tailrace tunnel) is a 2339m. long tunnel, having an inner diameter of 9.40 meters; the tunnel has a constant mild slope of 0.05% for almost its entire length, but, as it is usually the case for the PSH plants, the slope increases quickly to 12.5% at the outlet track, for a length of about 135 meters.

The intermediate sprayed lining has already been fully executed by means of no. 11 CIFA Spritz System units, two of them of crawler type, able to operate on sloped tracks up to 75%.

Figure 2. Shotcrete system crawler (left), working in Ingula Site (right)

The final lining, executed in reinforced blocks each one 13.50 meter long and 0.60 meter thick, is presently under construction by means of no. 2 full-round formworks, both of them of self-launching type and running inside the tunnel toward the two ends. The time cycle is approximately of one casting every three days, each formwork.

The first formwork, in operation since March 2012 toward the intake tunnel end, will exclusively be used on the flat part of the tunnel; the second formwork, supplied by CIFA S.p.A. (the Italian company of Zoomlion Group, leader in the design and construction of tunnel formworks) is in operation since October 2012 toward the outlet tunnel end and will also be employed on the final 12.5% upgrading tunnel track.

Moreover, CIFA formwork (assembled approximately 700 meters far from the outlet end of the tunnel), after the casting of 32 nos. flat blocks, shall have to perform the tunnel vertical curve from 0,05% to 12,5% of slope (carried out in three casting steps), before being used on the final 12.50% sloped track for the last no.10 x 13,5 m long blocks.

3 The full-round formwork of self launching type

The equipment consists of a 9,40m. whole-diameter steel form section, 13,5 meter long, equipped with own bearing devices located at both ends; the steel form section, powered by a 22kW electro-hydraulic unit, can slide on a special carrier having a double-length longitudinal beam (totally 33 meters long) which is also equipped with proper supporting portals at both ends. The total weight of the equipment is approximately 230 tons.

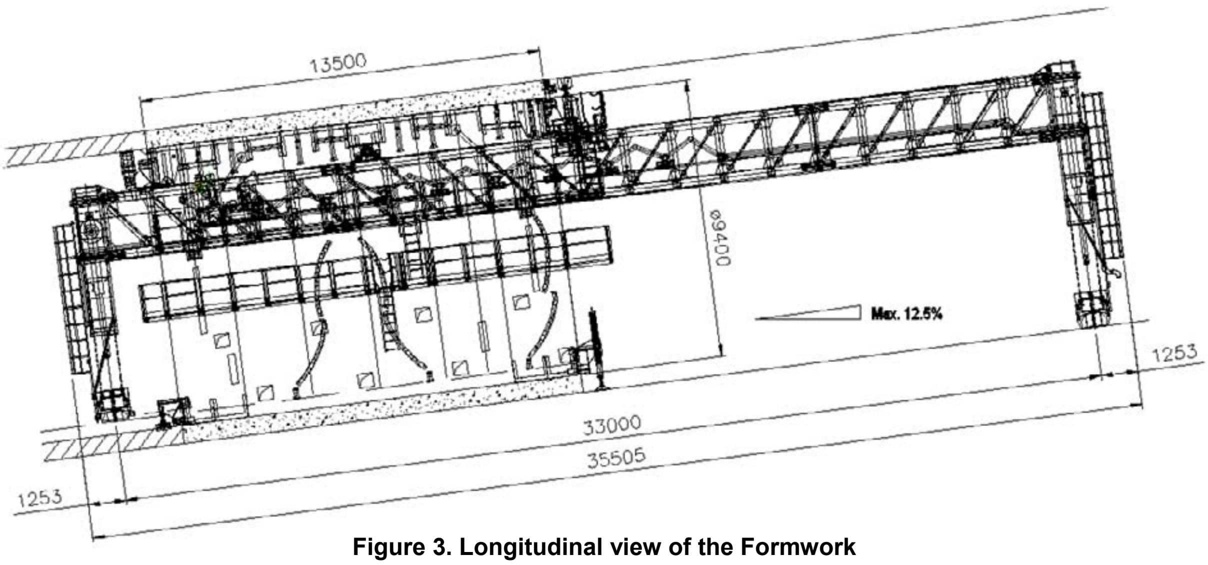


Figure 3. Longitudinal view of the Formwork

The advancement of the equipment is guaranteed by the relative movement between carrier and formwork, made by two hydraulic motors: when the carrier is supported on its portals, the formwork (in dismantled configuration) can slide forward along the beam of the carrier till the next block to be cast; similarly, when the bearing structures of the formwork are extended (against the rock in the front part of the form and against the previous cast in the rear part), the carrier can slide forward within the formwork structure and be launched to the next position. Minor cross adjustments of the supporting beam are also possible, by means of proper transversal hydraulic jacks installed on the portals.

The formwork cross section is divided into no. 5 different elements (one vault form on the top, two side piers and two invert forms), articulated each other and moved by proper double acting hydraulic jacks, which are able to collapse the forms after casting and re-set them again, in the new casting position (see figure 4).

As the most obvious advantage of a full-round formwork, the concreting of the whole section can be carried out just in one step, without any interruption between invert and piers; in addition, when the full-round formwork is of self-launching type (as in this case), the formwork can be moved along the tunnel without rails and wheels (so that, concrete and reinforcing rods can be placed simultaneously) and no intermediate supports are required inside the block to be cast (avoiding any type of hole or recess in the finished product).

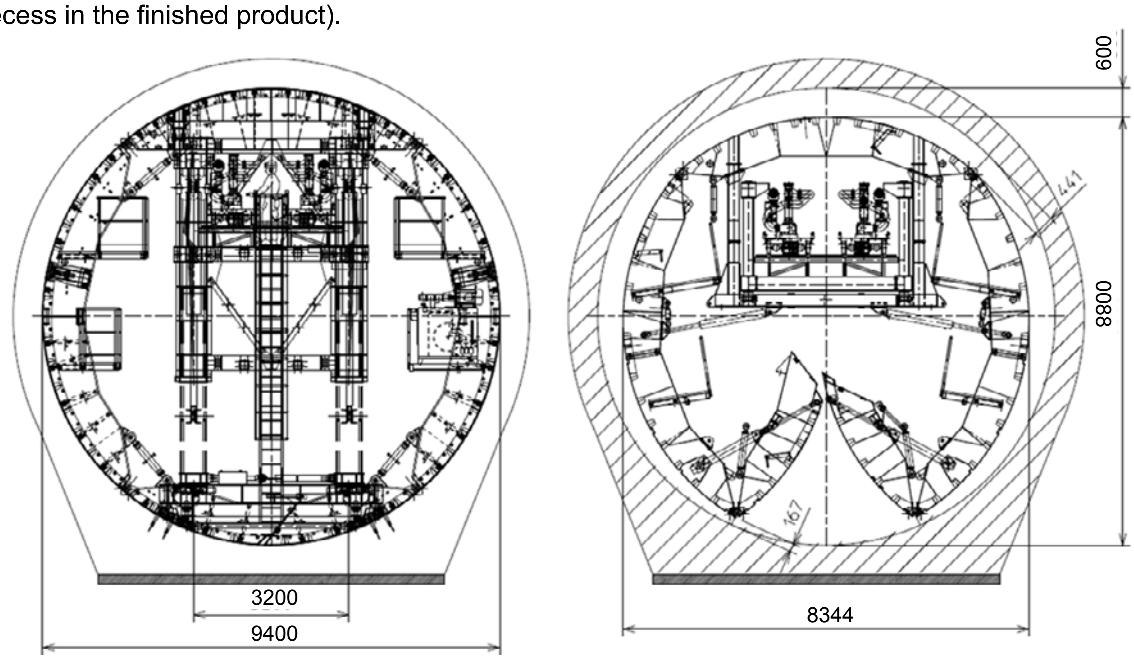


Figure 4. Cross section of the forms during casting (left) and in collapsed configuration (right)

This, however, implies the structures of the formwork, and in particular the aforementioned bearing devices, being able to handle and download all the horizontal and the vertical loads coming from the equipment during both the advancing and the casting phases.

During the casting operations, particular attention has been paid to the upward floatation force, always critical in all the full-round equipment, which is depending on the placing rate of the concrete (in our case, of 1.25 m/h corresponding to 55 m³/h), as well as on a series of physical and environmental parameters of the concrete, such as its setting time, its consistence and the placing temperature.

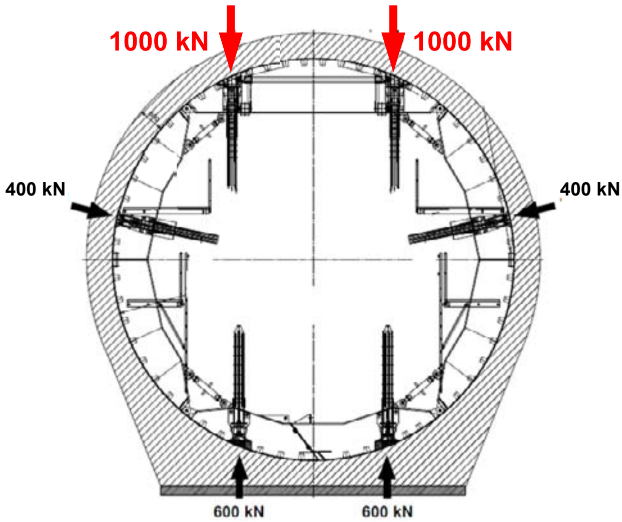


Figure 5. Reaction from the formwork

In this case, the maximum upward reaction against the ceiling has been calculated as approximately 2000 kN each side. It is a huge value (one of the biggest in our records) which has affected all the formwork design (calculation of the structures; how to remove it before dismantling; how to manage it on the overbreaking excavations; etc.).

Remaining reactions at the form ends are also notable: 400 kN acting on each side prop during the casting phases, due to the difference in height between the casting level of the two sides; the load of 600 kN on each bottom prop, acting during the carrier launching.

4 The formwork erection inside the tunnel

The erection of CIFA formwork was made inside the tunnel, in correspondence of the first casting position.

The erection was carried out using an innovative lifting mechanism, developed by CIFA and already used in many other underground assembly works.

This lifting mechanism consists of 4 telescopic columns, each one equipped with own climbing hydraulic jack and a set of extensions to be applied manually; those columns are anchored both to the ground and to the structure to be lifted and allow the needed vertical excursion, in our case from 2m. up to 5.8m.

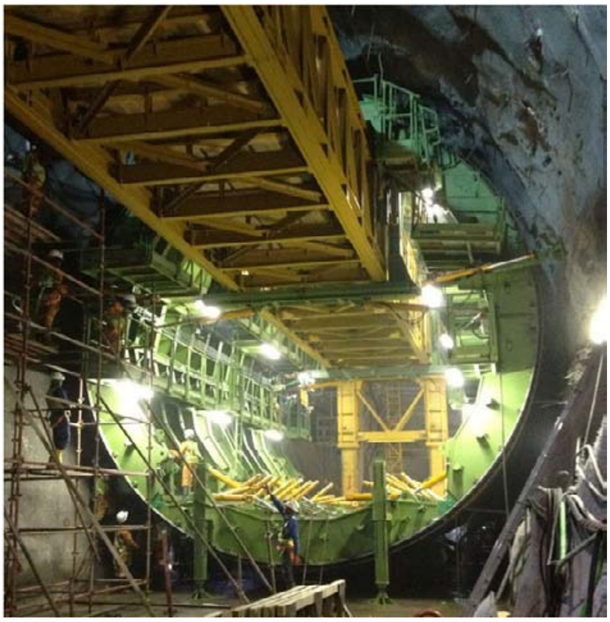


Figure 6. Formwork assembled on the first casting position: front view (left) and rear view (right)

The whole 33m long beam of the carrier was first preassembled on the ground, complete with the vault forms (located on the rear part of the beam), as well as the concrete distribution system and all hydraulic mechanisms, fully operational; then, the carrier beam was lifted till its final elevation, using the aforementioned lifting mechanism, and promptly connected to the carrier supporting portals, previously pre-mounted at both ends of the beam, so as to achieve the perfect stability of the structure.

Figure 7. Preassembly of pier and vault forms (left); preassembly of the beam (right)

Figure 8. Temporary CIFA lifting mechanisms (left) and final portal structure (right)

Subsequently, the vault forms were translated along the beam, up to reach and be connected to the pier forms, previously pre-assembled in the forward position, and then, shifted back again to the rear part of the beam, where the invert forms were also pre-assembled. All the elements of the formwork (vault, piers and invert forms) were connected each other just using the hydraulic jacks provided on board.

The assembly of this equipment, surely exceptional in size and weight (i.e. more than 35 meters long by 230 tons. heavy) was thus made possible inside the tunnel in only 40 working days, without the use of additional external hoists or anchorages on the rock.

5 The casting operations, using the invert membrane

During the initial tests carried out on site, a considerable quantity of air bubbles have been observed on the invert surface. This phenomenon is well known, since sometimes found in the casting of invert sections with full-round formwork and can usually be minimized, by acting on the concrete formula, as well as on the vibrators type and lay-out on the forms.

In this case, due to the tight requirements the concrete mixing was subjected to, it was agreed to solve the problem of the air bubbles by using a special drainage membrane, Zemdrain® type, to be cut to size and fixed manually to the bottom of the formwork.

The aforementioned membrane has allowed a clear improvement in the quality of the invert casting, as shown in the next figure 9 (outdoor tests, made on site).

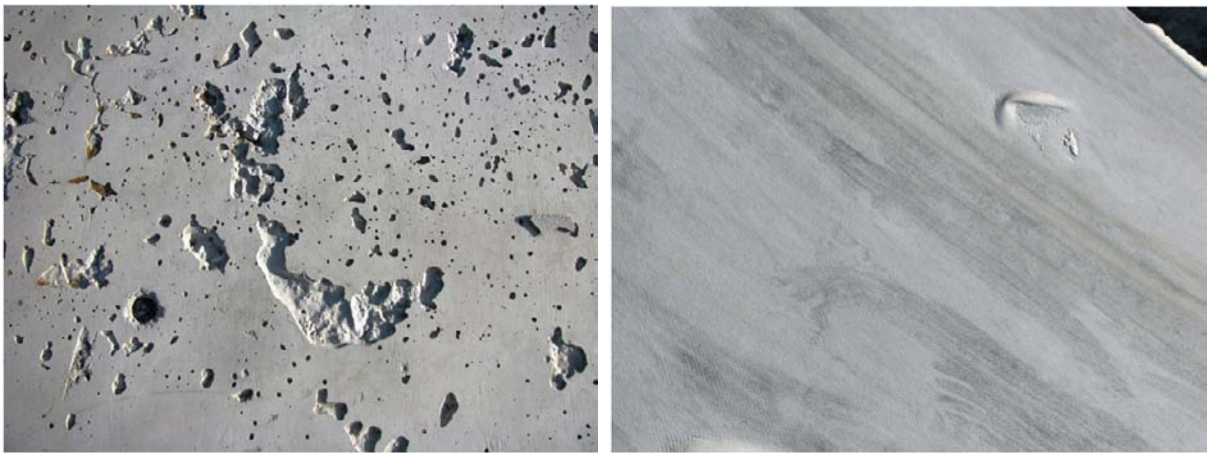
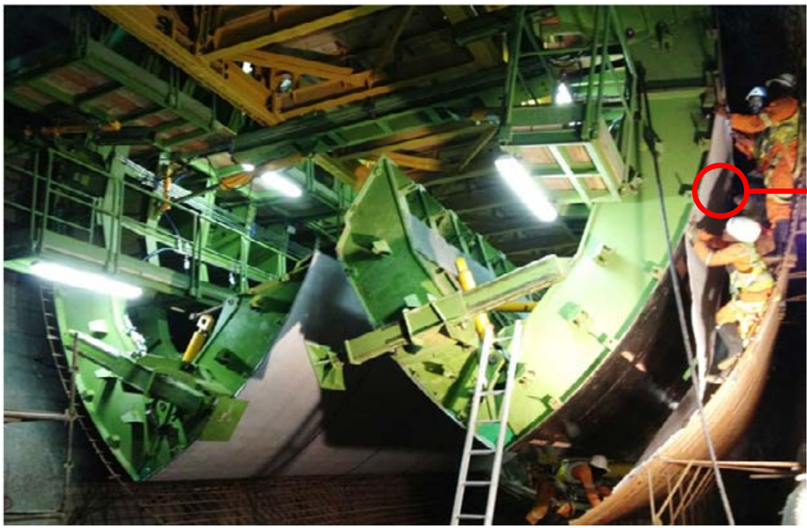
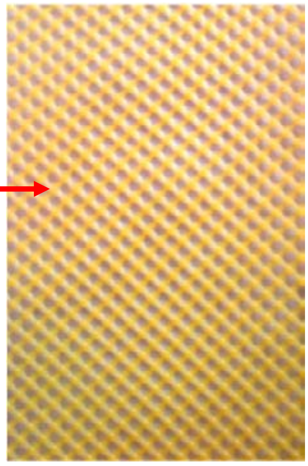


Figure 9. Invert surface without the membrane (left) and using the membrane (right)





The membrane

Figure 10. Application of the membrane on CIFA formwork

The formwork is equipped with 71 nos. air vibrators on the forms and 2 nos. independent concrete distribution systems, each one complete with a concrete distributor type CIFA DCL EI-750-300-5", self-propelled by hydraulic capstan winches, able to slide on the carrier beam for the whole length of the forms. Each DCL distributor is connected to both portals with proper 5" concrete piping lines, so to make possible the concrete supply from both ends of the equipment.

The minimum casting thickness is of 0.60m but almost everywhere the tunnel presents overbreakings on average of 0.25 m, up to a maximum of 1.25 meters. The volume of each concrete block is approximately of 400/500 m^3.

The formwork has been calculated for a max concreting rate of 55m^3/h so that the casting operations may take place in approximately 10 hours.

6 The vertical curve

In the original project, the change of slope from 0.05% to 12.50% had been designed in one single block (see figure 11), to be necessarily realized with a separate wooden shuttering, before the use of CIFA formwork. Subsequently, CIFA S.p.A. and CMI JV studied an alternative geometry of the vertical curve which made the use of CIFA formwork itself possible, in three straight casting sections, each one 13.50m long.

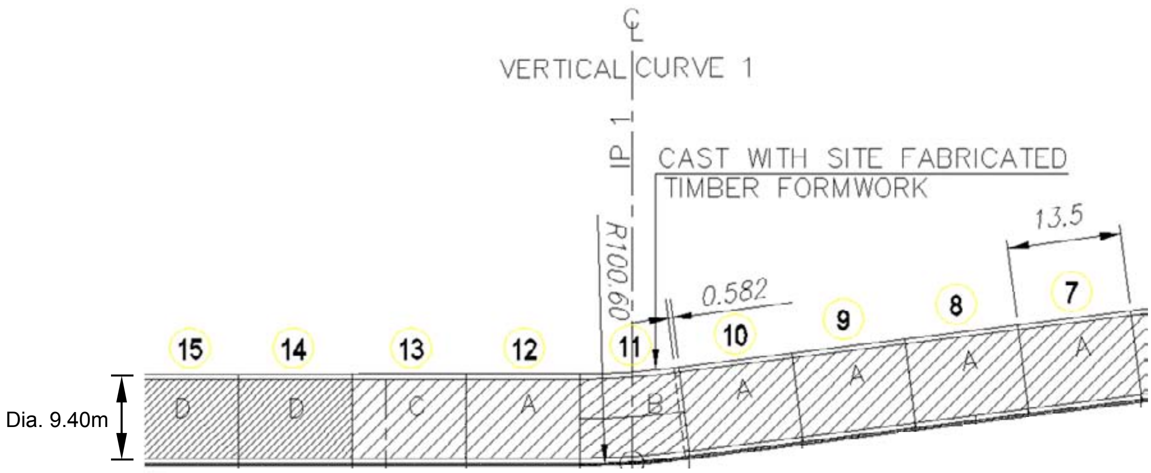


Figure 11. The vertical curve of the Tailrace tunnel as originally designed

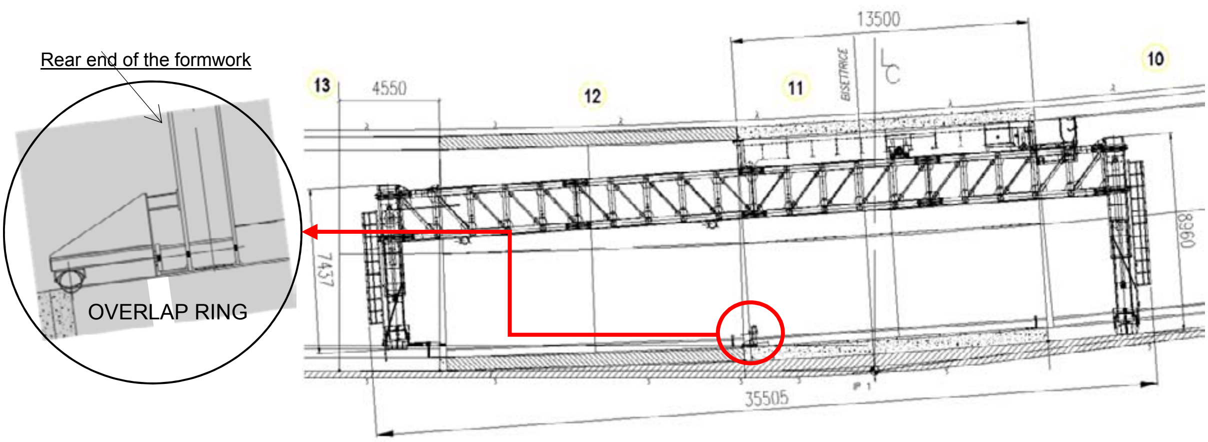


Figure 12. The vertical curve made in three steps, using CIFA formwork

This operation has influenced the design of the formwork considerably, particularly the vertical strokes (hydraulically driven) of the carrier portals, which had to be increased, in order to negotiate the vertical curve.

Furthermore, to compensate the trapezoidal gap between each block and the next one, CIFA S.p.A. designed a special flexible overlap ring, applied on the rear end of the formwork and able to match the previous block by means of a special pneumatic contrast device.

7 Conclusion

This case is an example of how a complex underground lining work can be successfully realized by using consolidated systems and methodologies, which always need to be improved with the analysis of the specific requirements, which occur case by case.

8 Acknowledgements

Thanks to Luciano Cicogna (JV Project Manager), Stefano Panetta (JV Plant Manager), Gianni Orlati (Chief Engineer, now working on another job-site) and Gino Brussa (Chief of Mechanics) for the kind hospitality during my visit to the site in February 2012 and for their help during the design of this big full-round formwork .

9 References

The “location map” and the “upper dam” and the “lower dam” pictures shown on figure 1, have been taken from: www.eskom.co.za/c/article/54/ingula-pumped-storage-scheme/