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ON AN ATYPICAL MORAINE OF THE SWISS PLATEAU AND THE PRESENCE OF A CONTINUOUS AQUIFER BETWEEN LAUSANNE AQUITANIAN GREY MOLASSE AND QUATERNARY DEPOSITS

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Abstract

Switzerland's geology is divided into the Alps, the Plateau, and the Jura, with the Plateau separating the other two and forming the glacial foreland. The Plateau's stratigraphy typically features sub-horizontal molasse overlain by Quaternary glacial or periglacial deposits from the Würmian glaciation, with ground moraine being the quintessential morainic facies. This moraine, with low permeabilities, sometimes separates underlying aquifers in molasse discontinuities from those in superficial moraine and periglacial formations. This article discusses that topic encountered in northern Lausanne during the design of a shallow railway tunnel at the molasse and Quaternary deposits interface. The moraine's in-situ permeability values, pumping tests, and piezometric surveys are studied, aiming to answer whether a tight waterproofed separation between the Lausanne Aquitanian grey molasse and Quaternary deposits does exist. This case underscores the extreme heterogeneity of glacial and periglacial formations and the importance of careful study for structure design and environmental impact control.

Key words

Quaternary, hydrogeology, water table, moraine, molasse.

1 Introduction

1.1 Context

The Swiss Confederation, represented by the Federal Office of Transport, is financing the underground relocation of the Lausanne-Echallens-Bercher (LEB) railway, in the municipality of Étagnières, in the Canton of Vaud, 10 km north of Lausanne, Switzerland. Today, the LEB line can be considered as a commuter rail like the RER (*Réseau express régional*) lines in Greater Paris area, with a frequency already at 15 minutes; its ridership has been continuously increasing for several years due to the economic development of the Gros-de-Vaud region. The project in Étagnières is part of the development of the Swiss railway network (*Étape d'aménagement* PRODES 2035) and aims to increase the frequency of this line of the Lausanne metropolitan area's RER to 10 minutes to meet a predicted increase in traffic (+50% by 2030 and +100% by 2040).

The new underground crossing will be 1 km long, including 440 m of tunnel and 133 m of underground station. The tunnel is at a shallow depth (10 m) and intercepts the different geological formations found on the Swiss Plateau: Aquitanian molasse and glacial, periglacial and postglacial deposits from the Quaternary period. As part of the project design, geological and geotechnical investigations were carried out between January and August 2023 to characterise the different facies encountered and the hydrogeological conditions.

This article presents these tests, the results obtained, and the interpretation made, particularly regarding the "basal" moraine whose local particularities have shown that it is not sufficiently watertight: thus, it does not make the roof of the molassic mass impermeable. This leads to the situation where an aquifer communication could exist between the Quaternary deposits and the molassic rock base, without it being possible to distinguish between perched lenticular aquifers present in the Quaternary deposits and a fissured aquifer in the molasse.

1.2 Geological survey carried out

In the spring of 2023, 20 cored boreholes (S21 to S27, S29 to S41) were drilled, complementing 14 others drilled in 2019 during an initial reconnaissance campaign. 11 of the boreholes were equipped with a piezometric tube, either screened in rock (S22, S24, S26, S34 and S35) or in unconsolidated materials (S27, S29 to S33). Figure 1 shows a location plan of the boreholes.

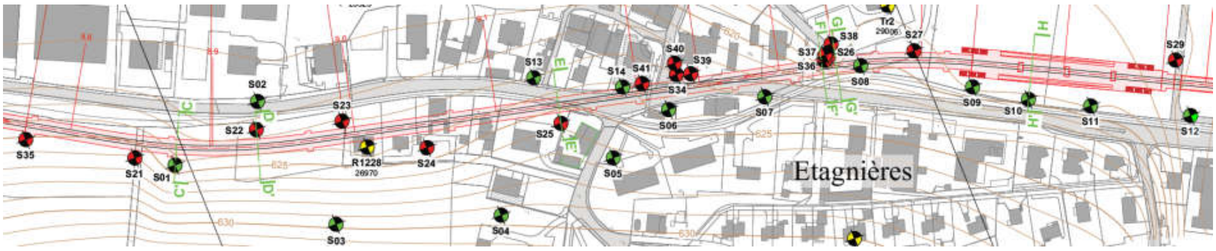

Figure 1. Situation of the drilled boreholes for both 2019 and 2023 surveys.

2 Geological context of the Swiss Plateau

2.1 Molasse

Switzerland is typically divided into three distinct geographical areas: the Jura, the Plateau, and the Alps. Regarding the Swiss Plateau, the substratum is composed of molasse; in the Lausanne and Gros-de-Vaud region, the molasse is a freshwater lower molasse, dated from the Aquitanian (Lower Miocene), called "Grey Molasse of Lausanne" (French: *Molasse grise de Lausanne*).

This molasse characteristically shows an alternation of sandstone and marl beds, sometimes indistinguishable. Generally, this rock formation consists of an alternation of thick sandstone beds with limestone cement and various layers with a more or less significant marly-clay component, including marlstone, marly sandstone, silty marl, more or less marl silts, and finally more or less clayey marls (Gencer *et al.* 2018).

In the Étagnières sector, the grey molasse shows a subhorizontal stratigraphy. Drilling has shown that the sandstone facies are weakly fractured, and the rock mass can be considered overall as quite massive. Only a few slightly open fractures (mm), sometimes oxidised, have been encountered in sandstone levels. The fractures can thus be considered as very spaced (more than 2 m) to locally moderately spaced (on the order of the meter). Their linear extension is generally several meters, sometimes up to a dozen meters. The fracturing is well observed in the sandstone levels. In the marls, it is marked rather by a tectonised matrix with lustrous surfaces.

2.2 Quaternary deposits

The Quaternary geology of the Swiss Plateau is dominated by glacial and periglacial deposits associated with the Quaternary glaciations, particularly the Würm glaciation. Morainic deposits are the most common in the region, with other periglacial or postglacial deposits interbedded within them. The formations encountered in the project are listed below:

- Peat deposits: These were found in the S26 borehole and are 2.35 m thick. They consist of peaty silts and clayey silts with sand and organic matter and are generally very soft and compressible.

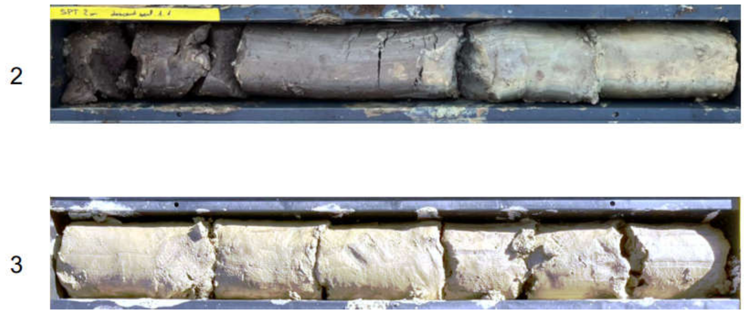

Figure 2. Former marsh: peaty facies at the top left and clayey facies in the rest of the cores (S26).

- Fluvio-glacial deposits: These periglacial deposits are present in the form of lenses with variable geometry and a thickness of 0.5 to 2.0 m within morainic deposits. They consist of gravelly sands and silty sands, sometimes limestone gravels, and are generally moderately compact. These fluvio-glacial materials are generally non-cohesive or slightly cohesive. Water inflows have been observed in several boreholes.

Figure 3. Fluvio-glacial deposits (S34).

- Glacio-lacustrine deposits: This second type of periglacial deposit is also present in lenses with variable geometry and metric thickness within morainic deposits. These materials are frequently associated with fluvio-glacial deposits. Glacio-lacustrine deposits are generally composed of clayey silts, varved, compressible, with a firm to hard consistency, becoming soft to very soft in the presence of water (often present in the overlying fluvio-glacial deposits). In the latter case, these materials are fluid.

Figure 4. Glacio-lacustrine deposits starting from 4.50 m (S09).

- Weathered moraine: This is sandy or silty moraine that has been altered and has a firm to very firm consistency, sometimes soft.
- Sandy moraine: The sandy moraine, more frequent in the southern half of the project, is composed of often silty sands with gravel. These materials have some cohesion, and their consistency can be described as very firm to hard. The presence of stones or blocks is possible. The thickness of the sandy moraine is generally 2 to 3 m.

Figure 5. Sandy moraine (S25).

— Silty moraine: The silty moraine is present mainly in the northern half of the project, often just above the rock, with a thickness of about 3 to 4 m. It is composed of generally gravelly silts, sometimes sandy, with a very firm to very hard consistency. This is not a typical basal moraine, which is why we have not named it as such.

Figure 6. Silty moraine (S25).

The longitudinal profile of the underground project established on the two different geological surveys is given hereafter (Figure 7):

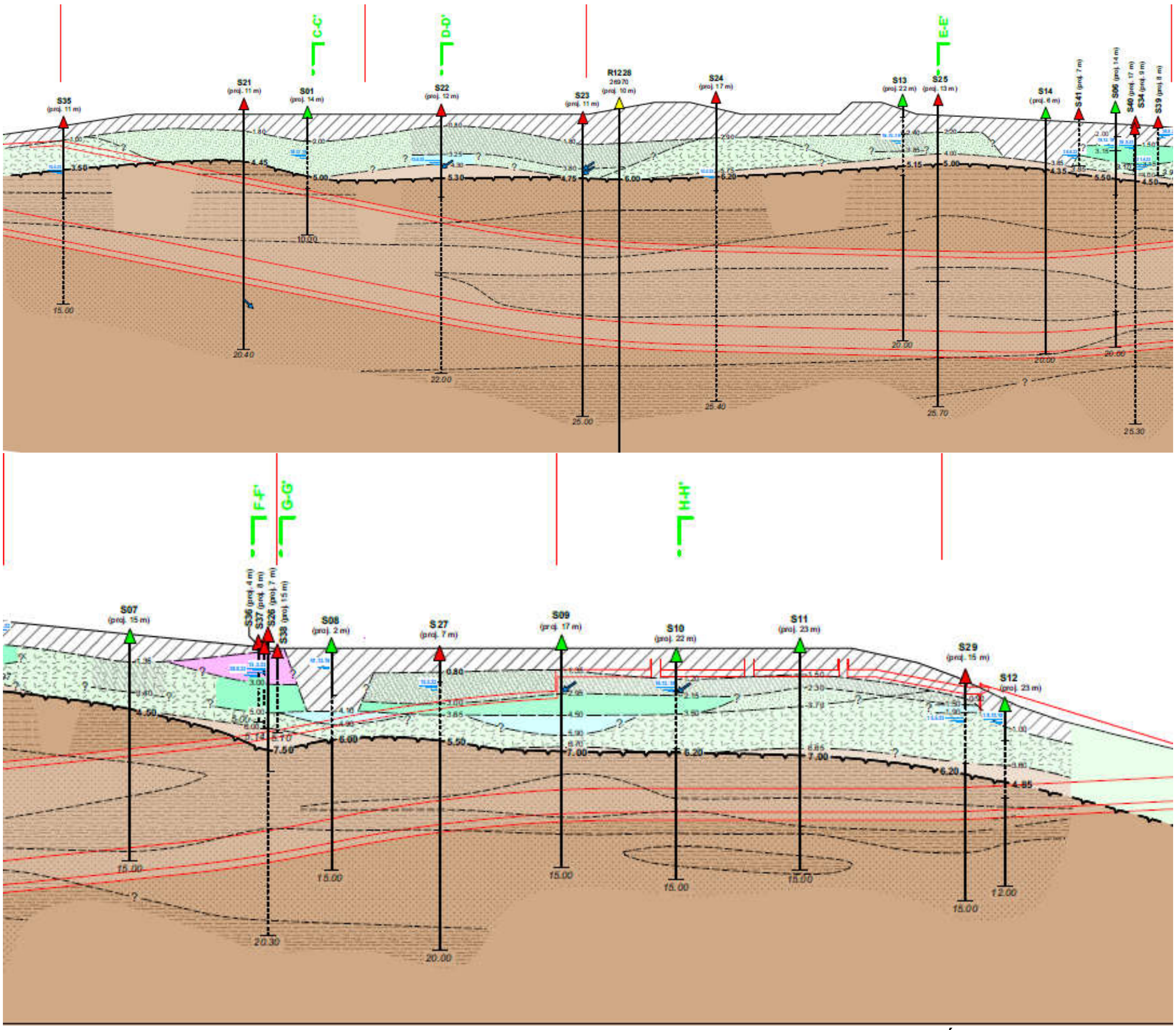

Figure 7. Longitudinal geological profile of the new tunnel and RER station in Étagnières.

2.3 Hydrogeological context of the Swiss Plateau

The glacial and periglacial facies exhibit quite different hydrogeological behaviours. The article by Parriaux and Nicoud (1993) provides a comprehensive synthesis on this subject regarding the formations encountered in the Northern Alps, based on several observations from glacial or periglacial terrains from the Swiss Plateau and Swiss and French Alpine valleys.

The basal moraine is generally considered to have low permeability (k < 10^{-6} m/s) in its typical facies. According to Parriaux et Nicoud, in some rare cases, when the permeability is sufficiently low and the moraine has not been altered, it forms an impermeable layer between the underlying rock and the overlying deposits. Fluvio-glacial and glacio-lacustrine deposits, on the other hand, have typical permeabilities that are higher (from 10^{-2} to 10^{-4} m/s and from 10^{-3} to 10^{-4} m/s, respectively).

Several engineering projects have provided feedback on the complex hydrogeology at the interface between molassic formations and Quaternary deposits in the Lausanne region over the past 30 years. For example, in the extension of the LEB to the centre of Lausanne (Flon station) in 1995, Tappy (1995) reported that no significant and permanent aquifer flow was observed between the molasse and the basal moraine of the Rhone glacier. In another adjacent project to put the LEB underground in the heart of Lausanne, Hey (2020) reports that glacial and periglacial deposits most often form aquifer lenses, without communication with the molassic rock where only punctual water inflows were observed. Risch (2005) also reports the same observation during the construction of the second metro line in Lausanne: two aquifers exist, one perched in the Quaternary cover soils, the other in the discontinuities of the molasse, without them clearly joining together.

2.4 Objective

The objective of this study is to discuss the hydrogeology of the presented terrains based on various in situ tests. From a design perspective, it is crucial to determine whether there is communication between the rock base and the overlying soils to choose between a drained or non-drained tunnel. The literature review suggests that aquifer communication may exist, according to observations by Parriaux and Nicoud, as cases where the basal moraine acts as an impermeable layer are rare. However, feedback from previous projects indicates a separation of aquifers between the fractured aquifer and the lenticular aquifer in the Quaternary deposits. In this article, we aim to establish whether aquifer communication exists or not.

3 Methods

In order to clarify the hydrogeological conditions of the entire mass consisting of the rock mass and the loose soils, 10 in situ permeability tests were carried out: 3 Lefranc permeability reduction tests during drilling, and 7 drawdown-recovery tests in the boreholes. The tests were carried out in the unconsolidated soils and in the molassic rock.

Three short pumping tests, each lasting 5 to 6 hours, were carried out in spring 2023 in the piezometers S26, S24 then S34, all screened in the molasse, in order to evaluate the drawdown that would be caused by the draining effect of the project, particularly in loose soils. During each test, the pump flow rate was set (very low flow rate between 0.1 and 0.2 L/min) so that the piezometric level (PZ) was gradually lowered to 1 to 2 m below the level of the project raft (3 successive stages of 1.5 to 2 h). The PZ in nearby piezometers was measured every 30 minutes.

Additional pumping tests were carried out in August 2023 to try to clarify the hypothesis of the presence of a single aquifer and the permeability of the rock. For the pumping test in the piezometer S26 (screened in rock), pressure probes were installed in the observation piezometers S36, S37, S38 as well as S08 and S27 (all screened in loose soils). They measured the water levels every 5 minutes, during pumping and for 6 days after the pump was stopped. At the same time, manual control measurements were carried out.

For the pumping test in S34 (screened in rock), the pressure probes were placed in the observation piezometers S39, S40, S41 and S05 (screened in loose soils) as well as S26 (screened in rock). They measured the water levels every 5 minutes, during the 3 days preceding the pumping, during it and during the 3 days after its stoppage.

4 Results

4.1 Permeability tests

The water tests carried out during drilling, after piezometer installation or after pumping made it possible to evaluate the permeability of the encountered soils. The results are summarised in Table 1 below.

In the loose soils, the lowering tests carried out in the silty moraine indicate, as expected, low permeabilities of $5.5 \cdot 10^{-7}$ and $1.4 \cdot 10^{-6}$ m/s. The test carried out in the fluvioglacial alluvium (drilling S27) and partially in the silty moraine shows a permeability of the order of 10^{-5} m/s, which somehow represents a mean value between characteristic permeabilities of both formations, especially considering the values given by Parriaux et Nicoud (1993).

As for the rock base, the drawdown-recovery tests carried out after piezometer installation or after pumping indicate low permeabilities of the mass of the order of 10^{-6} m/s (values between $9.4 \cdot 10^{-7}$ and $2 \cdot 10^{-6}$ m/s). Water circulation will likely occur mainly in the sandstone levels and their fracture network (fissural permeability).

Table 1. Values of permeability measured in situ.

	Borehole	Formation	Technique	Permeability (m/s)
Loose soils	S27	Fluvio-glacial alluvium and silty moraine	Lefranc lowering during drilling	$1.2 \cdot 10^{-5}$
	S27	Sandy moraine, fluvio-glacial alluvium and silty moraine	Drawdown-recovery in piezometer	$3.5 \cdot 10^{-7} – 1.6 \cdot 10^{-6}$
	S24	Silty moraine	Lefranc lowering during drilling	$1.4 \cdot 10^{-6}$
	S34	Silty moraine	Lefranc lowering during drilling	$5.5 \cdot 10^{-7}$
Rock	S22	Molasse	Drawdown-recovery in piezometer	$9.4 \cdot 10^{-7}$
	S24	Molasse	Drawdown-recovery in piezometer	$1.2 \cdot 10^{-6}$
	S26	Molasse	Drawdown-recovery in piezometer	$1.5 \cdot 10^{-6}$
	S34	Molasse	Drawdown-recovery in piezometer	$2.0 \cdot 10^{-6}$
	S26	Molasse	Drawdown-recovery after pumping	$1.8 \cdot 10^{-6}$
	S34	Molasse	Drawdown-recovery after pumping	$1.8 \cdot 10^{-6}$

4.2 Pumping tests

The results form the pumping tests are presented below in Table 2.

Table 2. Results from the pumping tests.

		Pumping borehole		
Observation piezometer	Formation	S24	S34	S26
S24	Molasse	-15.4 m (pumping)	PZ still increasing	Unmeasured
S34	Molasse	Unmeasured	-18.4 (pumping)	PZ still increasing
S26	Molasse	Unmeasured	PZ still increasing	-12.0 m (pumping)
S02	Loose soils and top of molasse	0	Unmeasured	Unmeasured
S22	Molasse	PZ still increasing	Unmeasured	Unmeasured
S05	Loose soils	0	0	0
S08	Loose soils	Unmeasured	0	-0.08 m
S27	Loose soils	Unmeasured	0	0

Note that some piezometers showed an increase in water level during pumping tests (S34, S22 and S24). For S34 and S22, this can be explained by water levels that were in the process of rising following the drainage of the piezometers a few days before the pumping tests. Regarding S24, the water level was also in a phase of rising following the pumping test that was carried out the day before.

The results of the complementary pumping tests carried out in August 2023 are summarised in the following table (Table 3).

Table 3. Observations made during the complementary pumping tests.

	Piezometers	Observations on the water table in the piezometers
	S36	The water level decreases regularly and slowly before, during and after pumping due to a dry period. The rise observed during the measurement on 05.09.23 is due to the rains on 26, 27 and 28.08.23. The stop of pumping on 18.08.23 has no effect.
	S37	Same as for S36. The measurements with the pressure probe show several "jumps" due to a displacement of the probe in the piezometer during manual measurements.
	S38	The piezometric level is rising because its equilibrium with the water table took several weeks after the drilling was completed, due to very low permeability. The stop of pumping on August 18, 2023 has no effect.
	S08	Same as for S36.
	S27	Same as for S36. The difference of about 20 cm between the manual measurements and those with the pressure probe is due to a problem with the reference level 0 of the measurements with the probe. The peak on 12.08.23 is probably related to the rain of the day.
	S39	The water level rises rapidly following the rains of August 26, 27, and 28, 2023, and then slowly decreases for about 2 weeks. The stop of pumping on September 1, 2023, does not induce any rise in the water level.
	S40	Same as for S39.
	S41	The water level rises quickly following the rains on August 26, 27, and 28, 2023, then decreases rapidly. No significant variation in the level during and after pumping.
	S05	The water level rises after the rains of August 26, 27, and 28, 2023, and then decreases slowly. The stop of pumping on September 1, 2023, does not induce any rise in the water level.
	S26	Same as for S41.

The monitoring of water levels in observation piezometers, whether using pressure probes or manual measurements, does not show any influence of pumping. The variations in piezometric levels are solely related to precipitation. These findings are summarised in table 3. This absence of influence can be explained by the low permeability of the rock (particularly the marl levels) and the unconsolidated soils. In S26, according to the water meter, only 730 litres of water were pumped during the nearly 8 days of pumping (very low pump flow rates of 0.1 to 0.2 L/min). This indicates that the radius of influence of the pumping around S26 was probably less than 1 metre and therefore explains why no influence was observed on the observation piezometers. In S34, the same finding was made (low volume of water pumped), although the exact value could not be recorded.

4.3 Sensitivity of the molasse permeability value

We wanted to numerically simulate the pumping test of borehole S26 in order to confirm the orders of magnitude of the permeability of the molasse with a 2D axisymmetric FEM on Plaxis. We took 624 m a.s.l. as the initial water table level, corresponding to the average level measured by the piezometers in the area.

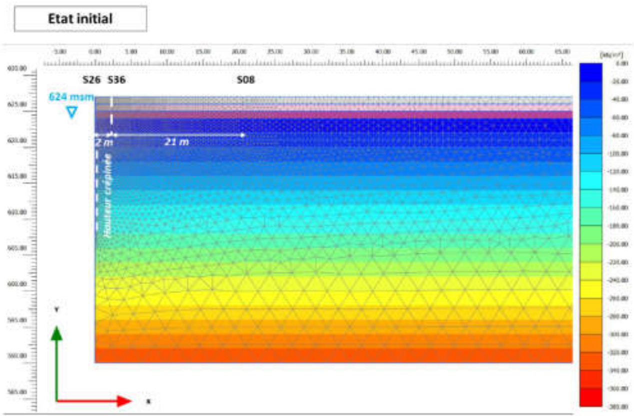

Figure 8. Initial state – Simulation of the pumping test in S26.

We simulated the pumping test by emptying the S26 piezometer and observing the cone of water lowering after 8 days (duration of the test). We carried out this exercise for different permeabilities of the molasse.

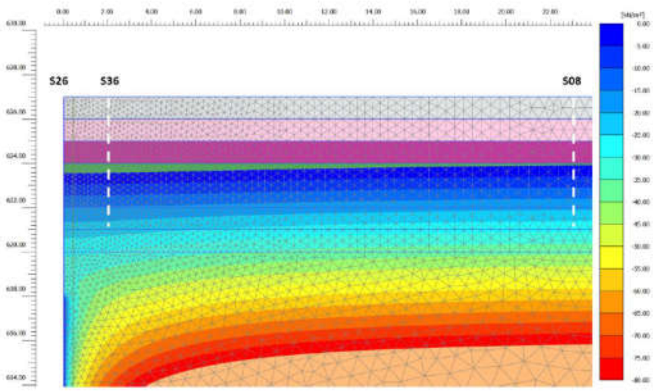

Figure 9. Simulation of the pumping test in S26 after 8 days, assuming $k = 10^{-6}$ m/s in the molasse.

With the permeability $k = 10^{-6}$ m/s, the piezometers S26 and S08 show a decrease in their level of 50 cm and 10 cm respectively. However, during the pumping tests, no effect was observed. Therefore, the permeability seems to be lower.

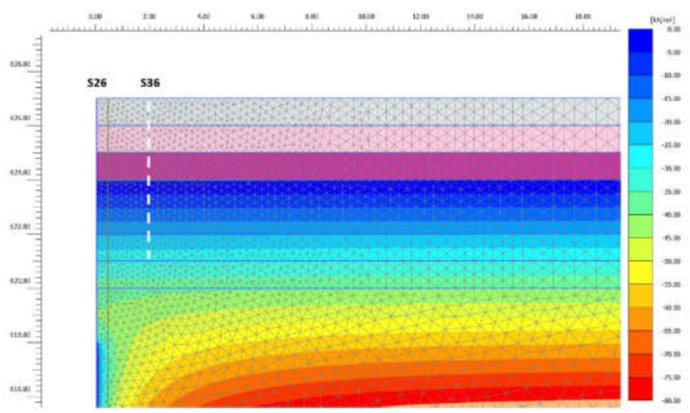

Figure 10. Simulation of the pumping test in S26 after 8 days, assuming k = 10^{-7} m/s in the molasse.

With such a permeability (k = 10^{-7} m/s), the piezometers S36 and S08 would have seen a decrease in their levels of 10 cm and 1 cm, respectively. However, no decrease was observed related to the pumping.

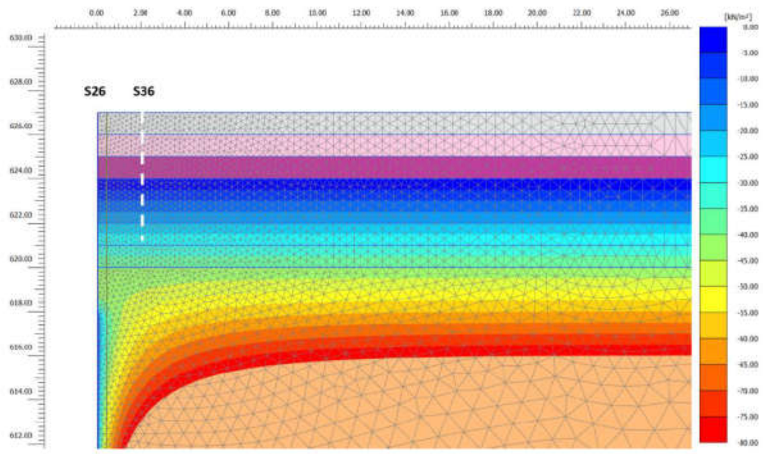

Figure 11. Simulation of the pumping test in S26 after 8 days, assuming k = 10^{-8} m/s in the molasse.

In this case (k = 10^{-8} m/s), there would be no effect of pumping on the water levels of S36 and S08, as shown in the figure below. Thus, the permeability of the molasse would probably be between 10^{-7} and 10^{-8} m/s, lower than that indicated in the permeability tests conducted in situ, which is on the order of 10^{-6} m/s.

4.4 Discussion

Similar levels were observed in the piezometric measurements carried out in December 2019 (high water regime; precipitation between 155 and 163% of the monthly average at the MétéoSuisse station in Echallens for the months of October to December 2019) and in April-September 2023 (average to low water; 127% and 105% of the normal in March and April 2023, 56%, 66% and 86% in June, July and August 2023). These measurements indicate that the unconsolidated soils and the underlying rock mass contain a groundwater table with a piezometric level generally located between 1 and 4 meters deep, locally up to approximately 6 meters (S24 borehole). The variations of these levels depending on precipitation are proven by the measurements (particularly during the pumping tests of August 2023) and confirm that this is not just water pockets in isolated lenses, but rather a single aquifer.

The possibility of distinct aquifers has been ruled out, but this does not answer the question of whether the molassic rock and the Quaternary deposits actually communicate. The silty moraine observed on site corresponds, in terms of depositional mode and in situ measured permeability, to the description of a classic basal moraine by Parriaux and Nicoud (1993). However, its lack of lateral continuity (incursions of sandy moraine, or even disappearance of the silty moraine in the southern part of the study area), as well as its sandier character compared to a typical basal moraine, suggest that it cannot guarantee complete sealing of the substratum. The absence of a thick and continuous layer of low-permeability deposits (basal moraine) at the top of the molassic rock, as well as similar piezometric levels in the unconsolidated deposits and in the molasse, indicate the probable presence of a single aquifer that can be considered continuous. However, despite this, pumping tests in piezometers screened in the molasse did not reveal a drawdown in the piezometers in the unconsolidated deposits, as if there were indeed a separation of groundwater into two aquifers. It may be thought that the very low permeabilities involved were an obstacle to visualising aquifer flows using pumping.

5 Conclusion

The present article aimed to highlight the difficulty, in the discussed case, of drawing a definitive conclusion, despite several geological surveys, regarding the aquifer communication between the molassic substratum and Quaternary deposits. The comparison between the geological synthesis at the scale of the northern slope of the Alps, feedback from tunnel projects in the Lausanne region, continuous piezometric measurements, and pumping tests has not yet provided a definitive answer to the question of the existence of a continuous aquifer along the new Étagnières underground crossing. This limitation poses a genuine engineering problem, and a choice had to be made. It was decided, in agreement between the project owner, the consulting engineer, and the experts checking the calculations, to assume that a single and continuous aquifer exists. This assumption, although very likely, remains the one that allows to control the geological risks to ensure the durability of the structure, and to avoid a drawdown of the aquifer with significant geotechnical (settlements) and environmental consequences. The construction of the tunnel will allow, through visual observation of the molasse and unconsolidated soils, to confirm or refute the assumption made. Finally, the article emphasized the sometimes-too-high value of direct permeability estimates from tests, which it is sometimes useful to compare with numerical simulations, even if the latter also have their biases.

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