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Artificial Ground Freezing to excavate a tunnel in sandy soil. Measurements and back analysis

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ABSTRACT

The paper is dedicated to the case history of a 13 m wide, 17 m high and 40 m long service tunnel at Toledo Station, previously constructed in a deep open shaft and belonging to the Line 1 of the Napoli underground network. The existing Line 1 has been recently extended with a new stretch consisting of five new stations connected by twin rail tunnels for a total length of about 5 km. Toledo Station main shaft is located by a side of the line and it is connected to the pedestrian platforms by the above mentioned large size service tunnel. The station is situated in the historical center of the city of Napoli, under a deeply urbanized area. In Fig. 1 a longitudinal section of the main shaft of the station and of the large service tunnel with the above and surrounding buildings is sketched. The focus of this paper is on the settlement caused by the tunnel excavation and on the use of the Artificial Ground Freezing (AGF) technique to allow the safe excavation of the large crown of the service tunnel, located about one half in a silty sand layer and one half in yellow tuff, well below the groundwater table.

1. The project

1.1. Introduction

The paper is dedicated to the case history of a 13 m wide, 17 m high and 40 m long service tunnel at Toledo Station, previously constructed in a deep open shaft and belonging to the Line 1 of the Napoli underground network. The existing Line 1 has been recently extended with a new stretch consisting of five new stations connected by twin rail tunnels for a total length of about 5 km. Toledo Station main shaft is located by a side of the line and it is connected to the pedestrian platforms by the above mentioned large size service tunnel. The station is situated in the historical center of the city of Napoli, under a deeply urbanized area. In Fig. 1 a longitudinal section of the main shaft of the station and of the large service tunnel with the above and surrounding buildings is sketched.

The focus of this paper is on the settlement caused by the tunnel excavation and on the use of the Artificial Ground Freezing (AGF) technique to allow the safe excavation of the large crown of the service tunnel, located about one half in a silty sand layer and one half in yellow tuff, well below the groundwater table.

1.2. The service tunnel

As reported by the design documents, the so called service tunnel had the transient function to serve as a starting point to enlarge the section of the running twin tunnels in order to include the pedestrian platforms. The service tunnel was also designed to permit the permanent connection of the two opposite sides of the platforms, overpassing the running tunnels through pedestrian passageways. Finally, it served also as starting point for the construction of a long pedestrian link tunnel allowing the passengers to emerge from a secondary exit located about 150 m far from the main shaft of the station. After the completion of the main shaft, the works for the excavation of the large service tunnel were just preceded by the construction of a smaller tunnel, the drift, running above it. This last tunnel was excavated in the same volcanic silty sand but immediately above the groundwater table and, for this reason, very close to the buildings foundation. The most of the section of the large service tunnel was excavated in a soft rock formation while only a minor part of the ceiling had to be excavated in a sandy layer. In Fig. 2 a more detailed longitudinal section along the service tunnel and the above drift is sketched.

The subsoil at the tunnel location is made by two main formations: a loose to medium dense pyroclastic sand (locally named Pozzolana) down to a depth 37–40 m from the ground surface, overlying a bedrock consisting of a soft volcanic rock (Neapolitan

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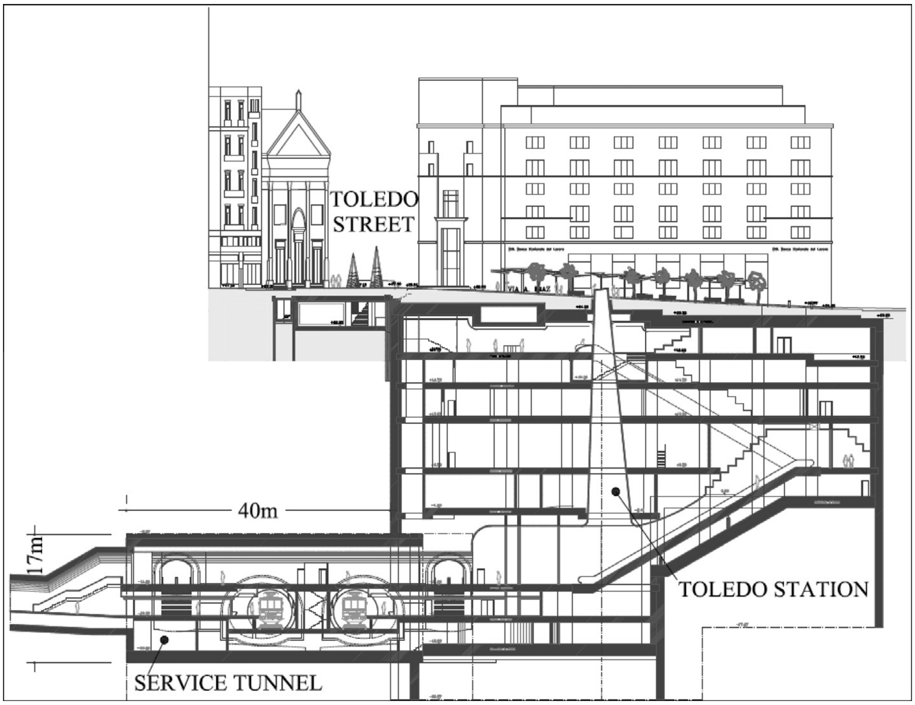

Fig. 1. A longitudinal section of Toledo Station.

Yellow Tuff). The groundwater table is nearly horizontal in the whole area and its position is about 27 m above the invert of the service tunnel. According to the design documents, the small drift was initially used for both chemical-cement injections at the sides and at the invert of the service tunnel (in the tuff formation) and for the execution of an end plug via jet-grouting (in the sandy layer). The same drift was then used to install the sub-vertical pipe system needed for the Artificial Ground Freezing. In Fig. 3 the soil treatments adopted around the service tunnel are sketched in the transverse section. In Fig. 4 the same sketch is proposed for the longitudinal section.

The Multi Packer Sleeved Pipe (MPSP) was adopted for the grouting. The system consists in the installation inside a borehole of a plastic or steel pipe equipped at regular intervals with rubber grouting sleeves and two bag packers (expanded against the hole walls through grout injection into the bags) to seal off the stretch where the grout injection has to be performed. The main role of the grouting was to improve the mechanical properties and to reduce the hydraulic permeability of the fractured rock. Initially, the cement grouting was used to fill the thicker cracks; afterwards the chemical grouting was used to close the thinner cracks. Both cement and chemical injections were executed by means of the sub-vertical pipes installed from the drift. The end plug was then realized using both simple grouting in the rock and jet-grouting in the above sandy soil (Fig. 4).

The AGF technique was extensively adopted in the construction of Line 1 of Napoli underground during tunnels excavation below the ground water table (Viggiani and De Sanctis, 2009; Russo et al., 2012). The application is well known even if not widely used for long lasting construction processes due to huge energy costs. It is based on withdrawing heat from the soil obviously converting the pore water into ice. The frozen soil mass has very low permeability and larger strength when compared to the natural undisturbed soil mass. For this application the AGF was carried out through both horizontal and sub-vertical freeze lances, the horizontal one being installed from the main shaft of the station and the sub-vertical one from the drift. To guarantee the exact alignment of the freezing lances, the 40 m long horizontal boreholes were drilled using the Magnetic Directional Drilling technique.

2. Geotechnical investigations

2.1. Site and laboratory tests

At the design stage geotechnical investigations were carried out for the station shaft and for the large service tunnel. They consisted, as usual, in both in-situ and laboratory tests. For the design of the service tunnel, no. 4 boreholes were drilled down to depths ranging between 39 and 41 m from the ground level. In Fig. 5 a plan view and a longitudinal section with the location of the boreholes are sketched. As already shown in previous figures, the subsoil can be divided into two main layers: a top loose silty sand, alternating with lens of pumices and volcanic ashes, extending down to an average depth of about 40 m, overlying the soft and sometimes fractured yellow tuff. At the execution stage, the excavation of the drift and the boreholes drilled for the installation of the freezing lances allowed a substantial increase of the general knowledge (Croce and Pellegrino, 1967; Pellegrino, 1967) of the geotechnical conditions at the site. Several SPTs were carried out in the boreholes S1–S4 and at the end of the drilling operations some Casagrande and standpipe piezometers were also installed. Samples were taken at different depths as sketched in the section of Fig. 5. Osterberg piston sampler was used for the loose sandy soil: samples were retrieved above the groundwater table, so they were only partially saturated. The adoption of an 86 mm diameter sampler together with the suction present in the soil samples helped to minimize disturbance induced by the sampling process. In the bedrock, the double tube core barrel was adopted to take undisturbed samples well below the groundwater table, therefore they were fully saturated. In Fig. 6, on the left side, SPT blow counts are plotted against the depth for the relatively loose sandy soil. They show as usual some scatter but also a trend to increase with the depth is clearly visible with values ranging from about 15 at