Geotechnical Aspects of Underground Construction in Soft Ground, Mair & Taylor (eds)
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Geotechnical aspects related to construction of a 5.5 km tunnel excavated in sedimentary soils of São Paulo Basin

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ABSTRACT: This paper presents construction aspects of a 5,5 km length tunnel, conceived to install cables of 345 KVA transmission line. NATM construction method is being utilized in non conventional transversal section, designed in order to dispose cables on the floor. It aims to discuss alternative construction methods utilized during the excavation of the tunnel, in view of specific hydro-geotechnical conditions and soil behavior.

1. INTRODUCTION

The tunnel, located below the water table, crosses the low areas of São Paulo Basin, in the central part of São Paulo city at a depth of 12 to 15 m, reaching in some points 20 to 30 m. Part of excavation crossed submersed sandy soils, formed by an erratic sequence of layers and lenses of medium, fine and coarse sands with thin layers of clean fine gravel; another crosses extensive and continuous layers of greenish gray clay.

Because of little experience in tunnel excavations in this part of São Paulo, during the underground excavation was necessary new test borings, studies about geological aspects, and technics of soil improvement, dewatering schemes, and construction methods. From these studies, associated with a recent knowledge brought by geological research, it was possible to evaluate some ground behavior, specially from the hydro-geotechnical point of view.

2. ASPECTS OF THE REGIONAL GEOLOGY

The São Paulo Sedimentary Basin is a unit of the so called Brazilian Southeast Continental Rift which is composed of various elevated or sunk blocks, cut by faults, where were deposited initially Tertiary sediments. The area of the basin is of about 5,000 km^2, situated between elevations 718 and 835 above sea level. The Basin sediments are composed of Tertiary deposits (São Paulo, Resende and Tremembé formation). On top of these, recent and later Quaternary sediments were deposited in a discordant form.

The tunnel cut part of São Paulo Basin in the North-South direction in the low region of the city and crosses basically Tertiary sediments. In some points, however, the tunnel passes through Quaternary sediments and bedrock outcrop, as can be seen on Fig. 1. The water table level alongside the layout is next to the surface.

3. SUBSOIL PROFILE AND ITS INFLUENCE ON THE TUNNEL EXCAVATION

3.1 General Considerations

The alluvial deposits are characterized by lenses of soft organic clays and submerged fine sands, with thickness which varies from 2.0 to 5.0 m. Immediately below alluvial deposits are found layers of gravel with thickness between 0.5 and 2.0 m and are characterized by pebbles of centimeter dimensions (0.5 to 2.0 cm) and coarse sands. Building of tunnels in such kinds of soil is quite complex and this demanded the implementation of dewatering and consolidations systems under very different conditions.

In Tertiary deposits, where almost all extension of the tunnel is developed, the soil is characterized by different types of deposits, either in fine and medium sands, compact to soft, or in clays strongly over-consolidated. The conditions for tunnel construction are favorable, however, the dewatering systems find difficulty in capturing and adequate lowering of the water table in the regions where are found erratic intercalation of the layers with different permeability.

During the construction was observed that the Tertiary superficial sand layer behaves more similarly to the gravel layer than to the typical sands of Tertiary origin. Such a fact made quite difficult the tunnel excavation, and demanded some times the tunnel to be lowered to inferior levels or its front of excavation to be consolidated through chemical and cement treatment. At the very beginning of the "shafts" execution, in particular where the thick layer of gravel is found, it was possible to check that this layer behaves like a big water bearing stratum, and is the main factor responsible for water table recharge, with

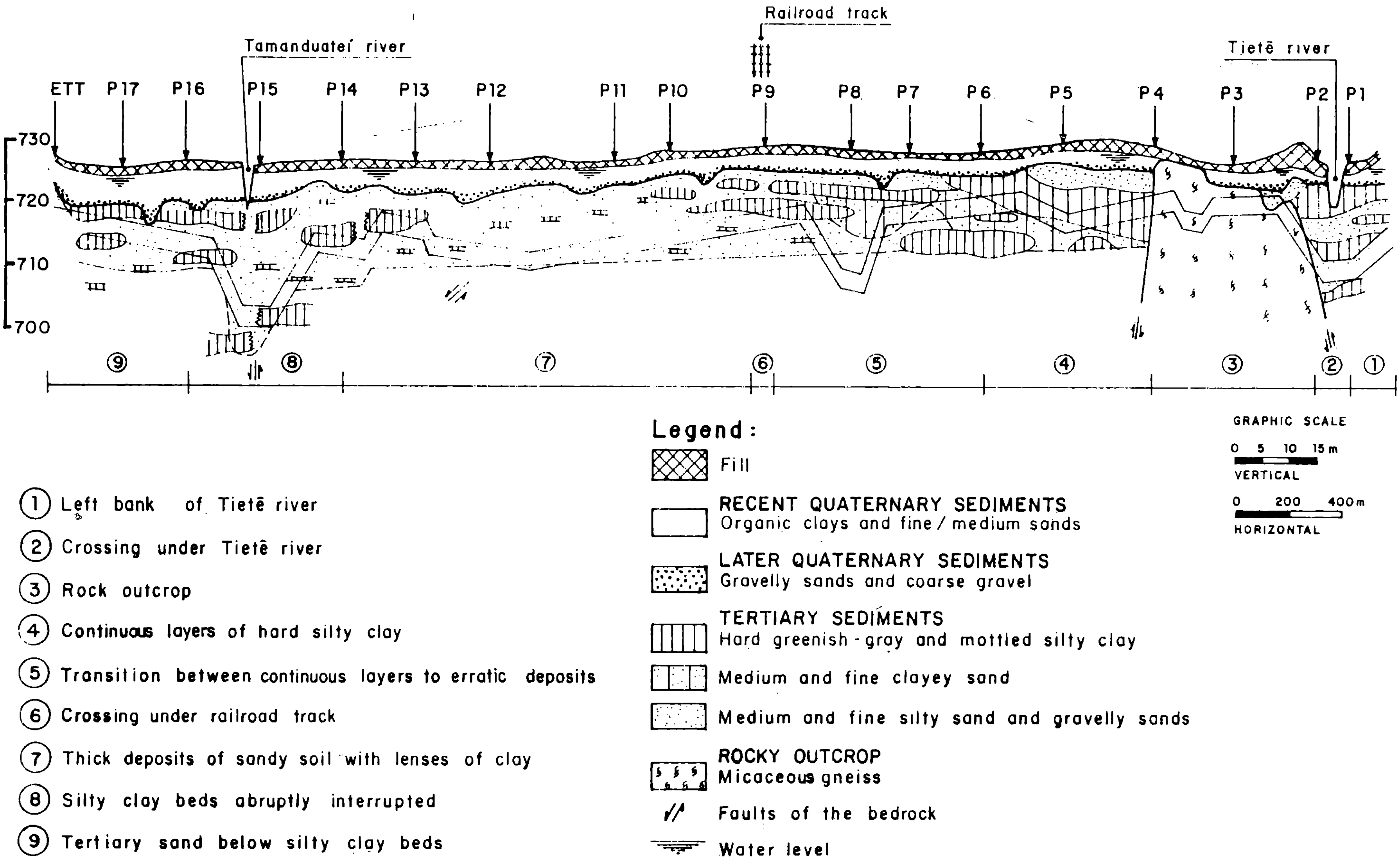


Fig.1 - Geological - Geotechnical profile along the tunnel.

permeability of about 10^{-1} cm/sec. It is important to emphasize that the behavior of superficial sand and gravel layers is difficult to predict, since the SPT results cannot reveal the importance of gravel; furthermore, information relative to construction in other places did not indicate such a high permeability as found. Also the samples gathered from silty fine sands did not indicate susceptibility to leakage under low values of hydraulic gradient, as happened in various regions.

On the basis of recent geological studies about tectonic evolution of structural framework of São Paulo Basin, and from evidence from the excavation frontal part, we can deduce that the presence of discontinuous clay layers found during the excavation would be associated with the occurrence of the tectonic movements sin- and post-sedimentary, which would have provoked block ruptures and sinking causing disturbances in the sediments. Such phenomenon would explain difficulties in excavating some sections, where sudden interruption of clay layers occurred which provoked leakage of material into the tunnel which was difficult to control.

3.2 *Description of Sections Crossed by the Tunnel and Engineering Solutions*

A brief description will be given of the subsoil through which the tunnel is constructed with various situations faced and engineering solutions.

Left Bank of Tietê River: The soils are formed in an alternate manner by sandy clay and fine and medium sands layers. The presence of fine and coarse gravel layers at on the base of alluvium and clean sands next to the top of the tunnel found during shaft P1 opening, indicated the necessity of deep wells installations with nozzle injectors and submersible pumps, and additionally well points up to alluvium base in order to capture water contained in the gravel layer. The presence of lenses of greenish-gray clay, fissured, and erratically distributed inside the sediments made necessary the utilization of internal horizontal vacuum drains (Dhp's) for local capture of water contained in sandy portions. Where the layer of clay was close to the crown of tunnel, injected forepoling was used in order to prevent block falls in the frontal part of the excavation. In general the advance of the tunnel was from 60 to 80 cm per day.

Crossing under Tietê River: Under the recent alluvium, on Tietê river bed, we find layers of hard greenish-gray clay and fine clayey sands, dense to very dense. In isolated sections, close to the faults of bedrock, the presence of quite hard clays was observed, with great mechanical resistance, which made excavation difficult and forced the utilization of a higher capacity drift hammers. In the initial excavation, from the left to the right bank of the river, the tunnel was excavated in a rock outcrop (micaceous gneiss). Initially the utilization of a "shield" with compressed air was foreseen; however, the more detailed survey of the geotechnical profile was possible only after special test borings, which permitted more simple construction method to be used since the presence of the greenish-gray clay layer was observed, with low permeability, close to the tunnel crown. The crossing was executed with NATM (New Austrian Tunneling Method) procedure, with top protection in the river bed region through CCPH columns ("Horizontal Jet-Grouting") up to mid-section. The presence of the gravel/clay contact made the installation of vacuum drains necessary, which had indisputable efficiency (average discharge of 200 l/h per drain and maximum of up to 1.0 m^3/h). CCPH steps were of 7.0 m with excavation of 5.0 m, with advances meter by meter. The section was partialized with the crown advance and Invert. Fig. 2 shows the scheme of the adopted executive process.

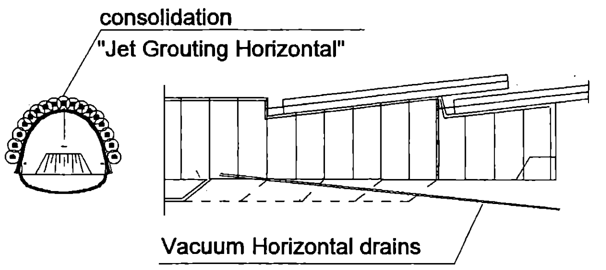


Fig. 2 - Construction Method - Crossing under Tietê River.

Site of the Rocky Outcrop: The tunnel passed through saprolite soil and altered fissured rock. The water level is very high in this site, but only some vacuum DHP's (Vacuum Horizontal Deep Drains) were used in the regions where pockets of more altered material, and therefore a better water conductor, had been observed. The utilization of vacuum horizontal drains in altered soils, where they sometimes prove not to be efficient, had the exploratory character in the front of the excavation. Although the test boring indicated altered material, easily excavated with pneumatic hammers, it was necessary to use explosives during the excavation. In the end of this section, in the vicinity of shaft P4, a fault of the rocky outcrop can be found, as can be seen on Fig. 1.

Site of continuous layers of hard greenish-gray silty clay: Between the shafts P4 and P6, in the environment of supposedly doldrums regime deposition, can be found a thick layer of silty clay, mottled, from stiff to hard, fissured, on top of a layer of fine sandy clay, compacted and very compacted, brown-yellowish. Near the shaft P4, the clay layer is interrupted by a fault, where the presence of conglomeratic lithified sediments is observed. For the excavation of this section the lowering of the water table was not necessary because the continuity of the clay layer over the tunnel guaranteed the WL isolation, which resulted in the "dry" sand excavation. Although the sediment was fissured, there were no problems with block instability, either by the tensions relief caused by the tunnel, or by the pronounced fracturing caused by recent reactivation of faults. The average progress of the tunnel was of 1.0 m per day.

Site of transition between continuous layers to erratic deposits: Between the shafts P6 and P9, we find a transition between the region of doldrums deposition, with homogeneous goetechnical behavior, to the environment of clay layers less thick, fissured, and without lateral continuity. Sand layers through which the tunnel crosses are mainly fine and medium with some portions of gravely sands with fine pebbles. The lowering of the water table was made by two lines of deep pumping wells with 5.0 m of space between the wells and the depth of about 20 m. The presence of clay lenses distributed in an aleatory manner inside the sediments caused the local perching of the water table and made difficult the efficiency of deep pumping wells, which were not able to avoid some infiltration, which was dealt with through internal drains. At isolated points it was necessary to use vacuum horizontal deep drains and excavation with forepoling method with bars and consolidation in the region of sand/clay contact.

Crossing under railroad track: Crossing under railroad track was made under the low clay cover with water table perched on the subjacent sand layer, as can be seen on Fig. 3. Due to the impossibility of deep pumping from the surface, a system of vacuum internal drains was adopted installed from the lateral part of the tunnel in order to reduce hydrostatic pressure. With this procedure, the tunnel was excavated with a reduced height until the drainage of the layer above the tunnel was made, and only after it the higher section was excavated. The tunnel is situated at 10 m depth and the surface settlements was the order of 0.0 to 2.0 mm.

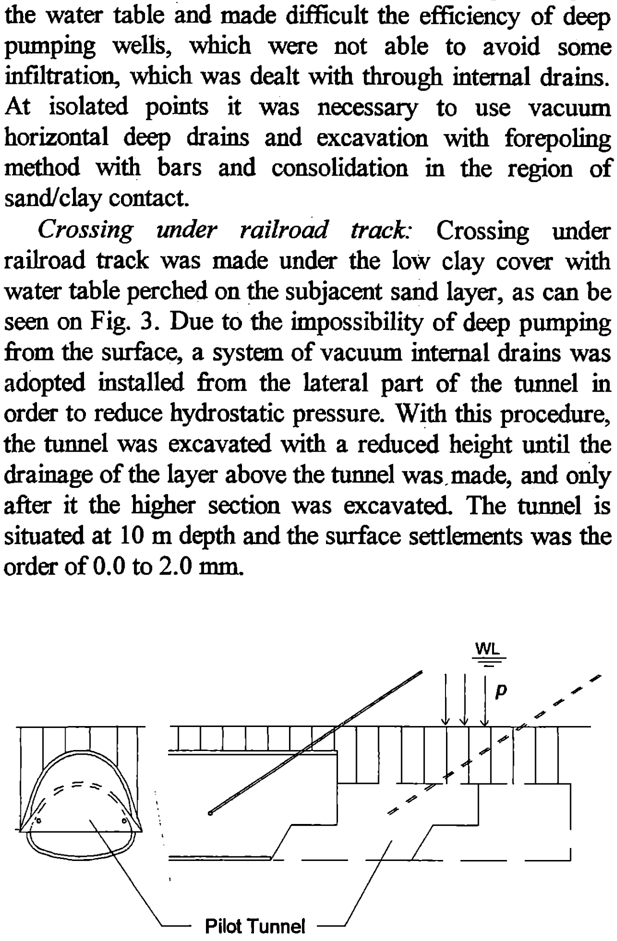


Fig. 3 - Construction method to underpass railroad track.

Place of thick deposits of sandy soils with clay lenses: Transition to the region with predominance of sands with diverse granulation, silty, compacted and fairly-compacted becomes evident from the shaft P11, where the presence of clay lenses becomes rare. All this sector was excavated with the help of deep pumping wells distributed on both sides of the tunnel. The water table lowering worked adequately, giving to the sandy soil an apparent cohesion, which guaranteed sufficient "stand-up time" for the process. Trial pumping and piezometric data indicated permeability values of the order of $5x10^{-3}$ cm/sec., with initial discharge of 4.0 m^3/h/well and stabilized discharges of the order of 0.5 m^3/h/well. The wells were installed on both sides of the tunnel, with depths of about 20 m and spaced at every 5.0m. After the shaft P12, the Tertiary sediments are formed basically from fine and medium silty sands, gray, dense to soft, and sometimes of clean fine sands. Excavation problems of this tunnel were enormous due to the presence of preferential percolation routes associated with the low resistance to leakage (running ground). In order to make possible excavation of this sector, the tunnel was lowered in a way to pass through a more compact portion of the Tertiary sediment, together with the necessity of execution of forepoling with chemical/cement injections and vacuum horizontal drains on the excavation front. The advance was made with provisory Invert and steps of about 0.6 m.

Site of silty clay beds abruptly interrupted: Between the shafts P14 and P16, we found again the presence of clay lenses with little lateral continuity. Although the deep pumping wells and vacuum Dhp's were installed, the water infiltrated through percolation preferential routes bringing with it more clean sandy materials from overlying layers. The hypothesis of a recent tectonic movements in the region of Tamanduatei river could explain the great difficulty in establishing the model for this type of soil, and even could justify the low SPT values obtained in deep clays. The excavation in this section was assisted by deep pumping wells, vacuum Dhp's and frontal partialization of excavation ("pilot" tunnel and provisory Invert).

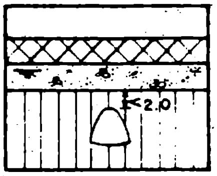
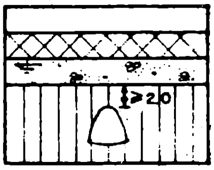
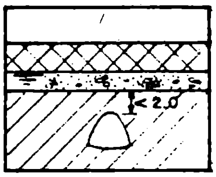
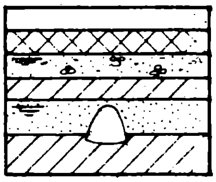
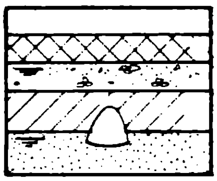
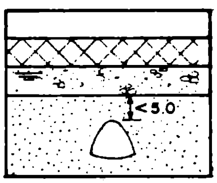
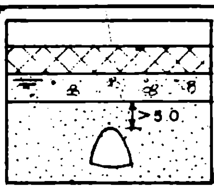
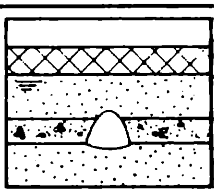
Excavation in Tertiary sands under silty clay beds: Between shaft P16 and ETT, the tunnel passes through silty and clayey sands. On the tunnel crown, a layer of hard silty clay isolates the excavation from Quaternary alluvial sediments. Where we found that the clay layer was not thick enough we installed short pumping wells to relieve hydrostatic pressure, and vacuum drains were installed inside the tunnel to drain the lower layer of sand. Since the adjacent area, the protective clay layer was eroded by an old meandering tributary of Tamanduatei river. In this case, large pockets of the Quaternary sediments are found and were duly consolidated before the excavation.

Fig. 4 shows a simplified selection of the found cases, citing possible problems and some solutions adopted. Intervention cases were divided in 8 types.

4. CASE OF RUPTURES

4.1 Rupture between shafts P13 and P12.

The rupture caused the opening of a surface crater. As already mentioned, there exists a layer of sand and gravel, the high permeability of which could not be foreseen by test boring, since the bigger diameter pebbles are not recovered in the sampler, and a small number of SPT blows indicated predominantly sandy soils. Two factors contributed to the rupture. The first was the distance between the gravel layer, very permeable, and the

TYPICAL PROFILE		EXCAVATION IN	PROBLEMS	SOLUTIONS
I		Residual soils with permeable layer close	– Roof instability – Uncontrolled seepage water	– Superficial dewatering with well points – Consolidation
II		Residual soils with permeable layer distont	– Block falls – Uncontrolled seepage water	– Forepoling method (bars) – Vacuum horizontal drains
III		Clays with permeable layer close	– Roof instability with block falls	– Superficial dewatering with well points – Consolidation – Pilot tunnel
IV		Interface between layers of different permeability	– Leakage – Uncontrolled seepage water	– Vacuum horizontal drains – Consolidation – Alignment change
V		Clays and foundation in sands	– Footing in flowing soil – Ascensional seepage flow	– Well points inside of the tunnel – Deep pumping wells
VI		Sands with greatly permeable layer close	– Instability of excavation (pipping) – Uncontrolled seepage water	– Shallow and deep pumping wells – Consolidation
VII		Homogeneous sands	– Instability of excavation (reduced stand-up-time)	– Deep pumping wells
VIII		Quaternary sands with gravel (Quaternary Sedim.)	– Large instability of excavation – Uncontrolled seepage water	– Consolidation

Fill and recent Quaternary Sediments

Sands with gravels (later Quat. Sedim.)

Residual soils

Silty clays (Tertiary Sediments)

Sands and sandy clays (Tertiary Sediments)

Fig. 4 - Typical cases of excavation and some of the problems and solutions utilized.

excavation front. Since the gravel layer behaves like a water-bearing stratum with high permeability the flow network which is established in this cases has a unfavorable hydraulic gradient, according to the contents of Fig. 5.

Other factor which contributed to the rupture was the presence of preferential seepage routes formed by piles and remains of old construction, as well as by soft sands pockets, not detected by trial boring and found only during the excavation. In this form, water communicated directly with the tunnel excavation instead of communicating with dewatering wells. Besides the above factors, the sand layers intercepted by the tunnel in this section are quite susceptible to leakage which increase the complexity of the problem.

In order to avoid repetition of these problems, the depth of the tunnel was varied to give more distance between the excavation and the gravel layer and the preferential seepage routes. At the same time, the tunnel was excavated in more compacted sands. Besides the lowering of the tunnel depth, the dewatering system was increased, as well.

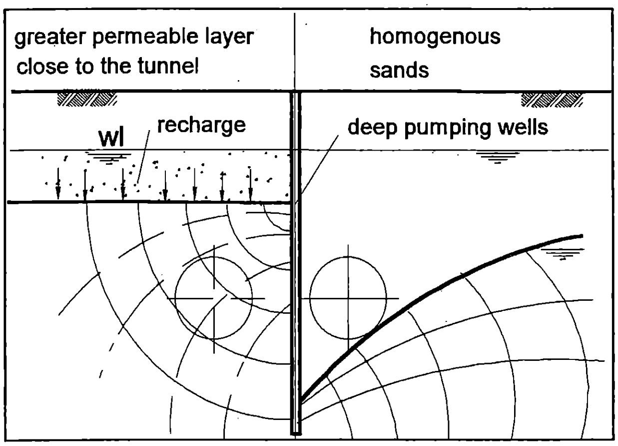


Fig.5 - Development of seepage flow in different cases of dewatering with deep pumping wells.

4.2 Rupture between shafts P17 and P18 (ETT).

The excavation passes through a sand layer which is under the protective clay layer indicated by test borings as continuous. Lowering of the water table was made by the vacuum drains and short pumping wells system to relieve the hydraulic charge over the clay layer, when suddenly the collapse of the left side of the tunnel occurred. After the additional test boring was possible to detect the presence of discontinuous clay layer. After many simple attempts to solve the problem and re-initiate the excavation, all of which failed, it was decided to consolidate the region through "Jet Grouting" vertical columns.

In order to avoid the necessity to consolidate large extension of the soil, the alignment of the tunnel was changed so that it continued under the protection of the clay layer. After this region, the excavation advanced

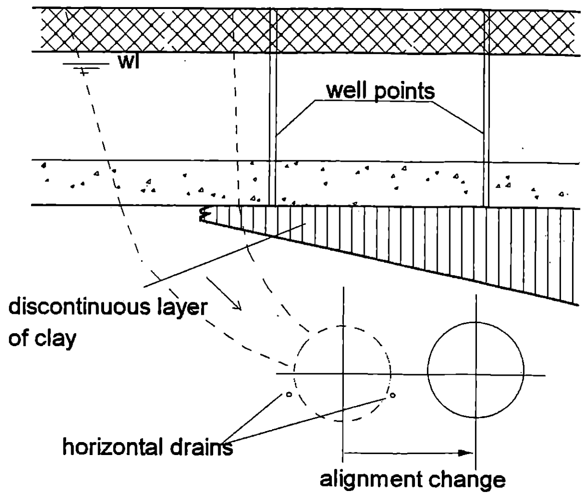


Fig. 6 - Rupture between shafts P17 and P18 (ETT).

with the utilization of internal drains and short pumping wells. Fig. 6 shows a schematic profile of rupture.

5. CONCLUSION

At present, 4.9 km of the tunnel are complete. A few extensive, but important parts will be built, specially the underpass of Tamanduatei river, where was detected the existence of silty clay beds, abruptly interrupted and partially lowered. Such fact suggested that soil was perturbed by recent reactivation of faults of the bedrock lying under São Paulo Sedimentary Basin.

Finally, it is necessary to emphasize that tunnel excavation with NATM process along the low part of São Paulo Sedimentary Basin requires from specialists the adoption of innovative and creative solutions, based on the detailed accompanying of excavation fronts, which makes the procedure interactive between the project and the construction. Diversity of soils found in one construction is a singular case in subterranean constructions in the city of São Paulo.

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