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Seepage experiences for deep urban excavation at the TBM Malatesta shaft, Rome

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ABSTRACT: The control of water pressure and seepage in a deep urban excavation, in elevated hydraulic heads conditions, has represented and continues to represent one of the main problems for the realization of the new C Line Subway stations in Rome. The subway line, which extends from the city center to the suburban southeast, is characterized mainly by pyroclastic materials over Pleistocene deposits. Dewatering systems for the C Line Stations have been implemented in order to lower the water level below the final excavation level, without appreciable repercussions on the external diaphragm walls. On the basis of carried out experience, this paper will describes and explains the results of the dewatering system that has been designed and executed for controlling the water underpressure and management of the seepage process in deep open pits subjected to elevated hydraulic heads.

1 INTRODUCTION

The realization of a deep excavation in a high hydraulic head condition, in absence of waterproofing treatment at the base, usually needs dewatering systems to control the piezometric condition and, more generically, is employed for lowering the water table within the diaphragm walls. This is a particularly sensitive aspect in the excavation of the new C Line Subway in Rome, where on account of the high density of archaeological remains, the subway stations are at an average depth of 25 meters below ground level. The stations are also characterized by elevated hydraulic loads. The purpose of this paper is to explains the dewatering system used for the TBM Malatesta Shaft, describing the monitoring devices that have been predisposed and the results that have been achieved by the dewatering system during the testing phases. The final section of the paper will cover another dewatering case that will arise in due course along the line, underlining the results and the differences in relation to the first case.

2 GEOLOGICAL PROFILE

The C line stations interest a large area characterized by the volcanic products of the Albani Hills, which represent the majority of excavated materials. The geological longitudinal profile of the TBM Malatesta Shaft, is represented in Figure 1 and synthesized below. The upper layer is constituted by backfill (R) which is so rich in archaeological remains that it has conditioned the construction sites. This is a heterogeneous material of a pyroclastic nature of a silt-sandy granulometry thickened by gravels. Below this there is an upper volcanic complex which extends over almost the entire line until to the bottom excavation. The pyroclastic formation is classified as Villa Senni Tuff (VS), Lionato Tuff (TL), Muddy Tuff (TT) and Black/Red Pozzolanas (PN & PR). These materials are of a sand-gravelly or slime-sandy granulometry, strongly cemented (TL) in parts. These are the main formations that interest the excavations of the stations. The pozzolana deposit in particular is chiefly concerned by the dewatering process on account of its elevated thickness. The Lower Tuff complex (TA, T1, T2) lies immediately above the Pleistocene deposits. The layer of Clayed Tuff (TA) is composed slime-sandy grain material of a good consistency. These layers run between hard tuff T1, T2 strata, which are sand-gravelly and subordinately slime-sandy in grain and size. Locally these layers can be of a rock consistency. Although strongly cemented at intervals, these rock layers are in a highly fractured condition (es. T1). Still further below are the Pleistocene layers (ST/STa, AR and SG). The first of these layers is made up of slime and sand (STa/ST) of average to elevated consistency. The intermediary layer is generally constituted by clays and lake slimes (AR).
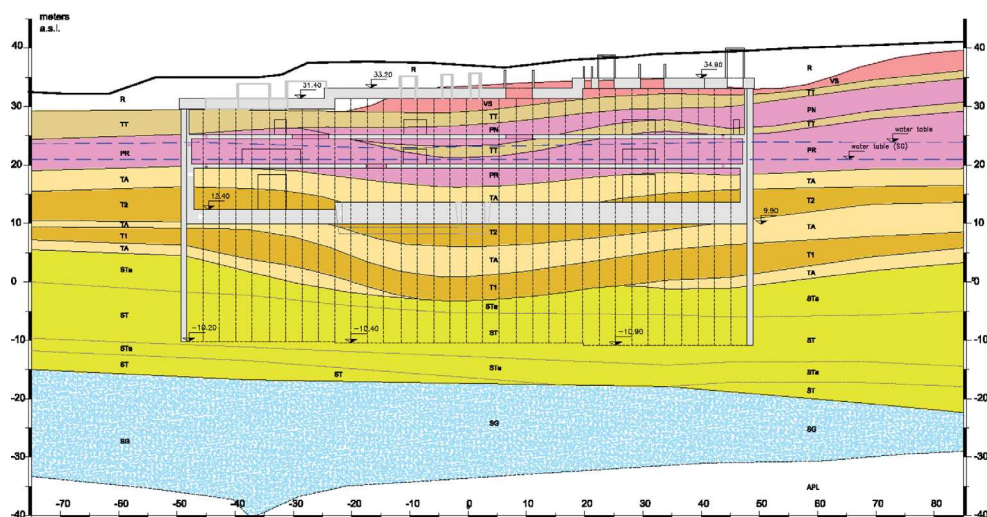
Figure 1. Geological profile of TBM Malatesta Shaft.

Table 1. Geotechnical design parameters of the strata.

Layer	W (%)	γ (kN/m³)	W$_L$ (%)	I$_P$ (%)	K (m/sec)
R	25	17	n.d.-46	n.p.-12	1 E-5
VS	45	17	n.d.	n.p.	1 E-6
TT	42	17.5	38	7	5 E-6
PN	35	17.5	n.d	n.p.	1 E-5
PR	37	17	n.d.	n.p.	1 E-5
TA	52	17	42-n.d.	8-n.p.	5 E-5
T1-T2	40	17	n.d.	n.p.	5 E-5
ST	28	18.5	28	6	8 E-6
STa	38	18	58	30	1 E-7
SG	–	20	–	–	1 E-4

The lower stratum is characterized generally by gravels in a sandy matrix, with few silty elements that has originated from the Paleotevere deposit (SG). This layer contains the main acquifer of the city of Rome, which in turn is sustained by an underlying basal formation of Pliocene Clays (APL).

Table 1 illustrates the geotechnical layout parameters of the various strata.

3 GENERAL HYDRAULIC CONDITION

In general terms the hydraulic situation of the area of Rome can be broken down into four main geological complexes: 1) the backfill complex, 2) the alluvial deposit complex, 3) the volcanic deposit complex and 4) the Pleistocene deposit complex, at whose base there is an impermeable substratum of Pliocene clay (bedrock). The main aquifer is located in the Pleistocene sediments and above the volcanic deposits. The drainage channels are constituted by the Tiber and the Aniene rivers and theirs affluents.

The C line runs mainly along the left bank of the Tiber, from the Albani Hills southeast to northwest. An acquifer in the superficial alluvial deposits, located in the central zone of the C line, is regulated by the water table of the river and has the tendency to disappear together with the alluvial deposits (Ventriglia, 2002).

4 SEEPAGE PROCESS: DESIGN ASPECTS

The design of the depths, diameters and distance between the wells is based on the interpretation of the permeability and punctual dewatering tests along the line (AGI, 1977) as well as on calculations of the volume of dewatering and the piezometric condition imposed by the drainage.

The calculation of the distance and depth of the wells refers to a hydraulic scheme that calculates the seepage process, cautiously imagined according to a minimum path directed from the base (water supply) to the top.

A budget for the in/out water volume through the excavation base was calculated, balancing out the two flows—the first from the outside inwards and the second from the inside, receiving and processing the volume of water from the first flow.

The seepage process around every drainage point was therefore assimilated to that of a well like that in Figures 2 and 3.
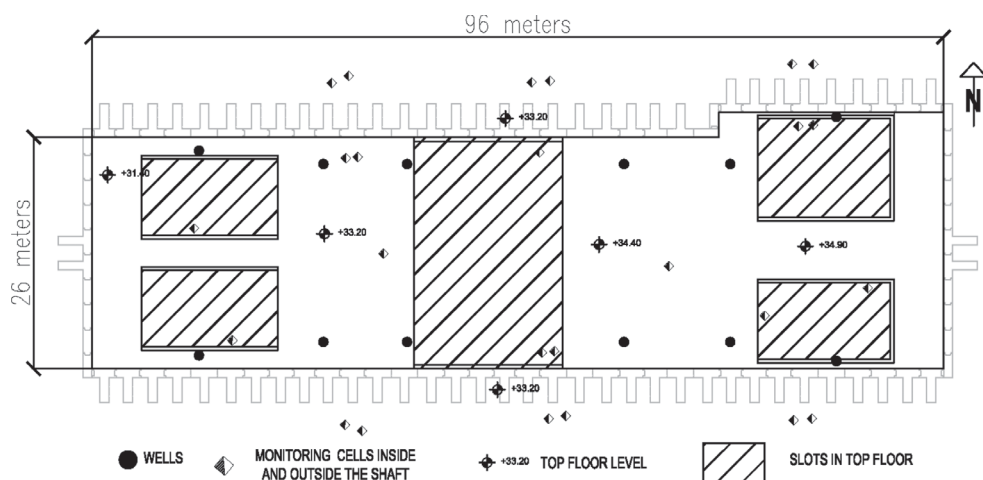
Figure 2. Design sketch of hydraulic flow during the pumping.

Figure 3. Scheme of seepage flow.

The following equation regulates the two flows:

$$\frac{\pi x R^2}{L} \cdot (\Delta H - \Delta P_m) \cdot K1 = \frac{2\pi \cdot K2 \cdot 2 \cdot D \cdot \Delta P_m \cdot G}{\ln\left(R/Ro\right)} \quad (1)$$

so the maximum overpressure value can be defined as:

$$\Delta P_m = \frac{\Delta H \cdot R^2 \cdot \ln\left(R/Ro\right) \cdot K1/K2}{R^2 \cdot \ln\left(R/Ro\right) \cdot K1/K2 + 4 \cdot D \cdot L \cdot G} \quad (2)$$

where:

- $K1$ is the permeability of outside strata;
- $K2$ is the average permeability of the strata under the bottom excavation;
- L is the seepage path, equal to h_0;
- $\Delta P_m = \Delta P_{max}/2$ unknown is the average hydraulic pressure;
- R is the distance between the wells;
- Ro is the radius of the well, equal to 20 cm;
- $\Delta H = H - h_0$ is the hydraulic head;
- G represents the degree of well penetration in the aquifer;
- D is the drainage thickness of the well.

To vary of the distance R between the wells, the underpressure ΔPm is drawn, compatible with the stability conditions that we want to reach and the flow Q for the single well. The dewatering efficiency has been studied

Figure 4. Schematization of the well.

through the Forchheimer's (1930) and Dachler's (1936) solutions in order to provide the real lowering phreatic level inside the open pit.

5 DEWATERING SYSTEM DESIGN

The dewatering system is made up of a total of 12 wells. The wells (Ø400 mm) are deep around the base of the diaphragm walls, inside the ST layer

Figure 5.   Monitoring plan of TBM Malatesta Shaft.

Figure 6.   Picture of pumping system of the Mirti Station: flow meter and pipes.

(−8.0 m a.s.l.) with a drainage window of 32 meters over a total depth of 40 meters. The dewatering interests both the volcanic and Pleistocene complexes, leaving out the SG layer. The wells have been equipped with a submerged 5.0 kW (7.5 HP) pump. The executive scheme is as illustrated in the following figure.

Before the beginning of excavation, the system has been tested.

During the dewatering test, the piezometric level was monitored by 25 piezometric cells: 12 Casagrande cells, located outside the perimeter of diaphragm walls and 13 Vibrating Wire cells, located under the bottom excavation inside the perimeter of the diaphragm walls.

In the Figures 5 and 6 it has been represented a monitoring devices planning in the TBM Malatesta Shaft and an example of the pumping system equipped for dewatering.

6   THE TBM MALATESTA SHAFT DEWATERING TEST: EXPERIMENTAL RESULTS AND DESIGN VALUES

The TBM Malatesta Shaft has been already completed in order to begin work on the four TBM tunnel excavations. It has an area of around 2500 m^2 and was built with T section diaphragm walls. The length of the diaphragm walls varies between 40 and 44 meters. The elevation of the bottom floor is +9.90 m a.s.l., or around 25 meters from ground level, for a maximum hydraulic head of 14–15 meters (water table at 24 m a.s.l.). As can be deduced in Figures 3 and 7, the calculated hydraulic flow is directed upwards by the excavation at the base and fed by the SG deep formation. The Inferior Tuffs complex has been pierced completely and the diaphragm walls are driven into the sand-silty ST/STa layer.

The dewatering system was tested in September 2008. It confirmed the presence of two different water tables, the uppermost at an elevation of +24.00 m a.s.l. and the principal water table at an elevation of +22.00 m a.s.l., separated by the silty (STa) layer. The most external wells in proximity to the angles of the shaft showed a smaller efficiency in comparison to the more central ones, with a greater dewatering area available. Overall the dewatering test produced positive results, with a lowering of the inside piezometric level beneath the bottom of excavation of over 15 meters in relation to the initial water table
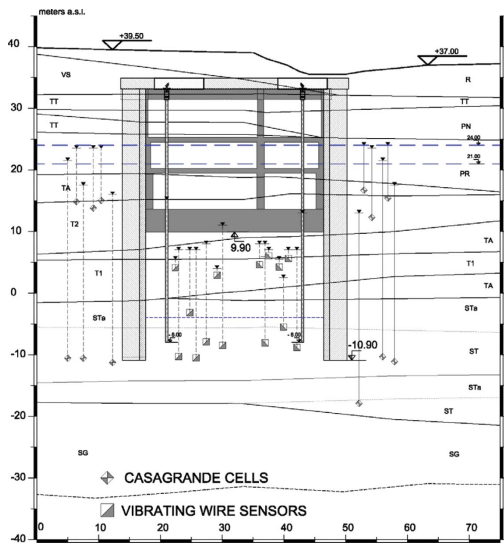
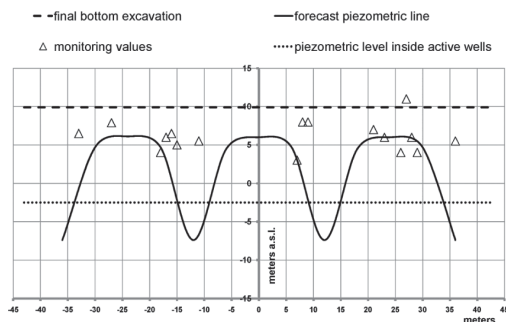Figure 7. Monitoring section of the TBM Malatesta Shaft.

Figure 8. Comparison between piezometric forecast line (4 wells) and experimental measures.

Figure 9. Example of the cavity in the T1 stratum during the excavation of Malatesta Station, about 25 meters under the water table.

(Figs. 7, 8 and 10). The recovery of the inside groundwater, measured in the 24 hours that followed the switching off of the system, underlined the substantial impermeability of the lower layers and the waterproofing of the diaphragm walls. In fact, after one day of recovery, the water table stood at an average of 15 m a.s.l., or 9 meters under the initial levels, with a slow tendency to rise. The outside piezometers located nearest to the diaphragm walls attested to the absence of repercussions on the upper phreatic level. The deep water table measured a lowering of piezometric levels of 6–7 meters in relation to the initial water table. This trend further confirmed the impermeability of the silty layer, highlighting the existence of a clear hydraulic separation between the two water tables. The calculated piezometric condition was confirmed by the values indicated on the monitoring piezometers placed within the shaft.

The global flow that resulted varied from around 700 m³/day with 8 active wells to around 800 m³/day with 12. The flow values on each single well were about equal to 1.0 l t/sec against a value of 1.4 lt/sec calculated during the design phase, or around 960 m³/day with 8 active wells.

7 ANOTHER SEEPAGE CASE ALONG THE LINE

This paper has illustrated the results of dewatering tests performed before the beginning of the excavations for the TBM Malatesta Shaft. The shaft has since been completed without any problems.

The seepage calculations were confirmed by the experimental tests performed. They also underlined the possibility of checking piezometric conditions in the presence of elevated hydraulic loads. In this case the study of the seepage processes in the sand-gravelly SG layer confirmed the basin of feeding and therefore the one-dimensional hydraulic flow directed upwards by the lower section. The high permeability of the fracturing hard tuff layers was exceeded, deepening the diaphragm walls until the upper layer of the Pleistocene formation. This layer has a variable permeability according to the size of the silty part but with a behavior that is well known and comparable to that of a saturated porous medium. Unfortunately this Tuff complex has not been closed by diaphragm walls in some stations. The flow recorded in these cases was much more during the dewatering tests.

For example, the Gardenie Station stands around 1200 meters away from the TBM Malatesta Shaft, with about 19 meters of hydraulic head
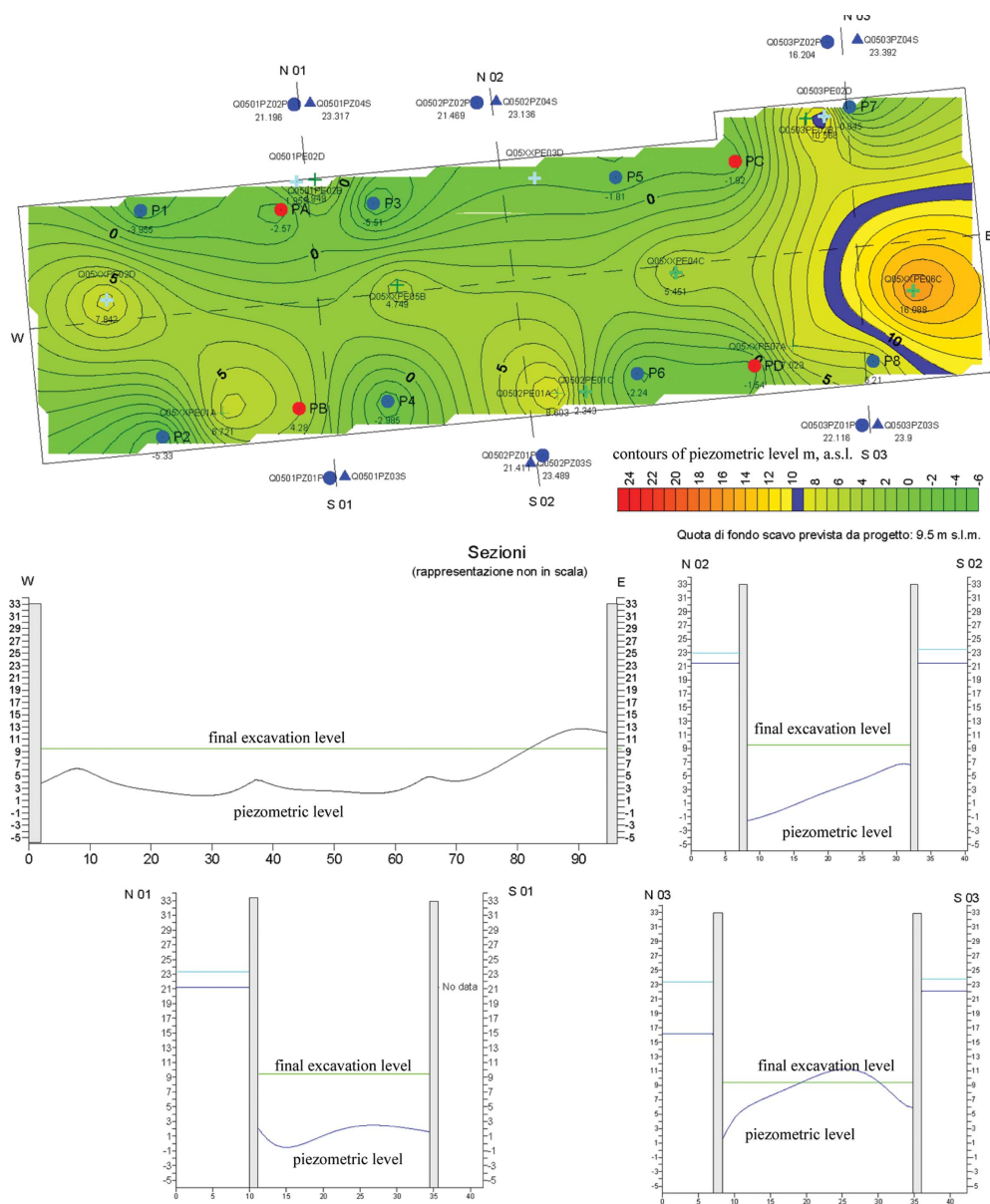
Figure 10. Lowering piezometric contours planning inside the TBM Malatesta Shaft and longitudinal/transversal dewatering sections during the test (IMG, 2008).

on bottom excavation and its dewatering system reached the lower tuff layers.

In this case the flow was about 6000 m³/day (1st testing, Fig. 11—Geoslope, 2002). A bottom plug was therefore made for reducing the permeability of the hard tuff layer, located under the base of the excavation. The ground treatment with cement injections considerably reduced the permeability

of the tuff, saturating the fractures and existing hollows (Fig. 9) in the several hard layers and recreating the characteristics of a medium akin to that of a traditional saturated porous mean. The global flow after the realization of the bottom plug was around 3500 m³/day (2nd testing), allowing for the lowering of piezometric inside level down to the base of the excavation.
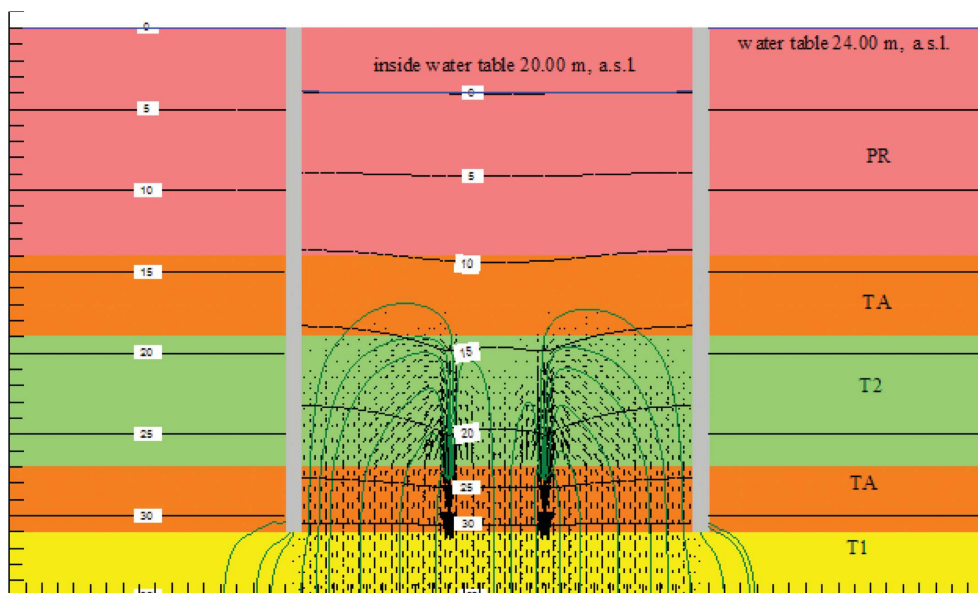
Figure 11. Groundwater back-analysis simulation of dewatering test in Gardenie Station without the bottom plug: hydraulic flow and piezometric contours.

When these hard layers are intercepted and confined by diaphragm walls, as in the TBM Malatesta Shaft, their flow contribution is therefore secondary because they are no longer fed. Alternatively, the hydraulic flow is preponderant and does not allow the attainment of the required hydraulic conditions.

8 CONCLUSIONS

The control of the seepage process is usually the major design aspect in underground construction with important hydraulic loads realized without a bottom plug. Piezometric conditions management is therefore the geotechnical aspect of greatest importance for the completion of the C Line Subway in Rome, in view of the considerable dewatering flows. The excavation of the Roman pyroclastic formation, on account of the well known difficulties of hydraulic behavior forecasting, was certainly the most difficult aspect of all.

The several punctual tests also recorded a discreet flow in these kinds of soil (around 5 lt/sec) but could not register a different hydraulic behavior from the traditional methods notoriously based on bi-dimensional seepage paths in aquifers confined beneath. Only when the hydraulic flow through mostly altered tuff layers (like T1) was interrupted by diaphragm walls or by a bottom plug execution, the seepage flow was limited.

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