Three case-histories deal with design and construction of large shafts

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Abstract

Shafts are usually very important in urban tunnelling projects, and are used during construction for starting tunnel excavation, servicing construction (supply of materials, mucking, ventilation, etc.), for breakthrough, for extraction of materials and equipment at tunnel completion, for intermediate accesses, as well as during operation for tunnel maintenance or other scopes. The design of a shaft requires important decisions covering excavation sequences, walling methods, groundwater control, testing of efficiency of construction measures, structural design of lining and choice of acceptable safety factor and of allowable ground settlements. Numerical modelling and construction risk analysis guide the design choices. Design solutions for large shafts are presented, concentrating on three recent case histories where important optimizations were proposed and validated by numerical analyses and probabilistic simulations.

1. INTRODUCTION

Shafts play a key role in tunnelling projects but their great importance during construction, operation and maintenance are seldom commented in technical publications.
This paper summarizes some recent experiences of Geodata Engineering in this field.
The three cases were selected to illustrate the variability of problems and related solutions.

1. Punta Carrasco Shaft (Buenos Aires, Argentina)
    Main problems in original design: a) complex geometry (3 circular shafts interconnected by common flat side walls); b) difficult ground conditions with sands under high water pressure which required special countermeasures to avoid piping, c) insufficient space for operation of the two TBMs which were to start excavation from this group of shafts.
    Solutions with new design: Optimization of the geometry by adopting a large single shaft divided into 3 compartments; diaphragm walls deepened so as to completely cross the Puelche sand layer and reach the stiff clay base layer to permit dry excavation and construction without soil treatment.

2. Piazza Maggione Shaft.
    Main problems: high water pressure in difficult ground conduction in critical urban area (historical centre).
    Solutions: Excavation by diaphragm walls (without drainage), using cut & cover top-down method with intermediate slabs, in order to stabilize the diaphragm walls themselves and curve bottom slab in order to contrast the heavy hydraulic pressure.

3. Soacha Shaft (Bogotá, Colombia)

Main problems in original design: a) excavation of two large shafts, very close to each other, in highly fractured rock and excavation of a tunnel to connect the two shafts; b) high seismic loads (peak acceleration 0.45g).

Solutions with new design: Hydraulic and geometrical optimization by adopting a single shaft; this choice eliminates detensioning between the two original shafts which unbalances pressures on the walls, as well as the necessity of building a tunnel between the two shafts. An innovative solution was proposed to connect primary and final lining in order to obtain a robust structure capable of withstanding the high seismic loads.

## 2 PUNTA CARRASCO SHAFT (MALDONADO PROJECT IN BUENOS AIRES)

2.1 The initial design

The Punta Carrasco outlet shaft represents the endpoint of the stormwater drainage system reached by two flood diversion tunnels crossing the central part of Buenos Aires. Near ground level, it is connected to a 100m-long canal which discharges the diverted floods into the Rio de la Plata. As shown in Figures 1 and 2, the two tunnels (T1 and T1) converge into this shaft
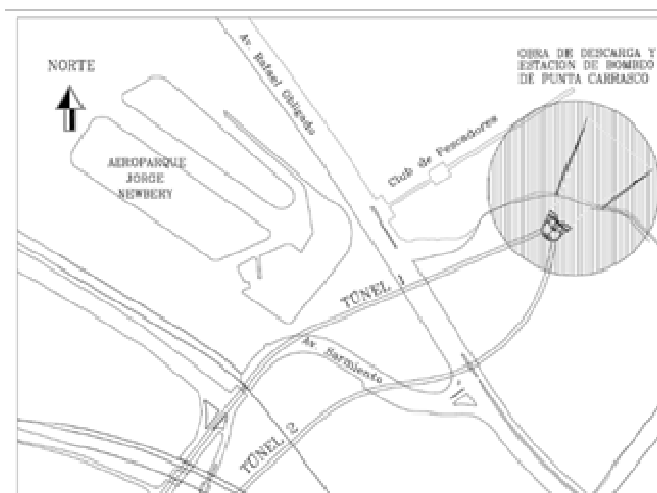
The Punta Carrasco shaft design was initially conceived as 3 circular shafts (each with an internal diameter of 14.4m), interconnected by common flat sidewalls, the first shaft being the end point of tunnel T1, the second being that of tunnel T2 and the third being the pumping station to empty the tunnels for maintenance (Figure 2).

The soil strata in the area are an alternation of silty clays and sand deposits: a top layer of soft clay, overlying an eolic soil deposit ("Tosca"), consisting of an alternation of silt and silty sand, above a layer of monogranular sand ("Puelche") and a deeper stiff clay base layer ("Paraná").

The water table is approximately 3m below ground level.
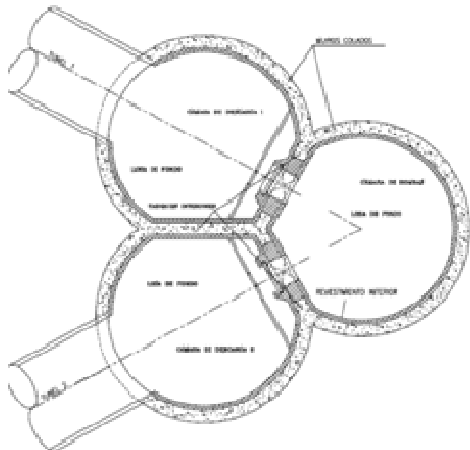
Figure 1: Initial design   **Figure 2: Shaft site**

Since the base of the 40m deep diaphragm walls was in the Puelche sands, shaft excavation was initially to be performed under water and was to be followed by pouring a 3m-thick concrete plug under water at a depth of 35m depth to avoid piping of the Puelche sands. Water was then to be pumped out so that shaft lining could be completed under dry conditions.

2.2 The final solution adopted

The original three-clover shaft design described above was modified before construction in favor of a single 40m diameter shaft divided into 3 compartments, each with the same scope as the corresponding shaft in the original three-clover design (Figure 3).
The diaphragm walls were deepened to 55 m in order to completely cross the Puelche sands and reach the stiff clay base layer, thus permitting excavation and concreting in dry conditions without soil treatment. Hydromill technology was used for diaphragm construction considering their great depth and the design requirements of verticality and waterproofing.
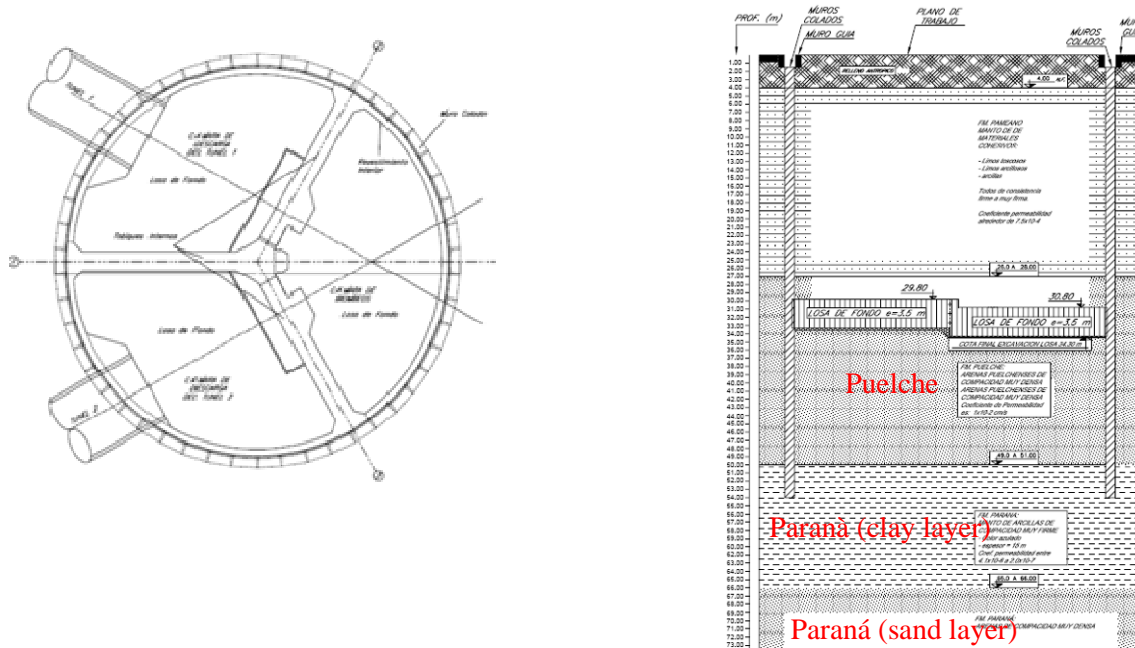

Figure 3: Punta Carrasco Shaft (as-built design)

2.3 Risk analysis of the proposed solution

A risk analysis related to the construction of Punta Carrasco shaft was performed, based on numerical modeling. Through FLAC (finite difference code) numerical analysis, in particular the risk of piping/bottom heave was analyzed considering the different construction stages.
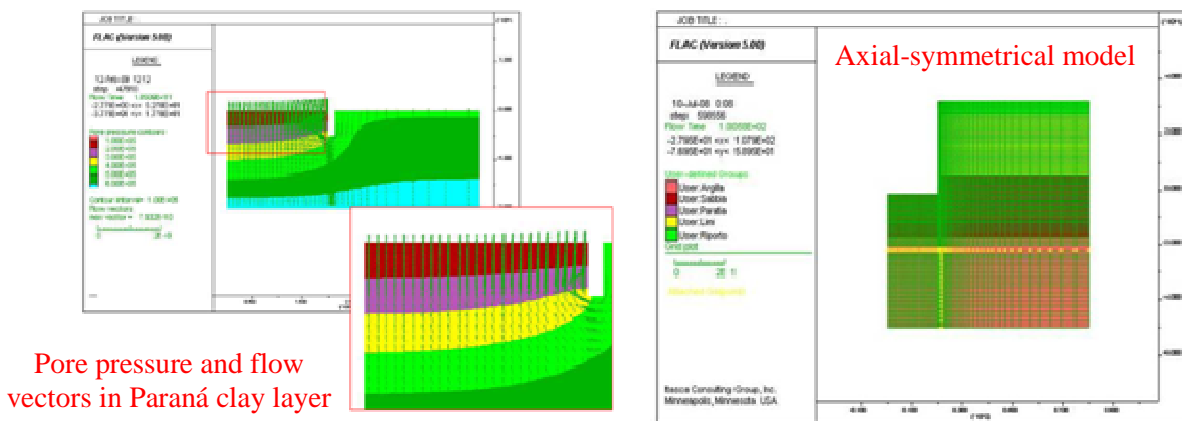
Figure 4: Numerical modeling for Risk Analysis of Punta Carrasco Shaft

Parametric/sensitivity analyses were performed, varying the following data: a) thickness of Paraná (impermeable) layer where the diaphragm walls are embedded, from 10 to 20m (min measured value from n. x borehole =yy m); b) hydraulic pressures in the mentioned layer d) drained/ un-drained behavior of the layers and related mechanical parameters.
The analysis was axial-symmetrical, uncoupled with groundwater flow calculation and subsequent mechanical calculation.
Only in the case of Paraná 10m-thickness, in the last stages of the analyses, numerical convergence failed, showing potential instability condition. The risk was consequently classified as Low / Very Low.

2.4 Probabilistic analysis and comparison of expected project construction times for the two solutions taking into account construction risks

One of the criteria followed in deciding for the design change from a triple-shaft to one large shaft was the comparison of expected total project construction time using probabilistic and risk evaluations. In brief, the following approach was adopted to evaluate construction time variability and uncertainty associated with each of the two solutions (smaller triple-shaft or larger single shaft):

a) On the basis of detailed construction schedules for the two solutions, the expected duration of each single activity was considered by estimating its possible minimum value, the most likely (generally coincident with the deterministic value reported in the planning) and the maximum probable duration. Consequently, triangular distributions were considered for the probabilistic simulation of these "ordinary" activities.
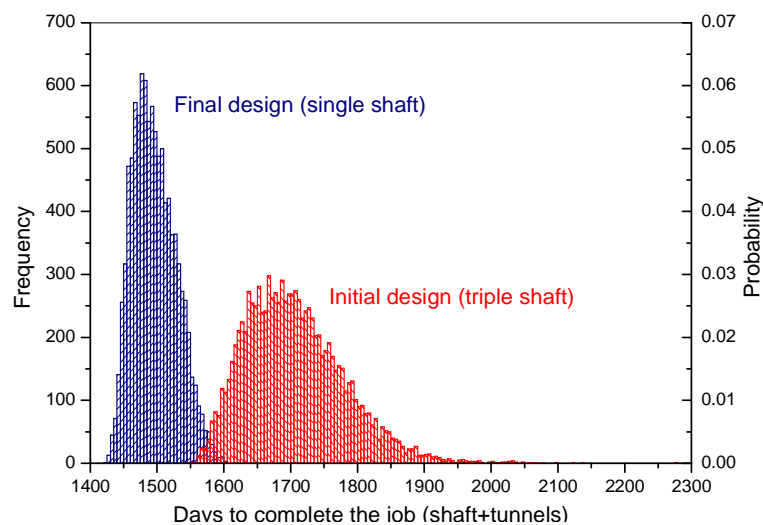
Fig.5: Result of the probabilistic simulation by Montecarlo method

b) The main construction risks ("accidents") were examined to estimate potential time drifts. The main differences in favour of the final proposed solution can be essentially related to:

-   lower risk of piping and/or floatation due to different geometry also in relation to geology and different construction methods;

-   lower risk of interference during simultaneous operation of two TBMs served (supply of materials and mucking) from the same shaft (be it single and divided into 3 compartments or triple) due to more available space.

- for modelling the potential construction delay related to the described "accidents", negative exponential distributions were considered to reasonably simulate the progressive decay of the probability of occurrence as potential delay increases.

c) In favour of safety, a positive correlation between the different input parameters (i.e. probabilistic distributions of single tasks and "accidents") was considered.

d) The probabilistic estimate of the construction time for both the original and the final solution was consequently performed by the Montecarlo method (n. 10.000 simulations).

The results of the probabilistic simulation are presented in Figure 5. As can be seen by comparing the two curves in the diagram, the proposed (final) solution of one large single shaft is clearly preferable in terms of construction time and prevention of potential delays. More specifically, this solution presents both a more favourable statistical index of position (mean, mode, median..) and of dispersion (standard deviation,..).
Considering the 50th and 95th percentiles, the difference between total project construction times with the two alternative solutions is 205 and 286days, respectively. In the worst case for both solutions (considering all potential "accidents" included in the model), the difference between the theoretical maximum construction time increases to 677 days.
It is important to note that, as illustrated in the next paragraph, the actual construction time employed for the large single-shaft solution practically coincided with the most probable expected construction time as forecasted through the probabilistic simulation over three years before.

2.5 *Shaft construction*

The adoption of one large diameter shaft proved to be a winning choice and the construction time forecasts very precise. Shaft construction started nearly 3 months after contract initiation because equipment had to be imported from Europe. The shaft was completed in one year, finishing 15 months after contract initiation while the EPB TBMs were being imported from Canada. The 5 km-long Tunnel T1 excavation started immediately after assembly and finished in September 2010, 28 months after contract initiation. The 10 km-long Tunnel T2 was excavated in 22 months between February 2010 and December 2011. In short, the two tunnels were completed within 1294 days after contract initiation, before the original contract deadline. The whole project shall be operational within mid-2012, less than 1500 days after initiation, exactly the most probable time for completion forecasted 3 years before, through construction risk analysis, for the single large-shaft solution.
The very fast tunnel excavation was undoubtedly due in part to the excellent Buenos Aires soils and in part to the Contractor's expertise (600-700 m of excavation per month was in the norm). However, the Punta Carrasco shaft dimensions and layout played an important role to permit higher production in tunnel excavation because shaft size permitted simultaneous and physically separated operation of 2 TBMs, simultaneous entry and supply of materials (segment lining and mortar grout) for the two tunnels and simultaneous mucking from the two tunnels. In addition, there was sufficient space for keeping workers separate from machinery and work, thus assuring safety.

**Figure 6: Punta Carrasco shaft during construction**

3. PIAZZA MAGGIORE SHAFT IN BOLOGNA METRO

A very complex and time-consuming work in a historical, urbanized area is always a challenge for designers. In the case of Bologna Metro line 1, different and difficult items were considered in planning and designing the underground works such as tunnelling under water table in very poor ground conditions, underpassing of buildings particularly at historical places, protecting archeological findings related to the Roman era, minimizing construction-site areas, and managing intensive surface traffic.

In particular, Piazza Maggiore Station is located at a historical square of Bologna where two major roads cross the town centre, with a lot of critical and historical buildings and a lack of space to for construction sites. For all these constraints the Piazza Maggiore Station itself can be considered as a project in the metro project.

The soil-layers are characterized almost exclusively by alluvial deposits which, by their lenticular geometry, show high vertical and lateral variations. This unit is formed by lens of coarse sand, gravely sand, gravel with sand, and sandy gravel, and clasts up to approximately 8 cm, as well as rare pebbles. In addition, in the first 40m it can be found a multilevel groundwater aquifer. It consists in four different levels, partially saturated and locally under pressure,

The circular shaft, from which curved platform tunnel and access tunnels will be constructed first (see following figures).
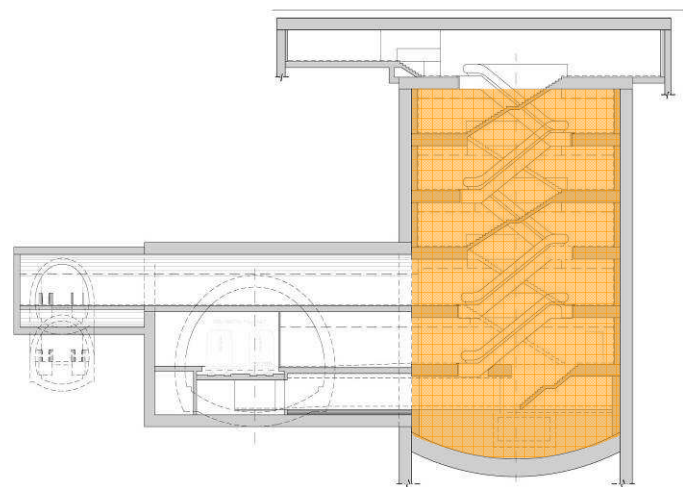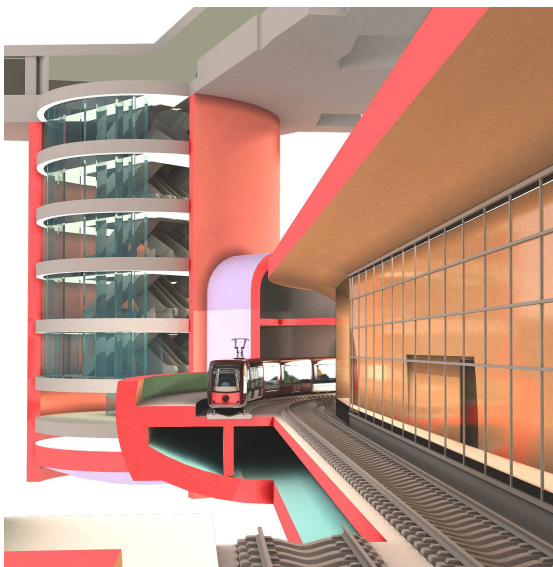
Figure 7: Piazza Maggiore Shaft (geometry)

Both 2D Finite Difference Method (FDM) using FLAC and 3D Finite Element Method (FEM) using ANSYS have been used to evaluate bending moments, shear and axial forces on the diaphragm walls, creating an axial-symmetric model with 3D analysis to simulate the creation of large openings in the structure. In the following figures the models used for the design of the shaft (axial-symetrical FLAC, ANSYS) are shown.
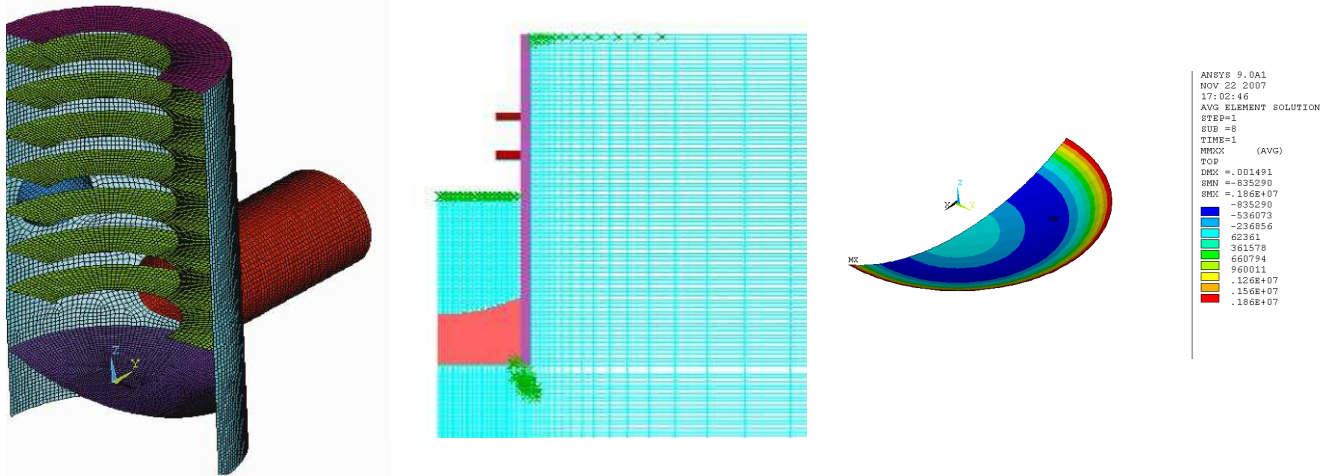
Figure 8: Piazza Maggiore Shaft (numerical modeling)

Taking into account the difficult geological context (soft clay under groundwater level) and the critical urban area (historical center, whereas the control of induced settlements is important), the focus of the design was also the impact on the surface in terms of settlement.

Being 20 m in diameter and 39 m deep with diaphragm walls of 45 m long, the circular shaft will be excavated using cut & cover top-down method. The shaft has intermediate slabs, every 4.8 m, to create support for stairs and to stabilize the diaphragm walls themselves.

Diaphragm wall provides structural support and water tightness and treatment of the excavation bottom (jet-grouting columns) counteract the risk of piping.

Bottom slab has an arched invert shape in order to reduce bending moment and to transfer bending forces stemming from compressive ground water forces on the diaphragms.

4. "CRIDADO Y SUCCION" SHAFT IN BOGOTÀ

The shaft will be located South-West of Soacha (a town close to Bogotá, Colombia), on the left side of the road which leads from the water reservoirs in town to Mondoñedo Muna, near the future Canoas wastewater treatment plant.

Design initially proposed two circular shafts, one of 42m internal diameter and the other of 60m, connected by a 63m-long tunnel (Figure 7). The first shaft is the arrival point of the sewer tunnel and its scope is to screen the wastewater (*Cribado*). The second shaft is a pumping station towards a canal which leads to the treatment plant (*Succion*).

The proposed final design (Figure 8) optimizes shaft volumes without changing the hydraulic performance of the system: pumps, design flow, number of units, total hydraulic load, volume control units remain unaltered. A single shaft was proposed with 65m internal diameter and 55m depth.
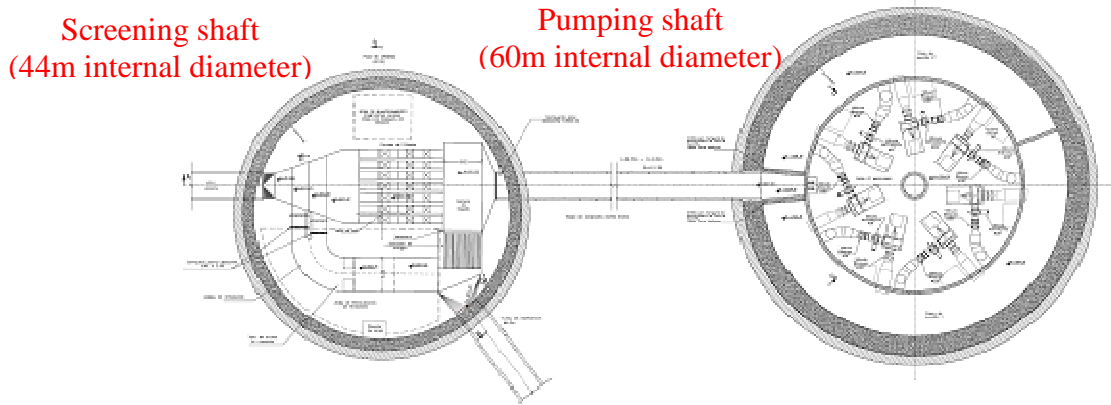
Screening shaft
(44m internal diameter)

Pumping shaft
(60m internal diameter)

Figure 9: Initial design (plan)

The numerical modelling performed focused on the following points:

- Stability assessment during excavation: structural analysis of primary support, checking conditions according to the construction sequence; this was accomplished with three-dimensional analysis of the continuum using FLAC 3D, Axial-symmetric analysis of the continuum using Plaxis, three-dimensional simulation analysis of the discontinuity using Unwedge.

Structural analysis the final support, considering the high seismic load; this was done with a three-dimensional model using Strauss with dynamic analysis.
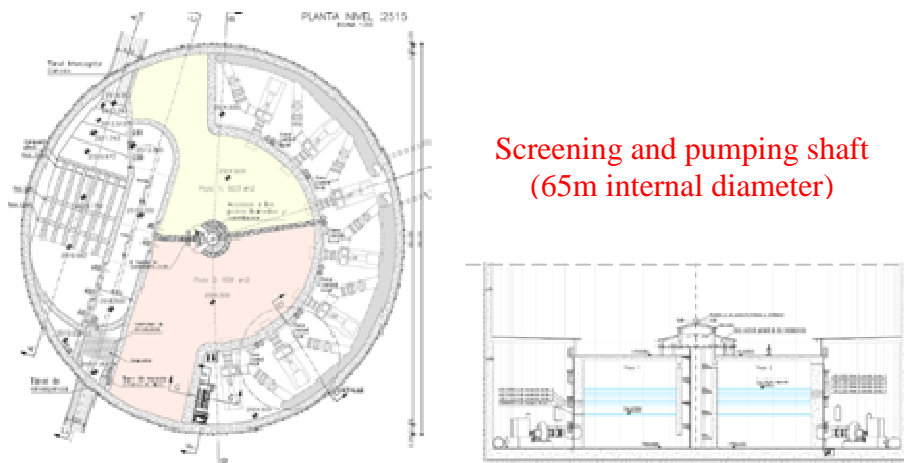

Screening and pumping shaft
(65m internal diameter)

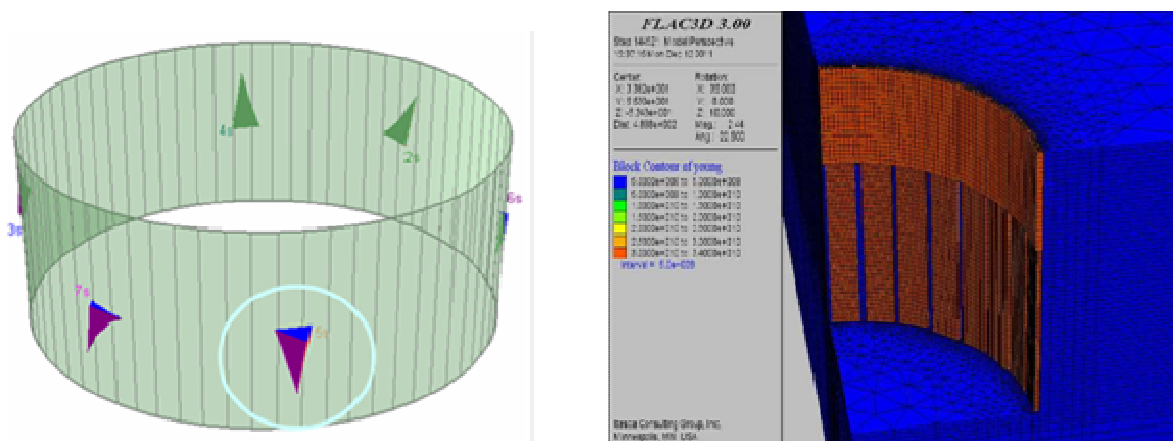**Figure 10: Final design (plan and vertical section)**

Figure 11: - Stability during excavation (UNWEDGE and FLAC 3D models)

Hydromill-excavated diaphragm walls were selected for primary support. With the design solution adopted, the diaphragm wall panels (0.83mx6m) are a part of the final lining thanks to the particular connection between panels and cast-in-situ concrete lining (see Figure 11). Between two panels a space of almost 1m is initially left unexcavated in order to subsequently complete reinforcement and concrete lining, proceeding top-down during shaft excavation.
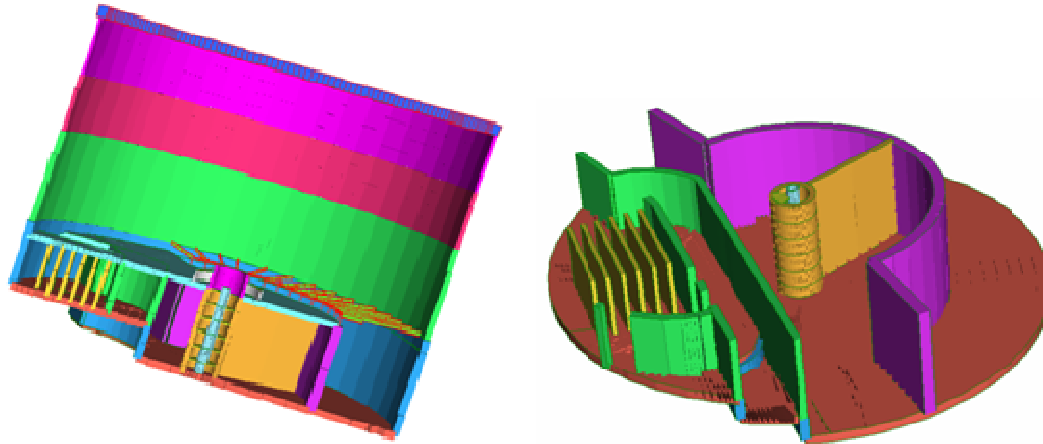

Figure 12: Modelling of the final support (Strauss model)
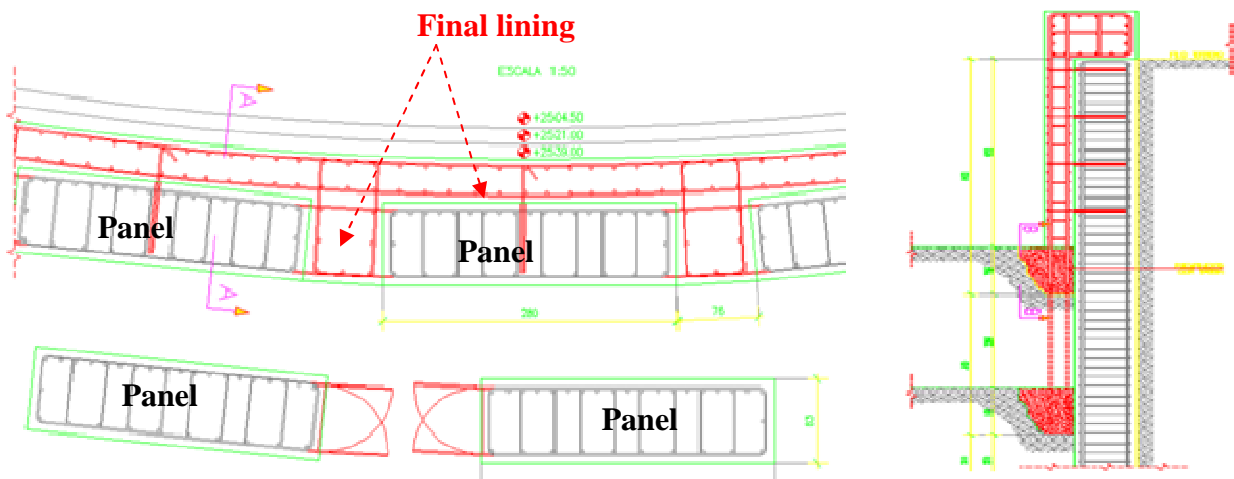

Figure 13: Connection between diaphragm wall panels and final lining

The proposed solution allows the following advantages against the basic design solution:
- Reduction of structural volumes with the same basic hydraulic design: the screening and pumping systems are the same, the tunnel connecting the two original shafts is no longer necessary; in general, the solution is simpler and more efficient.
- Elimination of a tunnel which would have been constructed in high risk conditions (high groundwater pressures and in detensioned material surrounding the shafts).
- Pressures on the shaft walls are more balanced: the excavation of two shafts would entail a more detensioned area between the two: symmetry of loads is always preferable.
- During excavation, logistics would be simplified. In fact, the two-shaft solution involves doubling many operations, doubling logistics, larger excavated volumes and additional primary support. Consequently, the single shaft solution benefits in terms of construction time and costs.

5. CONCLUSIONS

This paper presented three recent case histories of large shafts, where design efforts in geometrical optimization were aimed to faster, safer and more efficient construction, reduction of construction risks and more efficient operation of the projects. In all cases diaphragm walls were used, although for different reasons.

Basically, construction of a single large shaft often makes it possible to avoid the construction of multiple smaller adjacent shafts, thus simplifying construction sequences and reducing construction time and costs.

Urban tunnelling projects usually include shafts which heavily influence construction times and costs of the whole project. This is particularly true for shafts from which tunnel excavation starts and from where construction of the tunnel is serviced (material supply, muck removal, machinery and equipment entry and exit, etc.). In fact, adequate logistics are essential for construction efficiency and improved safety: sufficient space is necessary for workers and equipment to move, for mucking or material supply to take place or, in general, to permit concurrent activities without having to "queue" or wait for completion of other operations. For this reason, separate working areas should be dedicated to different tasks.

The first example deals with an important tunnelling project designed for flood protection of Buenos Aires in Argentina. The 40m-diameter *Punta Carrasco* shaft was the key to the success in the construction of the whole project which included two tunnels (T1 5km-long and T2 10km-long). A probabilistic construction risk analysis carried out at the beginning of construction had shown that the one-large-shaft solution would have probably saved over 7 months in the construction of the project; construction times recorded more than three years later showed that actual construction times coincided with the forecasted "most probable" expected times. Punta Carrasco shaft is the first application of hydromill technology in Argentina.

The second example (*Piazza Maggiore*, Bologna Metro) deals with a design example of large shaft in critical urban area (historical centre) and critical hydro-geological context (high water pressure in soft clay). The proposed solution was the excavation by diaphragm walls (without drainage), using cut & cover top-down method with intermediate slabs, in order to stabilize the diaphragm walls themselves and curve bottom slab in order to contrast the heavy hydraulic pressure.

The construction of the "*Cridado y Succion*" shaft (third example) will begin in 2012. The 68m-diameter shaft is part of an important project for rehabilitation of the heavily contaminated Bogotá River in Colombia. The proposed solution optimizes construction times and costs. Numerical modelling and construction risk analysis have shown its feasibility, highlighting the benefits which come from geometric and hydraulic optimization. An innovative solution was proposed to connect primary support (diaphragm wall panels) and final lining (cast-in-situ reinforced concrete) in order to obtain a robust structure capable of withstanding the high seismic loads.

The authors hope that the solutions described in this paper may be of help in construction planning of similar shafts in the future.

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