Dewatering Tests for Underground Stations in Rome

The new C Line of the Rome Metro runs northwest to southeast across the city center, with 30 new stations and a total length of more than 15.5 mi (25 km). Due to the presence of a dense urban environment, the selected solution for the construction of the stations consists of a cut-and-cover excavation, which is retained by multipropelled diaphragm walls to minimize settlement and prevent damage to the nearby structures. The bottom of the excavation of the underground stations are about 82 ft to 98 ft (25 m to 30 m) below ground surface, and about 66 ft to 82 ft (20 m to 25 m) below the groundwater table. To ensure dry conditions and to prevent hydraulic base heave instability, deep well systems were designed and used to lower groundwater level and piezometric head during excavation. The dewatering field tests showed how the local stratigraphy strongly affects the dewatering efficiency. Finite element modeling (FEM) of steady state filtration were used to compare the soil permeability with Lefranc in-situ test results and to verify the efficiency of the grouted plugs.

Hydrogeological and Geotechnical Conditions

The local hydrogeological framework is very complex due to the large variations of permeability resulting from granulometry, cementation processes and secondary fracturing of pyroclastic strata. The new C Line runs mainly through volcanic deposits deriving from the Colli Albani apparatus, prevalent in the southeastern areas of Rome.
The geological sequence along the new C Line consists of a very heterogeneous layered deposit. The base deposit of stiff overconsolidated clay (“APL,” Pleistocene age) is overlain by fluvo-palustrine very dense sandy gravels (“SG,” Pleistocene age), which are then overlain by medium stiff clayey silts or dense sandy silts (“AR” or “ST,” Paleotevere units). These deposits are overlain by covered by pyroclastic volcanic soils, tuff, silty sand and sandy silt (Middle to Upper Pleistocene) deriving from the Colli Albani apparatus. A layer of made ground (“R”) of varying thickness covers the stratigraphic sequence and the natural soil profile everywhere.

The local hydrogeological framework is very complex and characterized by a double groundwater system. The upper main aquifer is mainly represented by the “pozzolane sequences” (“PR/PN”), while the lower aquifer consists of a deposit of sandy gravel (“SG,” Pleistocene), which is overlain by marine claystone bedrock (“APL,” Pliocene). The pyroclastic deposits (e.g., pozzolane, lithoid and pseudo-lithoid tuff and clayey tuff) show large variations in permeability due to porosity, compaction processes, sealing and secondary fracturing. Permeability values for each soil type were determined using Lefranc tests at variable head and using pumping tests. The Lefranc tests indicated a wide range of permeability.

### Dewatering Field Tests

Dewatering field tests were conducted systematically and consisted of the following general steps:

1. Perform step drawdown and constant rate discharge tests (24 hr) in the first installed well
2. Perform a long-term dewatering test (8 to 21 days) by pumping all of the wells installed in each station
3. Perform measurements inside each station using electrical piezometers and outside each station using Casagrande piezometers, which were installed along the perimeter of the excavation

### Soil layer / type

<table>
<thead>
<tr>
<th>Soil layer / type</th>
<th>Permeability Low</th>
<th>Permeability High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pozzolane (PR/PN)</td>
<td>7.5 x 10^-7 cm/s</td>
<td>3.6 x 10^-2 cm/s</td>
</tr>
<tr>
<td>Lithoid and pseudo-lithoid tuff (T1-T2)</td>
<td>4.9 x 10^-6 cm/s</td>
<td>1.0 x 10^-2 cm/s</td>
</tr>
<tr>
<td>Pleistocene deposits (ST)</td>
<td>1.3 x 10^-6 cm/s</td>
<td>1.7 x 10^-3 cm/s</td>
</tr>
</tbody>
</table>

The main geotechnical and environmental problems related to water seepage are summarized into four main items:

1. Lowering the groundwater level to allow excavation in dry conditions
2. Ensuring base stability during excavation
3. Mitigating the seepage effect on the stability of the diaphragm walls
4. Minimizing ground settlements induced by the lowering of the groundwater table

### Teano Station

The excavation for Teano Station consisted of essentially an elongated box shape that was about 460 ft (140 m) in length by about 46 ft to 92 ft (14 m to 28 m) in width, and was excavated to a maximum depth of about 95 ft (29 m) from the ground surface. The natural groundwater level was about 46 ft (14 m) above the bottom of the excavation. The dewatering system consisted of 12 wells, each having a diameter of about 15.75 in (400 mm), and were installed within the excavation. The wells penetrated about 85 ft (26 m) into the volcanic deposits (“TA” and “T1-T2”), and each was fitted with a slotted screen that extended from the groundwater table to the bottom of the well. The total pumping rate was approximately 270 gpm (17 liter/s), which resulted in a lowering of the groundwater table by less than about 8 in (0.2 m), maximum, on the outside of the excavation. The dewatering operation allowed dry conditions during excavation.

### Gardenie Station

The excavation for Gardenie Station consisted of a rectangular box shape that was about 213 ft (65 m) in length by about 121 ft (37 m) in width, and was excavated to a maximum depth of about 112 ft (34 m) from the ground surface. At this station, the required drawdown of the groundwater table in the volcanic soils was about 59 ft (18 m). The dewatering system consisted of 14 wells, each having a diameter of about 15.75 in (400 mm), and were installed within the excavation. The wells penetrated into and pumped water from the volcanic deposits (“TA” and “T1-T2”). The total pumping rate was approximately 1,110 gpm (70 liter/s), which was significantly more than the design assumption and resulted in a pore water pressure profile different from a hydrostatic trend. The groundwater table was lowered by about 2.3 ft (0.7 m), maximum, on the outside of the excavation and was quite limited in drawdown away from the diaphragm wall. The dewatering operation allowed dry conditions during excavation.
Minimizing ground settlements are summarized into four main items:

1. Ensuring base stability during excavation in dry conditions
2. Ensuring base stability during excavation.
3. Perform measurements inside each dewatering system.
4. Minimizing ground settlements

Dewatering Field Tests

Dewatering field test results at Teano Station

Dewatering field test results at Gardenie Station

Dewatering field test results at Mirti Station

Seepage Flow Analysis

At Teano Station, water flow mainly derived from the deeper aquifer located in the silty sand/sandy silt stratum (ST, fluvio-palustrine). The upper volcanic deposits (PR) and the ST stratum were not acting as a single hydrogeological unit because the piezometric level recorded in the ST stratum was about 39 ft to 46 ft (12 m to 14 m) lower than the level measured into the upper volcanic (PR) deposits. The low pumping rate (less than 16 gpm [1.0 liter/s] for each well) indicated that the deeper aquifer is fed by the sandy gravels of the Pleistocene deposits (SG), and the flow is semi-confined by the low permeable altered pseudo-lithoid tuff (T2) and the clayey tuff (TA) layers. The hydraulic disconnection between the ST stratum and the overlying pozzolane (PR) caused no relevant effects on the shallow aquifer.

At Mirti and Gardenie Stations, the hydraulic seepage scheme was very different from the Teano configuration, and far from the design forecasts. At Mirti Station, seepage flow is mainly horizontal and derives from the aquifer located in the old altered tuffs (TA-T1), which are characterized by a high permeability. The overlying low permeability pseudo-lithoid tuff (T2), in which the piezometric pressure drop is concentrated, creates a hydraulic disconnection between the clayey tuff (TA) and the overlying pozzolane (PR). At Gardenie Station, seepage flow derives directly from the shallow aquifer located in the volcanic deposits. Piezometric measurements in the upper level of the old altered tuffs (TA)
indicated a similar piezometric level as in the overlying pozzolane (PR). Continuous pumping modified the shallow aquifer located in the pozzolane (PR).

When the flow of water occurs upward from the Pleistocene deposits (ST), the pumping rates were low, as observed at Teano Station (less than 16 gpm [1.0 liter/s] for each well). However, when the seepage flow directly derives from the shallow aquifer located in volcanic deposits, the quantity and velocity of water flow increases dramatically.

**Grouted Bottom Plugs**

For Mirti and Gardenie Stations, the quantity of water pumped out was quite greater than predicted by the design assessments. To reduce the local permeability of the granular and fractured tuffs and to minimize groundwater inflow, a horizontal grout curtain was installed using a multiple-packer sleeved pipe (MPSP) injection system. At Mirti Station, the total pumping rate of about 127 gpm (8 liter/s) ensured safe and workable conditions throughout each of the constructions phases. The lowering of the groundwater table in the volcanic deposits external to the excavation and the diaphragm wall was quite limited and was about 2.6 ft (0.8 m).

**Numerical Analyses**

A series of simplified, two-dimensional steady state flow FEM analyses using PLAXFLOW were performed. Permeability values were routinely calibrated to obtain pore water pressure distributions similar to those measured during the pumping tests in the field. An isotropic and constant value of permeability (k) for each stratum was assumed in the analysis. The diaphragm walls were modeled and simulated with “screen elements,” across which flow does not occur. To calibrate the permeability of each soil layer, it was necessary to force a specified outflow for each well by defining an equivalent discharge flow rate per unit width.

Pore pressure measurements after installation of grouted plug for Mirti Station

Pore pressure measurements and distribution inside the excavation after the installation of grouted plug and as determined using FEM analyses are provided. Analysis of the results indicate a wide range of permeability for the same soil type located at the different stations.
For mainly the lithoid and pseudo-lithoid tuff (T1-T2) and clayey tuff (TA), there was considerable discrepancy between the permeability used in the numerical FEM analyses that were calibrated using the results of pumping tests results and the permeability determined using the Lefranc in-situ tests.

<table>
<thead>
<tr>
<th>Location</th>
<th>Layer</th>
<th>Modeled calibrated ((k_\mu))</th>
<th>Permeability from variable head tests (Lefranc method)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mirti Station</td>
<td>TA</td>
<td>1.0x10^{-2} to 5.0x10^{-2} cm/s</td>
<td>2.9x10^{-6} to 2.8x10^{-2} cm/s</td>
</tr>
<tr>
<td>Gardenie Station</td>
<td>T1-T2</td>
<td>5.0x10^{-1} cm/s</td>
<td>4.2x10^{-5} to 9.5x10^{-2} cm/s</td>
</tr>
<tr>
<td>Gardenie Station</td>
<td>TA</td>
<td>9.0x10^{-3} to 5.0x10^{-2} cm/s</td>
<td>1.4x10^{-4} to 2.1x10^{-2} cm/s</td>
</tr>
</tbody>
</table>

**Conclusions**

The monitoring of the dewatering field tests was useful to understand more thoroughly the groundwater flow in a typical complex geological sequence of the subsurface beneath Rome. Numerical FEM analyses, which were calibrated using the results of pumping tests, facilitated estimating the average permeability values of the pyroclastic deposits more accurately than by using the classic Lefranc variable head tests results. Using the multiple-packer sleeved pipe grouting system was an appropriate method to control the permeability of the soils for the complex fractured lithoid tuffs and the coarse clayey tuffs strata.

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