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Geotechnical issues related to dry maintenance of open cut excavations below groundwater table in soft soils: Reliability of a simplified calculation model

F. Carnevale, R. Gallotti, F. Caneparo & P. Pampanin
Technital S.p.A., Milano, Italy

ABSTRACT: The construction of the so-called "Passante di Mestre" contemplated the realization of long stretches in cut section standing under the groundwater table. It was therefore necessary to foresee an accurate control of the water table level during the whole construction process, with a specific and careful attention on the subsidence effects of the existing nearby buildings. As the area of interest stretched for 4 Km, it was necessary to have a model as much versatile and consequently simplified as physically possible. The model was based on the considerations by Mansur & Kaufman, with the application of the superimposition. The validity of such simplified approach has been verified through a finite element model. Based on a results comparison, it was possible to assess how the simplified prevision method could catch with an acceptable degree of approximation the dewatering mechanism and its effects in the system.

1 INTRODUCTION

The Mestre connection is the bypass of the urban stretch of highway A4, see Figure 1.

The typical cross section is 32.5 m wide. The layout develops with 9 stretches in cut section, 8 artificial tunnels and 4 viaducts.

This paper focuses on the geotechnical issues faced along the stretch between Salzano and Martellago, where the road was built for about 4 Km on cut section standing below groundwater level.

Two are the main geotechnical aspects dealt with during design and herein discussed: the maintenance of a dewatered open cut excavation and the monitoring of subsidence effects on adjacent building caused by the type and method of excavation.

2 GEOTECHNICAL SOIL CHARACTERIZATION

Along the layout, 7 boreholes and 24 cone penetration tests with piezocone (CPTU) were carried out. The boreholes allowed for the definition of the soil stratigraphy while the CPT tests were used to define the resistance and deformability parameters, together with the permeability characteristics of the cohesive soils through the dissipation tests.

Figure 2 shows a stratigraphic cross section representative of the whole project area.

The average stratigraphy and the project geotechnical characterization are presented herein after.

DESIGN STRATIGRAPHY		
Elevation m from sea level	Layer	Notes
10.00÷2.00	IV	Superficial layer. Alternation of sandy and cohesive layers, sand and fill
2.00÷0.00	I_A	Silty Sand
0.00÷-6.00	III	Alternation of sandy and cohesive layers
-6.00÷-8.00	II	Clayey silt/ Silty clay with sand
-8.00÷-12.00	I_B	Silty Sand
-12.00÷-22.00	V	Alternation of sandy and cohesive layers

GEOTECHNICAL CHARACTERIZATION												
Layer	γ (kN/m^3)	OCR (-)	DR (%)	c_v (m^2/s)	c_u (kPa)	c' (kPa)	ϕ' (°)	E_{01} (MPa)	G_{max} (MPa)	M_c (MPa)	M_r (MPa)	ν (-)	k_0 (-)
IV	18.5	3	-	1E-6	0	0	36	15	50	2	10	0.35	0.5
IA	19.5	-	75	-	0	0	40	15	50	-	-	0.33	0.5
III	19.5	2	-	2E-6	50	0	32	15	80	-	-	0.35	0.5
II	19	2	-	2E-6	100	5	30	15	80	-	-	0.35	0.5
IB	19.5	-	75	-	0	0	38	30	200	-	-	0.33	0.5
V	19	2	-	1E-6	80	5	32	20	80	10	32	0.33	0.5

The groundwater table along the layout ranged between 1 and 1.5 m below the ground level. The design of the pumping system has been carried out based on the permeability of the depositional levels as reported in Table1.

3 WORK SCHEDULE AND RELATED GEOTECHNICAL ISSUES

The work schedule required the execution and maintenance of excavations under the groundwater table. Figure 3 shows a cross section aligned to the road layout, indicating the ground, the groundwater and the excavation levels. The more pervious layers are highlighted in grey.

The method of excavation and the pumping system design were defined based on this scenario.

Figure 1. Layout (taken from www.wikipedia.it).

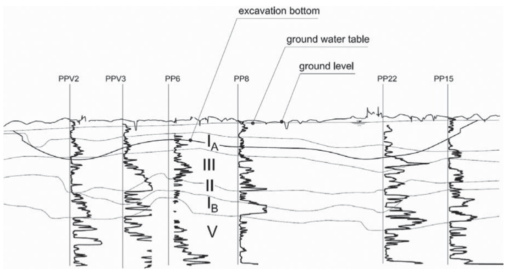

Figure 2. Stratigraphic cross section along the layout.

Table 1. Depositional levels and permeability coefficients.

Depositional levels	Description	Permeability (m/s) Kx	Kz
IA/IB	Silty sand	1E-5	1E-5
II	Clayey silt/Silty clay with sand	1E-8	1E-8
III	Alternation of sandy and cohesive layers	1E-6	5E-7
IV	Superficial layer. Alternation of sandy and cohesive layers, sand and fill	1E-7	1E-7
V	Alternation of sandy and cohesive layers	1E-7	5E-8

The excavations were kept dry through a system of active wells, installed at the slopes toe, which controlled the piezometric level in the deep permeable layer IB so to ensure stability of the excavation grade against hydraulic uplift.

Since the excavation grade was usually below the top of the first permeable level, water can infiltrate into the excavation sideways, therefore a passive well system was foreseen in order to avoid this phenomenon.

In Figure 4 the described wells layout is shown according to the medium stratigraphy.

The hydraulic drawdown necessary to keep dry the excavation could have sensible impacts at a distance from the excavation itself.

This aspect is crucial considering the nearby buildings, since the variation of the soil pore pressure could induce settlements on the structures.

It was evaluated that the area affected by the drawdown keeps within 50 m from the slope edge. Figure 5 indicates an example of existing buildings adjacent to the excavation.

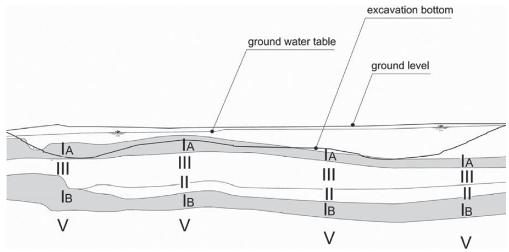

Figure 3. Excavation layout in relation to the stratigraphy and to the groundwater level.

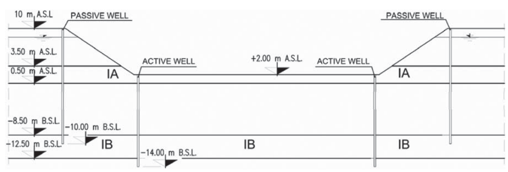

Figure 4. Typical wells layout.

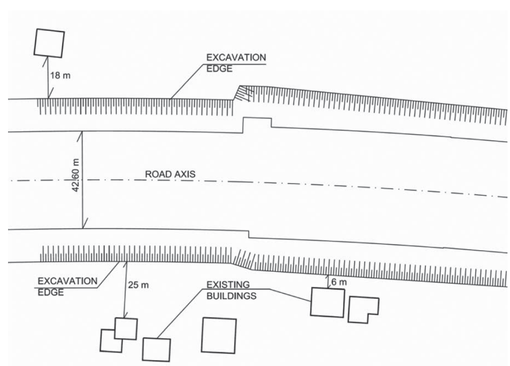

Figure 5. Plan of buildings nearby the excavation.

4 MONITORING SYSTEMS

Given the geotechnical issues to be faced, a coupled monitoring system was set up to control the piezometric level and the actual settlement development on nearby buildings.

Figure 6 shows a typical cross section with the piezometers locations for groundwater control. Two different piezometers typologies were adopted: deep piezometers and superficial piezometers for the control respectively of the piezometric level in layer IB and IA. Additional piezometers were installed nearby the buildings subjected to topographical monitoring so to allow for the correlation of the piezometric drawdown with the potential measured settlements.

The buildings topographic monitoring was composed of a system of benchmarks positioned in correspondence to the horizontal structural elements.

Differential settlements and the consequent angular distortions β, which express the damage of the building according to its structural typology, were obtained through the altimetric displacements of benchmarks themselves.

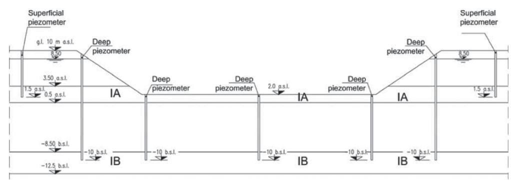

Figure 6. Piezometers location for the monitoring programme.

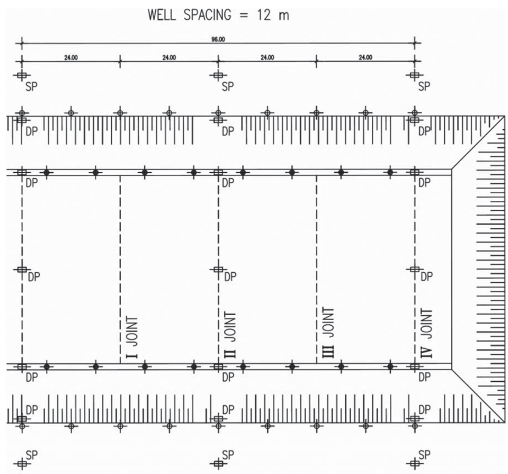

Figure 7. Wells system advancement module.

5 DRY EXCAVATION MAINTAINANCE

5.1 *Constructive scheme*

Wells spacing was set at 12 m. The open cut advancement module was 96 m long, equal to the distance of 4 construction joints for the structure, as illustrated in Figure 7.

In correspondence to the initial, central and final sections of the module, sections of measurement were placed, consisting of 5 deep piezometers, DP, and 2 superficial, SP.

Therefore the construction of the pumping system followed in several phases.

Phase 1: the active wells, the deep and superficial piezometers are installed.

Phase 2: the wells are activated and the piezometers are monitored up to the achievement of the system equilibrium according to the lowering estimations of the wells dynamic level and especially of the piezometers level.

Phase 3: the first excavation phase is executed up to the first advancement module of 24 m, joint I of Figure 7.

Phase 4: the bedding layer is placed up to the first subunit and the second subunit, joint II, is excavated.

Phase 5: the structural slab is completed up to first subunit so to guarantee the hydraulic stability, the bedding layer is executed up to the second subunit and the excavation proceeds up to the third subunit, joint III.

Phase 6: the wells system is activated and the following module, that is the following 96 m, is monitored and the structure completed up to the first subunit. The slab is constructed up to the second subunit to prevent hydraulic uplift. The bedding is executed up to the third subunit. The following module is monitored until the steady-state conditions reached. The excavation proceeds up to the fourth subunit, joint IV.

Phase 7: the bedding is executed up to the fourth subunit, the hydraulic stability is reached up to the third subunit and the excavation proceeds up to the first subunit of the following module.

Phase 8: the structure up to joint IV of the first advancement module is completed in order to achieve hydraulic stability. The slab up to the first subunit of the second advancement module is poured. The excavation up to the second subunit of the second advancement module is realized.

Phase 9: The wells of the first advancement module are switched off and the construction proceeds with the following module following the same sequence with bedding up to the first subunit and excavation up to the second subunit.

5.2 *Wells system design*

Once the piezometric drawdown required for uplift stability was defined, the scope of the design was to evaluate the dynamic water levels within the project area, the consequent required wells discharge and the expected drawdown in corresponce to the monitoring points.

As the monitored layout stretched for about 4 km, a simple and versatile calculation scheme was necessary. For this reason an Excel spreadsheet was created by implementing Mansur & Kaufman theory for confined aquifers, like layers IA and IB. Such model is versatile and adaptable to the stratigraphic and geometric changes along the 4 km layout, but on the other hand it simplifies the problem. The simplified Excel program was therefore validated through a 3D finite elements model implemented in Feflow and representing a single advancement module for the same stratigraphic conditions, geometric wells configuration and piezometric monitored verticals. The implemented geometry is that reported in Figure 4 and Figure 6.

5.3 *Simplified calculation model*

Since the scheme is 3D, the simplified model proposed by Mansur & Kaufman (1962) was adopted, considering that the wells system pumps water only from the deep permeable layer IB.

The wells system can work in two ways:

- constant discharge
- constant dynamic level

Since in practice it is easier to regulate the pump discharge than to maintain a constant dynamic water level, in the model a constant dynamic level in the wells was maintained.

Given a system with n wells the drawdown at the ith wells is evaluated as the sum of the effects of all the wells in the system.

In the present case, the aquifers are confined and the lowering inside well "i" is equal to:

$$H - h_{wi} = \frac{1}{2 \cdot \pi \cdot k \cdot D} \cdot \left(Q_{wi} \cdot \ln\left(\frac{R}{r_{wi}}\right) + \sum_{j=1}^{n-1} Q_{wj} \cdot \ln\left(\frac{R}{r_{j,i}}\right) \right) \quad (1)$$

Being:

H = undisturbed groundwater level;
h_{wi} = water level inside well i;
k = aquifer coefficient of permeability;
D = aquifer thickness;
Q_{wi} = well discharge;
R = well influence radius;
r_{wi} = radius of ith well;
$r_{j,i}$ = distance of each well from ith well or from jth point.

In a generic point "i" within the system, the drawdown is given by the sum of the drawdown induced by the other wells, that is:

$$H - h_i = \frac{1}{2 \cdot \pi \cdot k \cdot D} \cdot \sum_{i=1}^{n} Q_{wi} \cdot \ln\left(\frac{R}{r_i}\right) \quad (2)$$

If there were n wells and m control points the solver would be formed by $n + m$ equations in $n + m$ unknowns, which are the drawdown values in the wells or in the control points.

Being:

$\bar{\delta} = [\delta_1, ..., \delta_i, ..., \delta_N]$ the vector containing the drawdown in the n wells;

$\bar{Q} = [Q_1, ..., Q_i, ..., Q_N]$ the vector of the pumped discharges in the n wells;

$$\bar{\bar{D}} = \begin{bmatrix} \frac{1}{2\pi kD}\ln\left(\frac{R_1}{r_{1,1}}\right) & ... & ... & \frac{1}{2\pi kD}\ln\left(\frac{R_1}{r_{1,N}}\right) \\ ... & \frac{1}{2\pi kD}\ln\left(\frac{R_2}{r_{2,2}}\right) & ... & ... \\ ... & ... & ... & ... \\ ... & ... & ... & \frac{1}{2\pi kD}\ln\left(\frac{R_N}{r_{N,N}}\right) \end{bmatrix}$$

the matrix with the distances within the wells, the resolution system is the following:

$$\bar{Q} \cdot \bar{\bar{D}} = \bar{\delta} \quad (3)$$

Choosing instead in this case to fix the wells dynamic level, the corresponding discharge to be pumped out is given by:

$$\bar{Q} = \bar{\delta} \cdot \left(\bar{\bar{D}}\right)^{-1} \quad (4)$$

Once the discharge to be pumped from each well is determined, the system made of n+m equations can be solved, obtaining the m drawdowns in the m corresponding control points.

In this way, fixing the wells dynamic level, obtaining the discharges to be pumped from Equation (4), the drawdown induced by the n wells can be calculated in each defined control point using Equation (3).

5.4 *Finite element model*

The finite element model was implemented in the code FEFLOW 5.3 (2008).

The model was developed re-creating the advancement module 96 m long and 40 m wide. The geometry was extended for about 500 m from each side and up to a depth of 80 m.

In this way, it was possible to apply a potential boundary condition correspondent to the undisturbed groundwater level (8.5 m a.s.l.). The soil was modelled with 3D elements.

The following conditions were imposed to the aquifer: undisturbed groundwater level at the model boundaries, 8.5 m a.s.l, and in correspondence to the active wells at the toe of the slope a 10 m drawdown, that is –1.5 m b.s.l.; the wells are made of a permeable stretch only next to layer IB, as in the simplified model.

Based on the applied boundary conditions the following results were obtained and analyzed: pumped discharge from each active well located at the toe of the slope; total head at the top of layer IB next to the deep piezometers; total head at the top of layer IA next to superficial piezometers; total head at the top of layer IB. Figure 8 shows a 3D view of the finite element model and the mesh representing the wells and the excavation area.

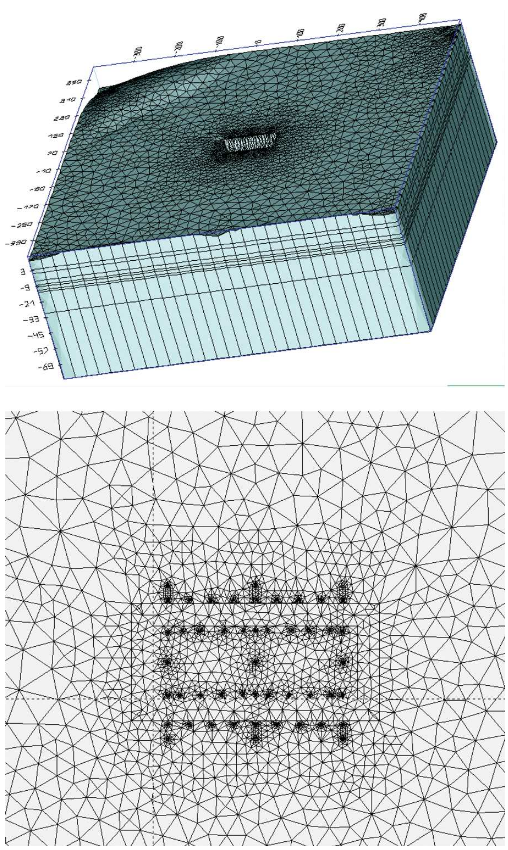

Figure 8. 3D FEM Modeling.

5.5 *Simplified model validation*

The comparison between FEM model results and those obtained from the simplified model herein is presented.

The common data input for the two calculation models were the stratigraphy, as already discussed, and the imposed dynamic level in the active wells, where a 10 m drawdown imposed in respect to the undisturbed groundwater level.

The comparison between the two calculation tools was done firstly in respect to the drawdown values at the piezometers location, both for the deep "DP" and the shallow "SP" ones. The results are given in Table 2 with reference to the names introduced in Figure 9.

A further comparison was done on the total discharge pumped out from the active wells.

The total pumped discharge calculated with Feflow is 2 l/s while the simplified model calculation provided 2.6 l/s. The two fold comparison suggests that the two models are in good agreement. Generally, the simplified model tends to predict fairly lower drawdown values compared to the ones obtained from the FE model. The gap between the results seems anyway acceptable and, from a qualitative standpoint, the use of the simplified brings to a reasonably more conservative well system design.

Based on the results obtained and considering the lower computational complexity, coupled with shorter calculation time, the simplified model seems therefore suitable for well system design in engineering practice.

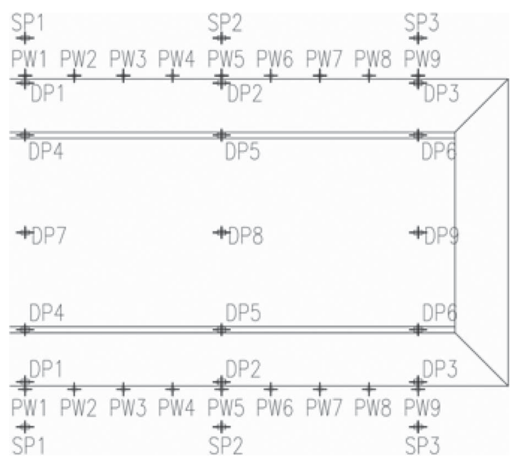

Figure 9. Observation points for piezometric lowerings calculation: "DP" = deep piezometer, "SP" = shallow piezometer.

Table 2. Results comparison between FEM and simplified model calculation.

Observation point	Calculated drawdown (m)	
	Feflow	Simplified model
SP1	5.94	5
SP2	6.75	6.03
SP3	5.9	5
PW1	6.34	4.7
PW2	6.84	5.64
PW3	7	6.41
PW4	7.25	6.82
PW5	7.3	7.03
PW6	7.27	7.09
PW7	7.19	7.03
PW8	6.72	6.82
PW9	6.3	6.41
DP1	6.48	8.55
DP2	7.6	8.68
DP3	6.58	8.55
DP4	7.37	7.8
DP5	8.90	8.67
DP6	7.23	8.68
DP7	7.28	7
DP8	8.73	8.88
DP9	7.17	7

6 INDUCED SUBSIDENCE NEXT TO THE EXCAVATION AREA

The wells system lowers the groundwater level inside the excavation perimeter, with obvious effects in the nearby external area. This can cause a subsidence settlement due to the increase of the effective stresses in the permeable layers and also in part of the cohesive levels.

The reduction of the hydrostatic head in the two permeable layers has been evaluated up to a distance of 50 m from the wells axes; at greater distances, the dewatering effect was considered negligible.

With the aim of assessing the effects of dewatering on the areas outside the excavation, settlements were computed at a distance of 25 and 50 m from the active wells position. The analysis was run in two scenarios:

- Pore pressure reduction within the sandy layers with no consolidation in the clay layers (short term conditions);
- Pore pressure reduction within sandy layer and consolidation of the clay layers (long term conditions).

The results are presented in Table 3.

Assuming that the maximum differential settlement could be 50% of the total value and considering the most frequent dimensions of the existing buildings along the layout, the following values of angular distortion have been calculated:

Table 3. Calculated settlements.

Distance (m)	Settlements (mm)	
	Short term	Long term
25	11	46
50	4.5	20

Table 4. Calculated distortions.

Distance (m)	Maximum distortion		
	Maximum differential settlement (mm)	Reference distance (m)	Distortion
25	23	5	1/200
50	10	5	1/500

According to the structural typology of the existing buildings, typically realized in masonry or in reinforced concrete frames, the maximum tolerable angular distortion has been establish between 1/250 and 1/150. In general it can be observed that within 25 m from the wells axes the evaluated distortion is next to the limit conditions.

Beyond 50 m instead the settlements induced by the subsidence are totally allowable.

Based on this results, during the whole construction period a mitigation system was foreseen for the buildings within 30 m from the active wells axes.

7 SYSTEMS OF SUBSIDENCE MITIGATION

The remediation measure was aimed to minimize the subsidence by limiting the water level variation close to the buildings.

Re-injection wells were therefore placed between the working area and the buildings. These wells were built as vertical drains and were all connected with a top trench where the water table was kept at the undisturbed level. The efficiency check of the system was accomplished in the buildings between progressive 2+247.5 and progressive 2+297.5, see Figure 5. Figure 10 shows a typical cross section next to the buildings illustrating the position of the re-injection wells system with respect to the active wells and to the excavation.

Through simplified Mansur & Kaufman model it was verified that the presence of 10 m spacing

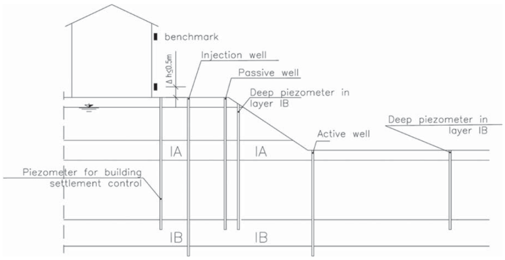

Figure 10. Section next to the buildings nearest to the excavation showing the measures for the mitigation of subsidence effects.

re-injection wells was enough to maintain the groundwater level constant while the pumping system was working.

8 CONCLUSIONS

Presently, the construction works along the whole road development have been completed and the highway road connection is now in service. The dewatering system turned out to be adequately designed and no particular problems were encountered during construction. The mitigation system composed of passive wells proved as well to be efficient in minimizing the effect of pumping.

All the pumped discharges and the piezometric measured levels resulted in good agreement with the mathematical modeling calculation.

The simplified model was able to foresee the actual behaviour of the pumping system inside and outside the excavation area. Its particular versatility proved to be successful being able to adapt to all geometric and stratigraphic configurations along the project development.

This simplified prevision model, validated with a finite element model, proved to be a reliable alternative to more complex computation tool.

From the application point of view it can be said that the simplified model, implementing Mansur & Kaufman theory, proved to be very efficient and entirely respondent to the design needs.

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