# EFFET DES PARTICULES FINES SUR LE COMPORTEMENT HYDRAULIQUE DU SOL DE LA COUCHE INTERMEDIAIRE

# *EFFECT OF FINE PARTICLES ON THE HYDRAULIC BEHAVIOR OF INTERLAYER SOIL*

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**RÉSUMÉ –** Le comportement hydraulique d'un sol de la couche intermédiaire prélevé à Sénissiat a été étudié. Différentes teneurs en fines ont été considérées. Les résultats montrent que la conductivité hydraulique à l'état non saturé est principalement gouvernée par les fines via l'effet de la succion. En revanche, la conductivité hydraulique à l'état saturé est gouvernée par le transfert d'eau dans des macro-pores.

**ABSTRACT –** The hydraulic behavior of an interlayer soil taken from Sénissiat was investigated. Different fines contents were considered and wetting-drying cycles were applied to the soil specimens. Results suggest that the unsaturated hydraulic conductivity is mainly governed by fine particles through suction effect. By contrast, in saturated state, the hydraulic conductivity is mainly governed by the water transfer through macro-pores.

## 1. Introduction

Many railway lines over the world have been in operation for more than one hundred years. In France, the conventional lines represent 94% of the whole railway network. As opposed to the new lines, the conventional ones were constructed by direct installation of ballast onto sub-grade without any separation layer. Over years of operation and with the increasing traffic, load, and speed of train, there are more and more problems related to loss of stability and strength of substructure. A number of studies have been conducted to assess the state of substructure and to develop adequate maintenance methods (Trinh 2011; Duong et al. 2013; Cui et al. 2013). It was found that one of the particularities of conventional substructure is the presence of a soil layer namely interlayer that has been created mainly by inter-penetration of ballast and fine particles of sub-grade.

In France, it has been decided recently to renew the conventional railway network. During the renewal, the interlayer will be kept as part of the substructure thanks to its high mechanical resistance related to its high dry unit mass (2.4 $Mg/m^3$ at the Sénissiat site, according to Trinh et al. 2011) reached by natural dynamic compaction corresponding to the circulation of trains. However, the mechanical behavior of interlayer soil can show large variability, depending on the proportion of fine particles contained in it. A number of studies (Babic et al. 2000; Pedro 2004; Naeini and Baziar 2004; Kim et al. 2005; Verdugo and Hoz 2007; Cabalar 2008; Seif El Dine et al. 2010; Ebrahimi 2011; Anbazhagan et al. 2011; Trinh et al. 2012) showed that the mechanical behavior of soil containing a large proportion of fines is strongly influenced by the water content. As the water content changes are governed by the hydraulic behavior of soil, it appears important to assess the influence of fine particles content on the hydraulic behavior of interlayer soil.

In this study, laboratory tests were performed using a large-scale infiltration column (300 mm in diameter) and a small-scale infiltration column (50 mm in diameter), and the instantaneous profile method was used to determine the hydraulic conductivity of soil. Both wetting and drying paths were performed and different fines contents were considered: natural interlayer soil ($ITL_0$), natural interlayer soil with 10% sub-grade added ($ITL_{10}$), fine-grained soil prepared by passing $ITL_{10}$ through a 2 mm sieve (*Fines*). The results enable the assessment of the effects of fine particles and wetting/drying cycles.

## 2. Materials and methods

The soils (both the interlayer soil and sub-grade) were taken from the railway site Sénissiat (North-West of Lyon, France). Mineralogy analysis reveals that the interlayer soil is a mixture of materials that come from the construction and maintenance (broken stones, gravel, sand, etc) of tracks, the aging process of track components and the sub-grade. It also showed that the fine particles in the interlayer soil mainly come from the sub-grade. The main geotechnical properties of interlayer soil and sub-grade are presented in Table 1. The results show that the sub-grade is high-plasticity silt. More details about the characterization of the interlayer soil can be found in Trinh et al. (2011).

Table 1: Properties of the soil studied

| Soil | Properties | Value |
|---|---|---|
| Interlayer soil ($ITL_0$) | $\rho_s$ (particles smaller than 2 mm) | 2.67 Mg/m$^3$ |
| | $\rho_s$ (particles larger than 2 mm) | 2.68 Mg/m$^3$ |
| | $d_{10}$ | 0.01 mm |
| | $d_{30}$ | 5 mm |
| | $d_{60}$ | 30 mm |
| | liquid limit wL (smaller than 100 µm) | 40.2% |
| | plasticity index Ip (smaller than 100 µm) | 11.3% |
| Subgrade (Fines to create $ITL_{10}$) | liquid limit $w_L$ | 57.8% |
| | plasticity index Ip | 24.1% |

In order to study the effect of fines contents on the hydraulic behavior of interlayer soil, a quantity of sub-grade representing 10% interlayer soil by dry mass was added into the interlayer soil to form a soil with a higher content of fines: $ITL_{10}$. The grain size distribution curves of the natural interlayer soil ($ITL_0$) and $ITL_{10}$ are presented in Figure 1.

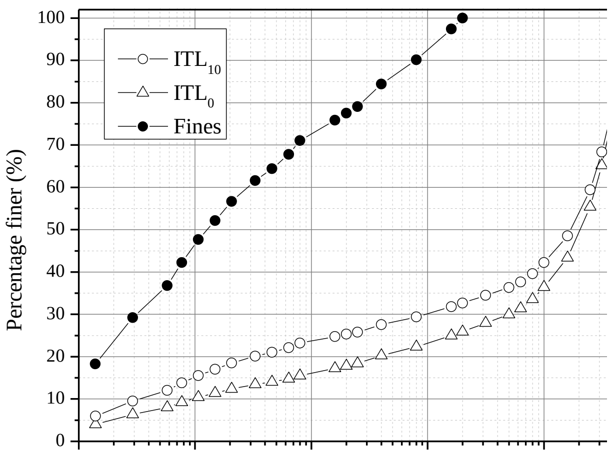


Figure 1: Grain size distribution curves of $ITL_0$, $ITL_{10}$ and Fines

To better evaluate the effect of fines on the hydraulic behavior of interlayer soil, the hydraulic conductivity of pure fine particles was also determined. For this purpose, $ITL_{10}$ was sieved at 2 mm to obtain the fine part (namely *Fines*). The grain size distribution curve of *Fines* is also presented in Figure 1.

The interlayer soil was tested in a large-scale infiltration column (Figure 2). The column (300 mm in diameter and 600 mm in height) is equipped with five water content sensors (TDR1 to TDR5) and five tensiometers for measuring pore-water pressure (T1 to T5) arranged at various elevations along the column (h = 100, 200, 300, 400 and 500 mm from the bottom of the soil specimen). The working pressure range of the tensiometers is from 100 kPa to -85 kPa. The accuracy of the TDR used is ± 2% and that of the tensiometer is ± 0.5 kPa. At each instrumented height, as the area occupied by the sensors is just 6.8% of the total apparatus section area, the influence of the sensors installation on water transfer is expected to be insignificant.

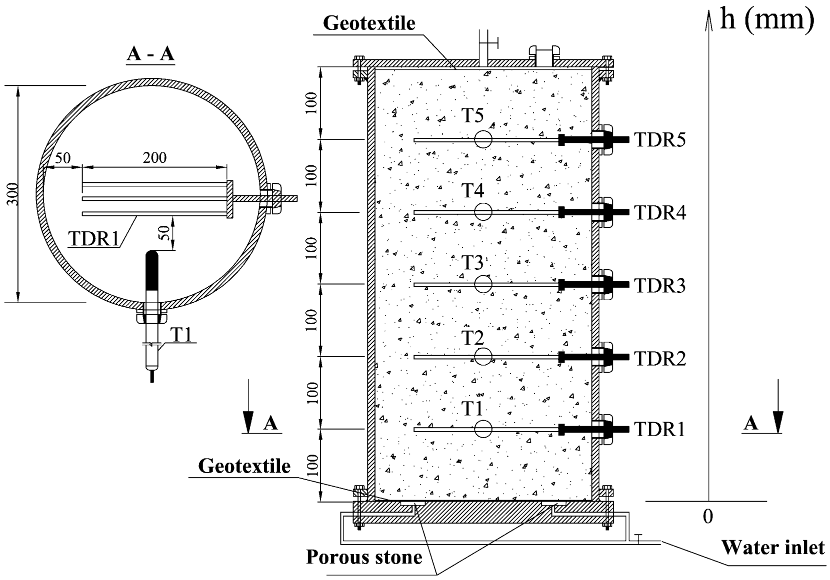


Figure 2: Schematic view of the large-scale infiltration column

For the $ITL_{10}$ specimen preparation, water and fine particles were added to the dry natural interlayer soil to reach the target water content and fine particles content, and a large mixer was used to homogenize the material. For the $ITL_0$ specimen preparation, only desired quantity of water was added to the dry natural interlayer soil. After mixing, the wet materials were stored in hermetic containers for at least 24 h for moisture homogenization. Soil compaction was conducted using a vibrating hammer in six layers of 0.10 m each at a dry unit mass of 2.01 Mg/m$^3$. Prior to compacting the subsequent layer, a TDR probe and a metal rod of 25 mm diameter were placed on the compacted layer.

Once the soil specimen was prepared, water was injected from the bottom and it flowed out from the outlet after about half an hour. After saturation of the sample, the metal rods were removed and the tensiometers were installed. This protocol was adopted to avoid damaging the tensiometers during the compaction and also any cavitation due to possible high suction in the column. More details about the large-scale infiltration column can be found in Duong et al. (2013).

The infiltration tests were conducted in two wetting/drying cycles. After installation of the tensiometers, the saturation of soil column was completed (Saturation 1). This wetting stage was followed by a draining stage (Drainage 1). Water was allowed to drain out through the bottom valves by keeping a constant water level at the bottom of soil sample using an external water source. The first wetting/drying cycle ended by a stage of evaporation (Evaporation 1) where the top cover of the column was removed to allow soil water evaporation. A fan was used to accelerate the evaporation process. The evaporation stage ended when the suction value indicated by tensiometer T5 (h = 500 mm) was about 60 kPa (higher suction would lead to cavitation). A second wetting-drying cycle was applied following the same procedure (Saturation 2, Drainage 2 and Evaporation 2). Before the second drainage, the hydraulic conductivity in saturated state was also measured by applying a constant water head of 0.61 m. The hydraulic gradient was equal to 1. According to Tennakoon et al. (2012), any hydraulic gradient smaller than 4 can be considered as being low enough to ensure the Darcy's flow. Note that the experimental procedure with saturation from the bottom and evaporation from the top is also recommended in an ASTM standard (ASTM 2010). During the measurement of hydraulic conductivity under saturated condition, the volume of water injected increased linearly with a rate of 50 $cm^3$ per minute.

The unsaturated hydraulic conductivity of *Fines* was determined using a small-scale infiltration column of 50 mm in diameter and 200 mm in height (Munoz et al. 2008). Suction measurements were performed by four high-capacity tensiometers (Cui et al. 2008) installed at 40, 80, 120 and 160 mm height from the base of the sample. The accuracy of this tensiometer is ± 1 kPa. The soil was statically compacted in the column in four layers of 50 mm each. Once the compaction was completed, the tensiometers were installed.

The dry unit mass and water content of *Fines* were taken equal to those of fine particles contained in the sample of interlayer soil. These two parameters can be calculated as follows:

$$\rho_{d,f} = \frac{M_{s,f}}{V_f} = \frac{M_s - M_{s,b}}{V - V_{s,b}} = \frac{(1-m)\rho_d V}{V - \dfrac{m}{\rho_{s,b}}\rho_d V} = \frac{(1-m)\rho_d \rho_{s,b}}{\rho_{s,b} - m\rho_d} \quad (1)$$

$$w_f = \frac{M_w}{M_{s,f}} = \frac{M_s w}{M_s - M_{s,b}} = \frac{w}{1-m} \quad (2)$$

where M, $M_w$, $M_s$ are the total mass, mass of water and mass of solid particles, respectively; V, $V_w$, $V_s$ are the total volume, volume of water and volume of solid particles respectively; $\rho_d$, $\rho_s$ are the dry unit mass of the specimen and unit mass of solid particles, respectively; the subscripts f and b stand for particles smaller and larger than 2 mm, respectively; m is the percentage of particles larger than 2 mm.

Based on the grain size distribution curve, a value m = 0.67 was obtained. From Eqs (1) and (2), a value of 1.33 $Mg/m^3$ was obtained for the dry unit mass of Fines.

The test procedure followed for the small-scale infiltration column was akin to that for the large-scale one. After the suction stabilization, the sample was saturated from the bottom (Saturation 1). After completion of saturation, an external water source was connected to the bottom in order to ensure a constant water level after the drainage. The top cover was then removed allowing water evaporation from the soil surface (Evaporation 1). When suction at 160 mm reached about 400 kPa, Evaporation 1 was stopped to avoid cavitation of the tensiometers. A second wetting-drying cycle was applied by following the same procedure as in the first cycle (Saturation 2 and Evaporation 2).

Unlike the large-scale column where both suction and water content were monitored, the small-scale column has only suction monitored. To obtain the water content changes during infiltration, the soil-water retention curve (SWRC) was needed. This was done separately by suction measurement using high-capacity tensiometers (see more details in Le et al. 2011 and Munoz-Castelblanco et al. 2012).

For the large-scale column, both suction and water content profiles were obtained directly. For the small-scale column, the suction profiles were obtained directly while the water content profiles were determined through the SWRC. The instantaneous profile method (Daniel 1982; Ye et al. 2009) was then applied for the determination of hydraulic conductivity for each soil. Note that this method is based on the generalized Darcy's law. The hydraulic gradient is determined by considering the slope of suction isochrones and the water volume passing through a given section between times *t* and *t+dt* is used for calculating the water flux.

## 3. Results and Discussions

The obtained hydraulic conductivities of $ITL_0$ and $ITL_{10}$ are presented in Figure 3. In the saturated state, the two soils have almost the same value: $1.67\times10^{-5}$ m/s for $ITL_{10}$ and $1.75\times10^{-5}$ m/s for $ITL_0$. Both values are lower than the critical value proposed by Selig and Waters (1994) for the railway substructures. In unsaturated state, even the data are scattered for the two soils, an identical trend can be identified: the hydraulic conductivity is decreasing with the increase of suction. Moreover, the average value for $ITL_{10}$ is slightly higher than that for $ITL_0$, suggesting a slightly greater hydraulic conductivity for $ITL_{10}$.

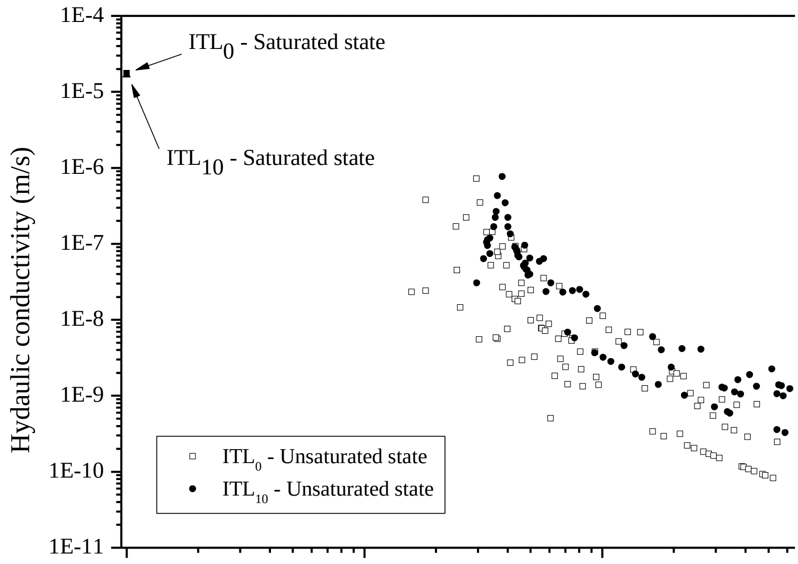


Figure 3: Comparison of hydraulic conductivity between ITL0 and ITL10

The results of hydraulic conductivity of Fines are shown in Figure 4, including the hydraulic conductivity measured at saturated state by applying a constant water pressure of 0.7 kPa: $2.6\times10^{-6}$ m/s. Albeit the large data scatter, a clear trend can be observed: as for the natural interlayer soil, the hydraulic conductivity increased when the suction decreased.

It is worth noting that the results obtained for the two drying paths are quite similar. The same conclusion can be drawn for the two wetting paths.

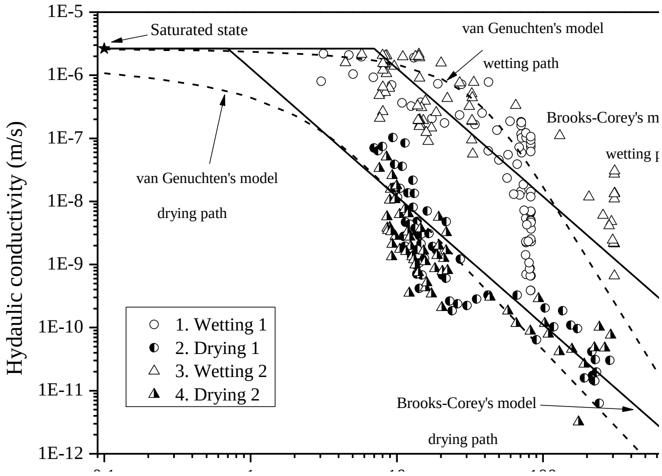


Figure 4: Hydraulic conductivity of Fines, obtained with drying/wetting cycles

In Figure 5, the hydraulic conductivity of $ITL_{10}$ and *Fines* is plotted versus suction. It can be observed that in unsaturated state the wetting and drying curves of the interlayer soil are quite close to those of *Fines*, suggesting that the hydraulic conductivity of the interlayer soil is mainly governed by the hydraulic conductivity of the fines contained in it. In other words, in unsaturated state, water transfer in the interlayer soil takes place mainly through the network of pores between fine particles, coarse elements like ballast behaving as inert materials. By contrast, in saturated state, a value of $1.67\times10^{-5}$ m/s was obtained for $ITL_{10}$, higher than the value for *Fines* ($2.6\times10^{-6}$ m/s). This difference is considered as being significant because as opposed to the determination of unsaturated hydraulic conductivity, the determination of saturated hydraulic conductivity can be deemed accurate. The higher value for $ITL_{10}$ can be explained as follows: the macro-pores in $ITL_{10}$ are larger than those in *Fines* and water flow in saturated state took place mainly through macro-pores. Thereby, the water flow mechanism in saturated state is different from that in unsaturated state.

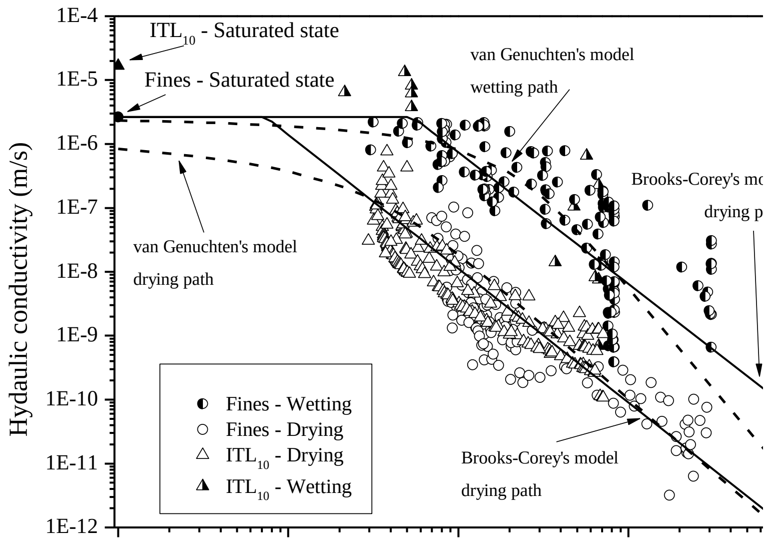


Figure 5: Comparison of hydraulic conductivity between ITL10 and Fines

From a practical point of view, Figure 5 shows that to determine the unsaturated hydraulic conductivity of interlayer soils, it is not necessary to use large-scale experimental devices to match the soil grain size; smaller devices can be used to determine their hydraulic conductivity by testing the fine particles only, provided that equivalent dry density is accounted for. This is however not valid for saturated state.

## 4. Conclusions

Infiltration tests were performed on the interlayer soil ($ITL_0$) and its derived soils - adding 10% of sub-grade to form $ITL_{10}$ and sieving $ITL_{10}$ at 2 mm to form *Fines*. Two wetting/drying cycles were applied for each test. The obtained results allowed the effect of fine particles on the water retention capacity and hydraulic conductivity of interlayer soil to be analyzed.

The effect of wetting/drying cycles on hydraulic conductivity was found negligible - the results of the first cycle are quite similar to those of the second cycle, suggesting an insignificant microstructure change by wetting/drying cycles.

Hysteresis exists for both the soil water retention curve and the hydraulic conductivity changes with suction. The wetting process was found to be much faster than the drying process, and the hydraulic conductivity during wetting is always higher than that during drying. This can be explained by the effect of ink-bottle and the difference between the water transfer through the network of macro-pores and micro-pores.

Adding 10% fine particles does not induce significant changes in hydraulic conductivity. In saturated state, the hydraulic conductivity of natural interlayer soil is $1.75\times10^{-5}$ m/s, while the value of the soil with 10% fines added is $1.67\times10^{-6}$ m/s. In unsaturated state, even though the results are little scattered, the results of $ITL_{10}$ are within the variation range of the results of $ITL_0$. However, it is worth noting that the mean value of $ITL_{10}$ is slightly greater than that of $ITL_0$.

The results of unsaturated hydraulic conductivity curves of $ITL_{10}$ and *Fines* showed a good agreement, regardless of the drying or wetting paths. This suggests that water transfer in the unsaturated interlayer soil takes place mainly through the network of pores between fine particles, coarse elements like ballast behaving as inert materials. On the contrary, in saturated state, a higher value was obtained for $ITL_{10}$, suggesting that in this case the hydraulic conductivity is mainly governed by the water flow through macro-pores. Thereby, the water flow mechanism in saturated state is different from that in unsaturated state. From a practical point of view, this finding shows that to determine the unsaturated hydraulic conductivity of interlayer soils, a device as small as the small-scale infiltration cell can be employed by testing the fine particles only, provided that equivalent dry density is taken into account. However, this is not valid for the determination of saturated hydraulic conductivity.

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