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Hydraulic Characterization of a Pervious Concrete for Deep Draining Trenches

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ABSTRACT

Reduction of pore water pressures is a useful strategy to improve the stability of slopes. Deep draining trenches can be used for this scope. For the realisation of deep trenches, the usual conventional construction techniques are not adequate and the use of adjacent vertical panels, built by means of the methods well established for diaphragm walls, is necessary. However, unbonded materials (i.e. gravels) cannot be used, since the excavation of a panel adjacent to already built ones will cause instability. For this scope a bonded material such as the pervious concrete can be used. It must have high permeability, filtering capacity in order to prevent the internal erosion of the soil in which the trench drain is installed, sufficient shear strength after a short curing time avoiding the instability of adjacent previously built panels. This paper reports the hydraulic characterization of two mixtures of pervious concrete carried out in the laboratory. The hydraulic conductivity has been measured in saturated conditions. Then, the water retention functions of the mixtures have been experimentally deduced, by investigating different calculation options, and their impact on the simulation of seepage processes through an unsaturated soil mass, in which an ideal trench is located, has been studied.

KEYWORDS

Pervious concrete; deep trenches; drainage; porosity; hydraulic conductivity; suction.

INTRODUCTION

The stability of soil slopes can be effectively enhanced by reducing the pore water pressures within the soil mass, since its shear strength depends on the effective stresses (Terzaghi, 1950). For this purpose, different solutions can be adopted, such as draining galleries, sub-horizontal drainholes and draining trenches (Kenney et al., 1977; Nonveiller, 1981; Lau and Kenney, 1984; Burghignoli and Desideri, 1987; Di Maio et al., 1988; Nakamura, 1988; Rahardjo et al., 2003; González de Vallejo et al., 2005; Tsao et al., 2005; D'Acunto and Urciuoli, 2006; Valore and Ziccarelli, 2015; Cotecchia et al., 2016). Draining trenches, also called trench drains (Hutchinson, 1977), essentially working based on gravity seepage, are often the most convenient solution when the slope is not steep or very steep. For excavations deeper than 5-6 m, draining trenches are usually built by means of the same equipment available for the realisation of secant piles and diaphragm walls.

As it is well known, the construction phases of a deep drain trench (consisting of contiguous vertical panels) are the following:

a) the odd panels (panels 1 and 3, Fig. 1) are first constructed;

b) afterwards the even panels are realised (panel 2 between the two already realised panels 1 and 3 in Fig. 1).

In the case of Fig. 1a, even if the excavation is performed in presence of temporary support, for example by using polymeric slurry, instability of the filling of panels 1 and 3 may occur when it is made of cohesionless material (Valore et al., 2017b). If the filling material has sufficient shear strength and stiffness, the excavation of the intermediate panel (panel 2 in Fig. 1b) can be carried out without instabilising the already built panels 1 and 3. Partially bonded granular particles (involving true cohesion), interconnected pores and good permeability characteristics are the other requirements of a good filling material. For these purposes the pervious concrete can be effectively employed. Pervious concrete has long been used in other fields of civil engineering, such as draining road pavements, residential roads, driveways, sidewalks, tennis courts, sustainable constructions, etc.. Research has been extensively performed in those fields, essentially focusing on no-fines concrete (containing no or small amounts of sand) which has high permeability (Tennis et al., 2004; Haselbach et al., 2006; Kevern, 2006; Schaefer et al., 2006; Chen et al., 2008; Collins et al., 2008; Haselbach, 2010; Martin III et al., 2014; Mrakovcic et al., 2014; Chandrappa and Biligiri, 2016).

Pervious concrete differs from the conventional concrete in some properties such as lower density (1400-2000 kg/m^3), higher porosity and (normally) lower compressive strength (Ghafoori and Dutta, 1995; Abadjieva and Sephiri, 2000; Mageswari et al., 2016). The porosity of pervious concrete ranges from 15 to 30% (Haselbach and Freeman, 2006; Neithalath et al. 2010); the diameter of pores ranges from 1.5 to 8 mm (Sommerville et al., 2011; Martin III et al., 2013; Torres et al., 2015). Moreover, it is a good environmental and sustainable material (Neithalath, 2004; Goel, 2006; Neithalath et al., 2010; Haselbach et al., 2011; Shu et al., 2011; ACPT, 2012; Nemirovsky et al., 2013; Barnhouse and Srubar, 2016). However, when employed as filling material for draining trenches, it must protect the soil surrounding the trench (i.e. the soil in which the trenches are installed) and hence it must also have good filter properties.

Valore et al. (2017b) reported an extensive laboratory investigation on the mix-design of pervious (or permeable) concrete that is able to meet both drainage and filter requirements which are well known in the field of earth dams (Fell et al., 2014), with reference to the saturated material. The results reported by Valore et al. (2017b) suggest that a pervious concrete, in order to satisfy the above-mentioned requirements, must be realised with coarse aggregates (particle size typically from 2 to 60mm), sand (0.06 < *d* < 2 mm), cement and water. The addition of sand, or fine gravel (particle size from 2.5-5mm), is necessary when the pervious concrete has to work both as draining material and as protective filter. Results of this study also confirm the high variability of the hydraulic and mechanical properties with respect to conventional concrete. Some aspects, however, need to be thoroughly investigated, especially with regard to the partial saturation, which represents a condition that may occur in situ, at least temporarily and in some portions of the trenches. Besides, experimental research is needed to deepen the knowledge on the clogging resistance of the pervious concrete, especially for applications of draining trenches for clayey soils, and therefore on durability and environmental sustainability of this type of remedial works. Moreover, further research is necessary for a deeper study of the three dimensional variability of the hydraulic and mechanical characteristics when the concrete is cast in place and involves volumes much greater than those of laboratory specimens. This last point, along with the in situ installation technologies, will not be discussed here since they are out of the scope of this research. In this paper, results of an experimental study on the hydraulic (in both saturated and unsaturated conditions) properties of the pervious concrete and of a numerical study on the influence of these properties on the seepage regime within unsaturated soil mass, in which a trench drain is installed, are shown and discussed.

The hydraulic characterization for unsaturated conditions has been carried out on specimens of two different mixtures (two specimens for each mixture), while, for the determination of the saturated hydraulic conductivity and the mechanical properties of the mixtures, thirteen and sixteen specimens have been used, respectively. With respect to the unsaturated hydraulic characterization, although the number of the tested specimens is not high, also due to the time-consuming procedure, the authors consider the adopted methodology useful, particularly when stating the van Genuchten fitting parameters which are more affected by different options of interpolation. Indeed, the results should inform further and more extensive investigations.

MATERIALS

The studied pervious concrete is quite different from the common no-fines concretes, since the percentage of sand is predominant or very significant among the aggregates (Fig.2).

It has been made by using high early strength Portland cement Tecnocem II B-LL 32,5 R, (EN 197-1 – Cem II / B-LL 32,5). The cement composition, in terms of mass, is characterized by clinker (65% - 79%), limestone (21% - 35%), TOC (total organic carbon, ≤ 0.20%), minor constituents (including sulphates such as SO3, chlorides ≤ 0.10%). The aggregates are calcareous gravel and silica sand.

The grain size distribution of each aggregate and the resulting grading of the mixtures M1 and M2 are shown in Fig. 2. The composition of mixture M1 is the following: gravel 1 (d_{50}=7.7mm) 30% in weight, sand 1 (d_{50}=0.95mm) 70% in weight; that of mixture M2 is the following: gravel 2 (d_{50}=2.5mm) 50% in weight, sand 2 (d_{50}=0.45mm) 50% in weight. Further physical characteristics of the mixtures are summarized in Table 1.

As can be observed from Fig. 2, the grain size distribution of both mixtures M1 and M2 is gap graded. These particular granulometric distributions of the aggregates give rise to size and distribution of interconnected pores of the pervious concrete providing excellent permeability and resistance to clogging (Valore et al., 2017b).

All the specimens have been cast into testing cylindres (cylindrical PVC tubes) and gently compacted with three hammer hits. The specimens of mix M1 and M2 have been cured in air in the laboratory at a temperature of 20±1 °C and relative humidity of 45-50%. Other specimens, of the same mixture, have been put into pure water after 1 day since their preparation and left to cure completely submerged in the same water. The last represents a very extreme condition for the concrete of the trench, but allows to determine the minimum values of its mechanical properties. In fact, it is well known that the mechanical properties of the concrete (i.e. compressive strength and stiffness) are influenced by the water in which the curing takes place. In case of curing in pure water, the leaching of the free calcium hydroxide causes a reduction of strength.

The physical characteristics of the investigated specimens (Fig. 3) used for the unsaturated hydraulic characterisation are summarised in Table 1. The total porosity *n* was determined following the water displacements methodology suggested by Montes et al. (2005). These values of *n* are quite higher than the previously mentioned porosity range observed for pervious concretes used in other fields of civil engineering.

The most important characteristics governing both compressive strength and hydraulic conductivity of this kind of material are the overall porosity and the size and distribution of voids and interconnected voids (Ghafoori and Dutta, 1996; Abadjieva and Sephiri, 2000; Sommerville et al., 2011; Alam et al., 2012; Thakre et al., 2014; Ushane et al., 2014).

As can be observed in Fig. 4, the two mixtures show relatively different stress-strain curves, though many initial features are quite similar. The compressive strength σ_f of the M1 mixture is 1.16 MPa, while that of the M2 mixture is 1.92 MPa, measured at values of the axial strain of 0.7% and 0.4%, respectively. The secant stiffness *E* of M1 is 166 MPa while that of M2 is 480 MPa. Both compressive strength and stiffness of the two mixtures depend on size and distribution of pores that are relatively different, although their total porosities are similar. The maximum increase of both strength and stiffness occurs in the early days of curing time. Considering all the results obtained in the tests, the uniaxial compressive strength is ranging from 0.5 to 3 MPa; the minimum values were recorded for specimens after two days of curing time. For the same mixtures and for the same curing time, differences even higher than 50% are recorded, depending on the overall porosity and size of voids. The compressive strength and stiffness of the mixtures ensure that the geotechnical system made by the panels (filled of pervious concrete) and by the surrounding soils will have adequate safety factors. The uniaxial compressive strength values fall in the typical ranges of σ_f of no-fines concretes with similar void ratio (Ghafoori and Dutta, 1996; Abadjieva and Sephiri, 2000; Kevern et al., 2008; Sommerville et al., 2011; Alam et al., 2012; Kevern and Farney, 2012; Singh and Scanlon, 2013; Thakre et al., 2014; Ushane et al., 2014; Zhong and Wille, 2016). Poisson's ratio ν can be assumed equal to that of the normal concrete (Mahesh and Lavanya, 2016) and equal to 0.2.

Considerations on the depth of the panels of the draining trenches that can be reached by using the pervious concrete as filling material can be done. It is well known that the height of a slope depends on the geometry of the problem, the mechanical properties of soils or rocks forming the slope, the presence of layering and discontinuity and, eventually, constitutive minor geological and geotechnical details (Terzaghi, 1929; Rowe, 1972; Leonards, 1982), the influence of the latter being sometimes very significant (Valore et al., 2017a; Ziccarelli et al., 2017). For homogeneous vertical slopes, such as the sides of panels 1 and 3, when the excavation of panel 2 is realized between them (see Figure 1b), and assuming a purely cohesive behaviour for the concrete, a partial factor of safety equal to one and neglecting positive 3D effects, the limit height, h_{lim}, is (Pastor et al., 2000):

$$h_{lim} = \frac{3.8\,c}{\gamma_c} \qquad \text{(Eq.1)}$$

in which c ($c=\sigma_f/2$) is the true cohesion of the concrete and γ_c is its unit weight.

Assuming a conservative value of the uniaxial compressive strength σ_f of 0.3 MPa (lower than the minimum value obtained after a curing time of 2 days in pure water), a critical value h_{lim} of 30m results for γ_c=19 kN/m^3. This calculation demonstrates that very deep trenches can be built safely and without long delays in the excavation of the even (or intermediate) panels as defined in Fig. 1. This allows an efficient and relatively inexpensive site planning.

METHODOLOGY

The hydraulic conductivity of pervious (no-fines) concrete has been studied by several authors with both the falling head permeameter and the constant head permeameter (Neithalath, 2004; Kevern, 2006; Haselbach, 2010; Deo et al., 2010; Coughlin et al., 2012; Martin III et al., 2014; Kevern, 2015; Chandrappa and Biligiri, 2016; West et al., 2016). In the present work, the hydraulic conductivity k_s of saturated specimens has been determined by means of the falling head permeameter, using the relative well known relationship. This relationship is valid under the assumption of laminar flow and the validity of Darcy's law. Montes and Haselbach (2006) demonstrated that the flow in pervious (no-fines) concrete normally falls within the laminar or at most in the transitory domain. Hence, it is applicable for the pervious concrete used in the experiments being the mean particles (and consequently the size of pores) smaller than the ones by which the no-fines concrete is made.

The analysis of the pervious concrete retention properties has been carried out, for specimens of mixture M1 (labelled as MP53 and MP5, Fig. 3) and M2 (labelled as MP54 and MP56, Fig. 3), by using the filter paper method (Chandler and Gutierrez, 1986). All the specimens have been initially subjected to the monitoring of the weight in order to obtain a reliable evaluation of the hygroscopic weight. This operation has been necessary because it was not possible to put the specimens in the oven to determine the dry weight since this could have led to the deterioration of the physical and chemical properties of the concrete.

The volumetric water content θ (equal to nS_r, where n is the porosity and S_r is the saturation degree) has been determined under the hypothesis that the void ratio remains constant during wetting due to the stiffness of the material. This hypothesis has been experimentally checked after the tests and it will be discussed later. Consistently, it has been possible to determine the volume of water to be dispensed to each specimen during the application of the filter paper method to induce a progressive wetting.

The suction ($s=u_a-u_w$,where u_a is the air pressure and u_w is the water pressure) measurements have been performed by means of the in-contact filter paper method (Chandler and Gutierrez, 1986) and they are representative of the matrix suction. The filter paper calibration employed to deduce the suction values is the one reported by Chandler et al. (1992) for filter paper Whatman n.42.

These tests have been carried out following the procedure suggested by Ridley (1993), which makes use of appropriately sealed perspex devices to place filter paper disks in contact with both the top and bottom of the specimen. A cling film has been used to isolate the specimens from the external environment, for a period of time greater than or equal to eight days.

During the tests, the estimated volume of water has been dispensed to the specimen via a syringe and the filter moisture, after equalization, has been measured at both top and bottom of the specimen and the corresponding suction has been determined as the average of the two values.

When the suction became negligible, it was possible to start the drying. The specimens have been left to dry for a period of time greater than or equal to two weeks. In this case, it was possible to calculate the average value of suction for each step of drying. The specimen MP54 has been subjected to a "3rd wetting" after previous cycles.

At the end of the tests, the specimens have been disgregated and measurements of their weight after drying in the oven at the temperature of 105°C have been carried out to allow the determination of the real dry weight. Moreover, a free swelling test carried out on a disgregated specimen, after removing the coarser fraction, has corroborated the hypothesis that the material has low swelling ability: a material column of about 30 mm diameter and 70 mm height has been put into a graduated cylinder and soaked with water and no swelling has been observed. This fact, along with the condition of partially bonded material for the pervious concrete, justifies the rigid skeleton assumption.

In the following, the pervious concrete hydraulic behaviour will be shown and discussed in terms of both saturated permeability and *volumetric water content* (θ) versus *suction* (s) relationship (i.e. water retention curve,WRC). Thereafter, the results of 2D finite element (FE) analyses of the transient seepage, carried out by means of the software SEEP/W (Geo-Slope 1991-2002) with the aim of determining the performance of the draining trench and the pore water distribution in a soil mass, will be illustrated.

EXPERIMENTAL RESULTS AND DISCUSSION

Typical results of the permeability tests carried out on different specimens of the mixture M1 and M2 (similar to MP53-54-55-56, used for measuring the WRC) are shown in Figs. 5 and 6. In the figures, the velocity v and the saturated hydraulic conductivity k_s as a function of the hydraulic gradient i are reported. For both mixtures, velocity and hydraulic conductivity depend on the hydraulic gradient i as found by other researchers (Martin III et al., 2014; West et al. 2016; Valore et al., 2017b). This non linearity depends on the mix of the concrete which influences the flow characteristics such as the tortuosity of the seepage paths, the effective porosity (i.e. the porosity related only to the interconnected pores) and some possible turbulence, etc. (Chandrappa and Biligiri, 2016; West et al., 2016).

For tests performed on the coarser mixture (M1), the saturated hydraulic conductivity k_s ranges from values of about 0.003 m/s, corresponding to the higher values of i reached in the tests (i=5-6), to values of about 0.0085 m/s related to the lower values of i (i=0.1-0.2), as shown in Fig. 5. For tests performed on the finer mixture M2, k_s ranges from values of about 0.0002 m/s for $i \cong 1$ to values of about 0.00035 m/s for $i \cong 0.1$, as reported in Fig. 6.

The mean values of saturated hydraulic conductivity k_s obtained for the two mixtures M1 and M2 are summarized in Table 2. For values of the hydraulic gradient ranging between 3 and 6, the permeability k_s of the specimens of mixture M1 ranges from 0.003 to 0.004 m/s, while the permeability of the specimens of mixture M2 is almost constant with values of k_s of about 0.00022 m/s for i ranging between 1 and 6. These values of the coefficient of permeability fall within a permeability range lower than that relative to no-fines concrete used for example for pavement roads (Shaefer et al. 2006; Chen et al., 2008; Haselbach, 2010; Sriravindrarajah et al. 2012; Mrakovcic et al., 2014).

Considering that draining trenches are most frequently installed in fine grained soils, such as clays, silts and fine sands in which the seepage velocities are low, and that for practical applications the interesting values of the hydraulic gradient are also low (i=0.1-0.5), both mixtures M1 and M2 satisfied the requirement of permeability that the filling material of the trenches must assure.

Fig. 7 shows the plot θ versus s, which describes the retention behaviour of the specimens MP53, MP54, MP55 and MP56. The experimental points labelled as “drying” refer to states near to the shrinkage limit and, therefore, these points have been considered to lie on the initial part of the wetting branch. Consequently, no consideration about the magnitude of the loop of hydraulic hysteresis has been made.

It is evident that the material reaches very low suction values during wetting at degrees of saturation not higher than 30%. This behaviour is typical of several coarse-grained soils (Cafaro et al., 2008; Bottiglieri, 2009) and for the studied material it seems to be even more marked. This aspect suggests that for this material it is not necessary that the voids between the grains reach full saturation to lead the overall suction to negligible values.

The retention curves of the two mixtures have been deduced, according to the van Genuchten model, by fitting the experimental water retention data. The interpolation of the experimental water retention curve has been performed by using the RETC software (van Genuchten et al., 1991), through the use of van Genuchten’s and Mualem’s models for the retention function (eq.2) and the conductivity function (eq.3), respectively:

$$\vartheta_w = \vartheta_r + (\vartheta_s - \vartheta_r)\left[\frac{1}{1+\left(\alpha(u_a-u_w)\right)^{n'}}\right]^m \qquad \text{(Eq.2)}$$

$$k_w = k_s\left(\frac{1-\left(\alpha(u_a-u_w)\right)^{n'-2}\left[1+\left(\alpha(u_a-u_w)\right)^{n'}\right]^{-m}}{\left[1+\left(\alpha(u_a-u_w)\right)^{n'}\right]^{2n'}}\right) \qquad \text{(Eq.3)}$$

in which θ_s is the saturated volumetric water content, θ_r is the residual water content and α, m, n' are fitting parameters. The parameter n' depends on the pore size distribution (van Genuchten, 1980) and it controls the shape of the curve, the parameter m could be related to the parameter n' through the Mualem model (i.e. m = 1-1/ n') and α is related to the inverse of the air entry suction (m^{-1}).

In the van Genuchten model, the saturated volumetric water content θ_s is the parameter value obtained when the saturation degree is equal to one and the suction value is equal to zero. Actually, different behaviour for soils can be detected in the literature. For example, it has been observed (Cafaro and Cotecchia, 2015) that, for natural clays under wetting, full saturation can be reached not at zero suction, but for a quite high suction value (Fig.8). On the other hand, it has been observed (Leal-Vaca et al., 2012) that, for silty sand under wetting, suction disappears not at full saturation but at a degree of saturation quite low (Fig.9). This experimental evidence should guide the modelling of the WRC. In Fig. 10 a possible framework for porous media under wetting is proposed: for materials with high air entry value, here defined as "right of intermediate behaviour", the van Genuchten model allows to fit the real behaviour by varying the α parameter, while for materials needing positive pore pressure to be fully saturated, here defined as "left of intermediate behaviour", the fitting could involve a volumetric water content at zero suction, θ_0, lower than θ_s.

In this work, in order to fit the retention data of the pervious concrete three different options have been identified:

a) In the first approach, the van Genuchten parameters have been deduced by fixing $\theta_s = n$ (rigid skeleton), for each data set concerning the two mixtures. Following this way, two different WRCs have been obtained, one for each mixture.
b) In the second approach, to overcome the problem related to the relatively poor data sets characterizing each mixture, the van Genuchten parameters have been obtained by optimizing θ_0 for the only data set resulting from joining of the two different sets, due to the similarity of the two mixtures. The result of this fitting approach is a unique common WRC.
c) In the last approach, the van Genuchten parameters have been deduced by fixing a common θ_0 for each data set concerning the two mixtures, but the θ_0 value comes from an optimization procedure using a unique data set arising from the joining of the two different sets. As for the first approach, two different WRCs have been obtained.

The third approach is characterized by the following logical steps:

1) When optimizing the van Genuchten parameters, to obtain two different WRCs, a non consistent $\theta_0 (\theta_0 > \theta_s)$ has been found, probably due to the relatively poor data set of each mixture;

2) For this reason, θ_0 has been fixed as a plausible value by taking only the other parameters under optimization;

3) A plausible $\theta_0$value could be assumed from the literature concerning pervious concrete. Alternatively, it could be optimized by interpolation of a unique data set (MP53-MP54-MP55-MP56) since the two mixtures are quite similar in terms of porosity;

4) In the last case, it is necessary to check if $\theta_0 \leq n$.

The fitting parameters resulting from the above-mentioned approaches are shown in Table 3.

Although the α values are consistent with the air entry range pertaining this type of granular material (Fredlund and Rahardjo, 1993), the differences in the α parameter are not negligible (Table 3). It must be underlined, therefore, that practitioners should not base the design on a unique interpolation approach.

In the following, the “approach *c*” has been used in order to study the impact of the concrete retention properties and related conductivity functions on a boundary value problem.

NUMERICAL RESULTS AND DISCUSSION

In order to deduce by numerical simulation the different hydraulic performance of the two investigated mixtures in a boundary value problem, an ideal model constituted by a natural soil has been defined: the clayey silt of Abate Alonia (Cafaro and Cotecchia, 2015), which forms a horizontal ground level and hosts a draining trench of 12 m deep and 1.5 m wide filled by pervious concrete. The geological features of this soil are described in Cotecchia and Lonoce (1963) and Monterisi (1996). The specific gravity is 2.76, the clay fraction is 8-9% and the in-situ void ratio is about 0.6.

2D FE simulations have been carried out by using the software SEEP/W. The trench has been simulated like rectangular elements 4 m deep (Fig. 11). The lateral boundaries of the mesh have been fixed at a distance of 20 m from the centre. The bottom of the mesh is impermeable and the depth of the model has been set equal to 30 m from the ground level. A water table 13 m deep below ground level has been set in the analyses and a hydrostatic profile has been assumed for the negative pore pressures.

The soil hydraulic parameters have been obtained through interpolation by using the RETC code and they are shown in Table 4, whereas in Fig. 11 a vertical cross section of the model, reporting the geometry of the draining trench and the initial boundary conditions, is presented. The interceptor drain pipe, in correspondence of which the pore pressure is imposed equal to zero, is schematically represented by the lower end of the trench in Finite Element (FE) calculation.

A wetting path has been hypothesized for the soil, e.g. as a result of an infiltration by rainfall starting from an initial suction profile, and, therefore, the wetting WRCs of the pervious concrete have been accordingly implemented in the FE calculations. A rainfall of intensity equal to 80 mm/d has been assigned at the ground surface for duration of almost 3 days. To deduce the *k(s)* functions, the employed values of the saturated hydraulic conductivity k_s have been: k_s= 0.0075 m/s for mixture M1 and k_s= 0.000285 m/s for mixture M2, based on the graphs of Fig. 5 and Fig. 6, respectively, in correspondence of an assumed hydraulic gradient of about 0.2. To simulate the transient seepage resulting from infiltration, time steps have been generated in the code: number of steps, starting time, initial increment size and expansion factor have been defined in order to obtain both good time resolution at the beginning of the process and clear evolution with time of the overall process.

This numerical analysis has been carried out with two different aims. Firstly, to point out the impact of implementing the WRC and the *k(s)* functions (*Trench Model 1*) on the seepage simulation and, hence, on the variation of pore pressure *u (x, z, t)* with respect to the analysis which, in a simplified way, models the trench as an atmospheric pressure cluster (*Trench Model 2*). This last one is the conventional way to model drains in civil engineering. Secondly, to point out the incidence of the two different pervious concrete mixtures studied when using *Trench Model 1*. Although the numerical results are tied to a specific seepage scheme, they have a useful comparative value which could assist the performance analysis of permeable concrete.

Fig. 12 shows the *pore water pressure u* versus *time* plot from the start of the rainfall, in correspondence of nodes 40, 41, 42 for mixture 1 (M1) only, for both *Trench Model 1* and *Trench Model 2*. It can be observed that for all the considered nodes, the pore pressure increases more rapidly when *Trench Model 2* is implemented in the FE calculation. It is also evident from the plot that for node 42 the suction reaches the value of zero after more than 15 hours in the case of the *Trench Model 1*, whereas for the *Trench Model 2* the suction disappears after almost 6 hours.

When predicting the safety evolution with time, it seems that implementing the hydraulic functions of the drain in the analysis could imply a non-conservative design, since suction slowly disappears. Therefore, in terms of recommendation for practitioners, this realistic approach should be used only for serviceability assessment. In this respect, more accurate numerical analyses should be addressed to study the group effect of the trenches (Cotecchia et al., 2016), the 3D and the slope effects.

As said before, a comparison between numerical predictions obtained by assuming the two different mixtures for the draining trench is also of interest. Fig. 13 reports the *pore pressure* versus *time* plot at nodes 40, 41, 42 (see Fig. 11) for the case of the *Trench Model 1*. It is evident from the plot that for all the monitored nodes the pore pressure predictions are quite similar for both mixtures until about 5-6 hours. Beyond these time values, the pore water pressures predicted with mixture M1 are lower than those predicted with mixture M2.

CONCLUSIONS

In this paper the results of a laboratory investigation on the saturated and unsaturated hydraulic properties of a pervious concrete for deep draining trenches have been reported and discussed. The importance of taking into account the partial saturation of pervious concrete (which fills a trench drain) and surrounding soils when predicting the pore water pressures for a transient regime has been stated, by showing results of numerical modelling of a boundary value problem.

On the basis of the obtained results, the following conclusions can be drawn.

The strength of the pervious concrete, even after only a few days of curing time, is enough to safely build deep trench drains, hence avoiding delays in the excavation of intermediate panels and with advantages in terms of overall costs and efficient construction site planning.
The saturated hydraulic conductivity of both mixtures of pervious concrete tested is high enough and adequate for deep trench drains installed in sandy and fine-grained soils.
The incidence of different ways of fitting the experimental data by using the van Genuchten equation has been shown, although all the calculated fitting parameters seem to be consistent with the values expected for the investigated material grading. In particular, it has been considered that the volumetric water content at zero suction differs from the saturated one and this involves substantial differences for the fitting parameters.

Results of two-dimensional FE calculations have been shown to point out the influence of the hydraulic properties on the modelling of the seepage through a draining trench placed within an ideal unsaturated soil mass during rainfall. The draining trench has been modelled both by implementing its WRC and the *k(s)* functions and by neglecting them (i.e. conventional approach). Differences in the numerical predictions arise from both the different way of modelling the trench and the different investigated composition for the pervious concrete. Difference in grading for the two investigated mixtures of pervious concrete does not seem to influence the response in terms of pore water pressures significantly, despite their differences in terms of saturated hydraulic conductivity. However, further investigations are necessary to better understand this aspect.

RECOMMENDATIONS AND FUTURE WORK

Recommendations for the design of deep draining trenches filled with pervious concrete can be provided based on this study. When predicting the transient seepage in unsaturated soil mass and, then, the evolution with time of the soil mass stability degree, it appears that implementing the hydraulic functions of the drain in the analyses could imply a non-conservative design. Therefore, this realistic approach should be followed only for serviceability assessment. Moreover, practitioners are suggested to employ several fitting approaches when deducing the WRC of the pervious concrete, since it has been shown the incidence of different interpolation options.

Future work should concern the physical modelling of pervious concrete deep draining trenches, in order to give more general meaning to the element testing results here discussed, given the non negligible variability that pervious concrete can have in-situ. In this respect, the three dimensional variability of the hydraulic and mechanical properties when the concrete is cast in place and involves volumes much greater than those of laboratory specimens should be directly investigated, by in-situ sampling.

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Table 1. Physical characteristics of the specimens of pervious concrete subjected to tests

Mixture		M1	M2
Specimens		MP53 and MP55	MP54 and MP56
Specific gravity (Gs)	-	2.62	2.65
Solid unit weight of aggregates (γ_s)	(kN/m^3)	26.7	26
Water - cement ratio (*W/C*)	-	0.4	0.4
Cement content (amount of cement per 1 m^3 of pervious concrete) (*C*)	(kg/m^3)	161.4	169.6
Dry unit weight (γ_d)	(kN/m^3)	16.4	16.5
Porosity (*n*)	(%)	39.7	37.6
Aggregates weight - total weight ratio(A/W_t)	(%)	88.5	88.5
Aggregates weight - cement ratio (*A/C*)	(%)	10.8	10.9
Water weight - total weight ratio (W/W_t)	(%)	3.29	3.28
Cement weight - total weight ratio (C/W_t)	(%)	8.23	8.21

Table 2. Saturated permeability of the two mixtures.

Mixture	k_s (m/s)	Ranges of hydraulic gradient *i*
M1	0.004	3 ÷ 6
	0.006	3 ÷ 0.1
M2	0.0002	1 ÷ 6
	0.00025	1 ÷ 0.1

Table 3. Fitting parameters for M1 and M2 experimental water retention curve: a) Approach a; b) Approach b; c) Approach c

a)

Mixture	θ_r	$\theta_S = n$	α (m^{-1})	n′	m = 1-1/n′	l
1	0.01	0.4	98.55	1.5	0.33	0.5
2	0.01	0.38	73.15	1.45	0.31	0.5

b)

Mixture	θ_r	θ_0	α (m^{-1})	n′	m = 1-1/n′	l
1 + 2	0.01	0.12	4.21	1.49	0.33	0.5

c)

Mixture	θ_r	$\theta_0 < n$	α (m^{-1})	n′	m = 1-1/n′	l
1	0.01	0.12	6.3	1.5	0.33	0.5
2	0.01	0.12	3.2	1.5	0.33	0.5

Table 4. WRC fitting parameters for the Clayey Silt of Abate Alonia (Cafaro and Cotecchia, 2015)

θ_r	θ_0	$\alpha (m^{-1})$	n'	$m=1-1/n'$	l
0.1	0.358	0.005	1.73	0.42	0.5

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Table 1. Physical characteristics of the specimens of pervious concrete subjected to tests.

Table 2. Saturated permeability of the two mixtures

Table 3. Fitting parameters for M1 and M2 experimental water retention curve: a) Approach a; b) Approach b; c) Approach c

Table 4. WRC fitting parameters for the Clayey Silt of Abate Alonia (Cafaro and Cotecchia, 2015)

Figure 1

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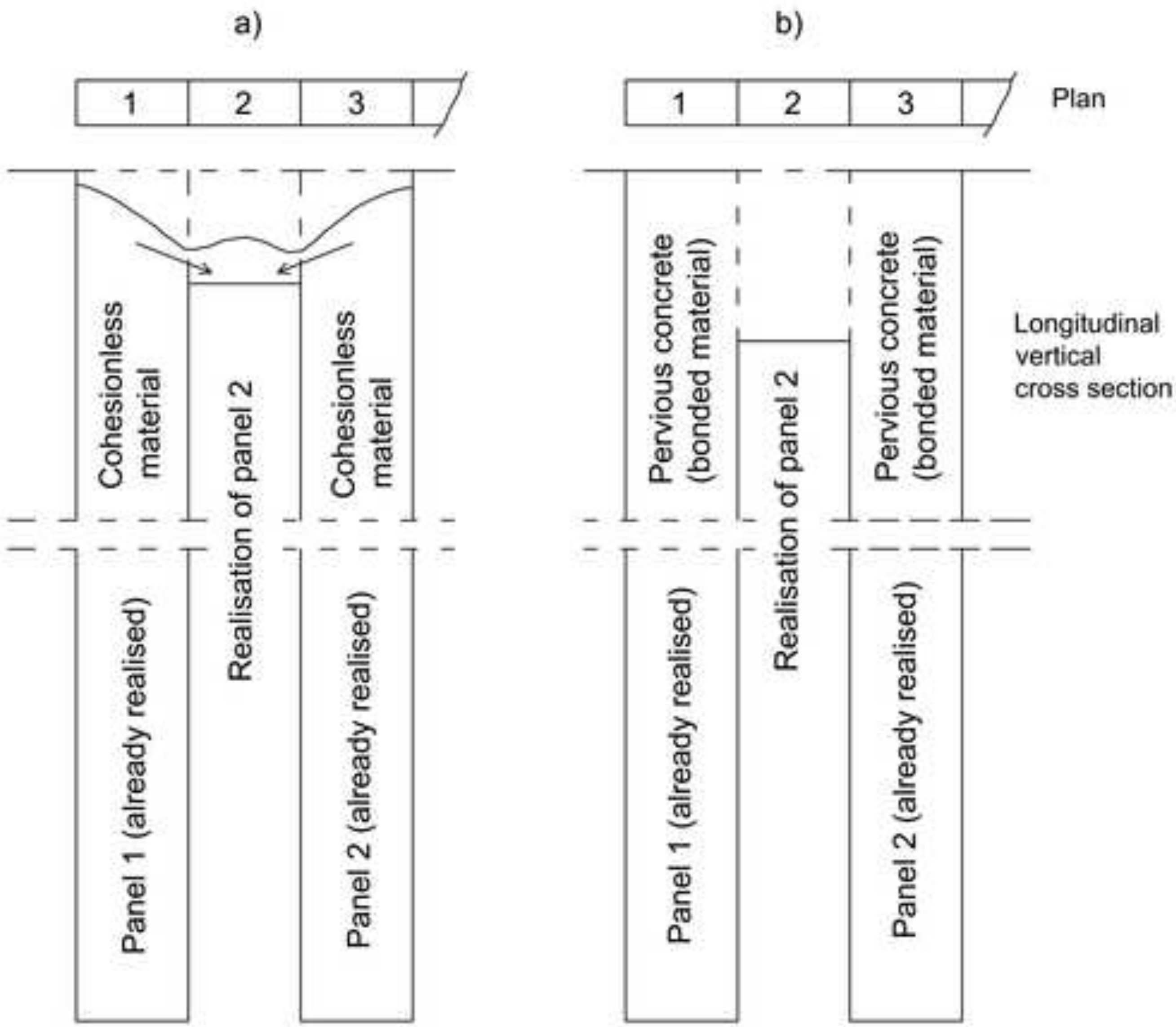

Figure 2

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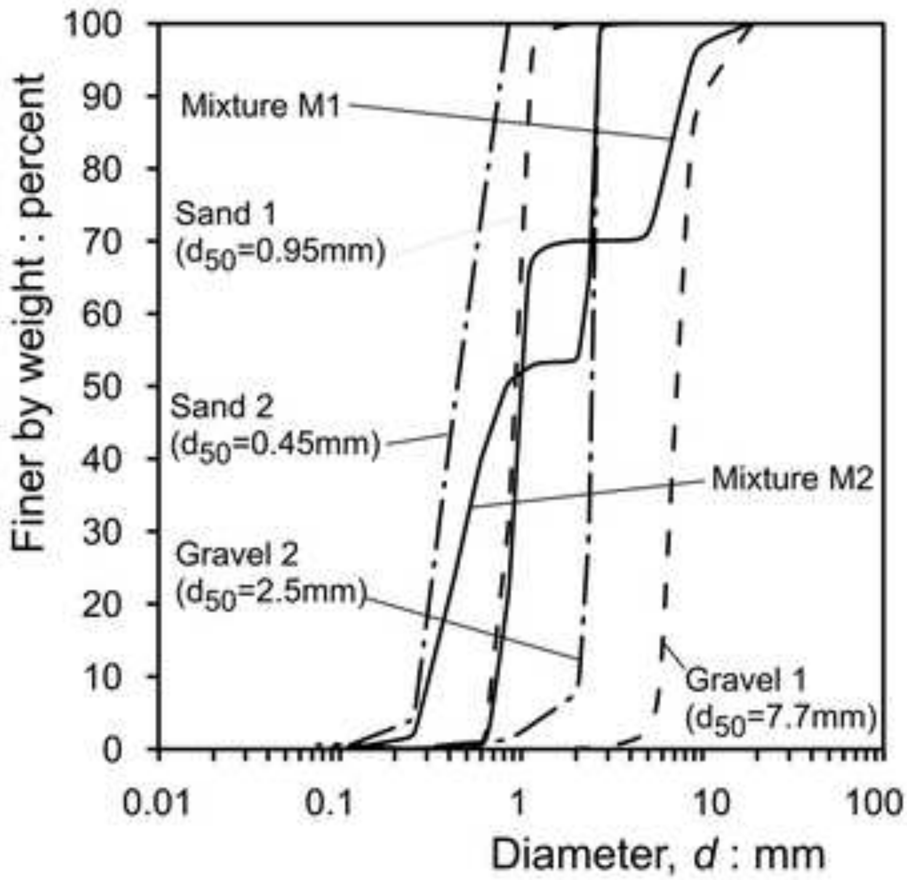
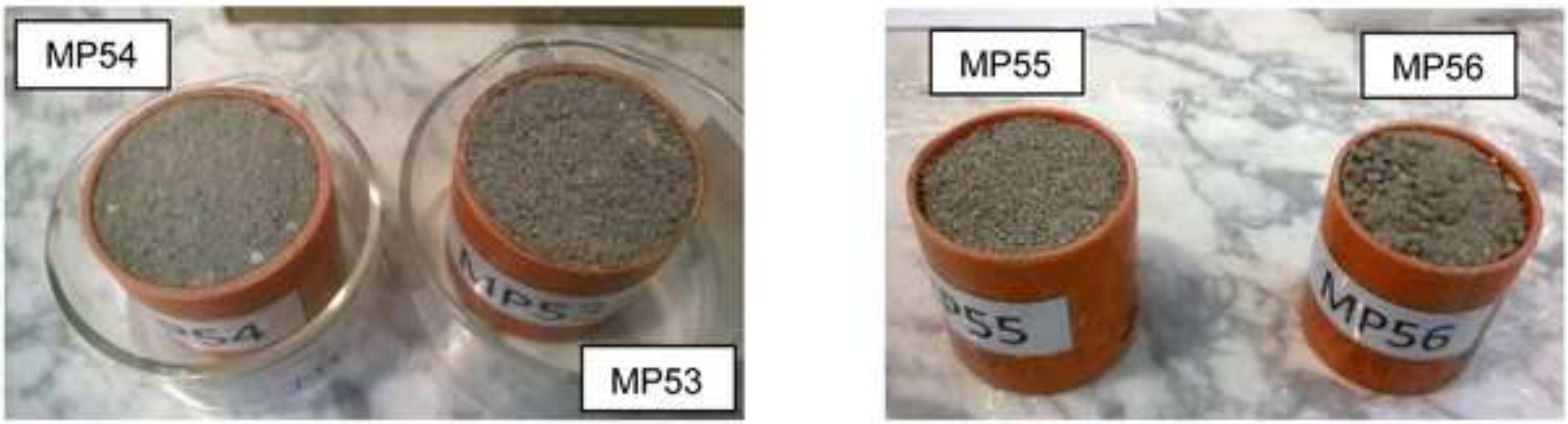


Figure 3



(a) (b)

Figure 4

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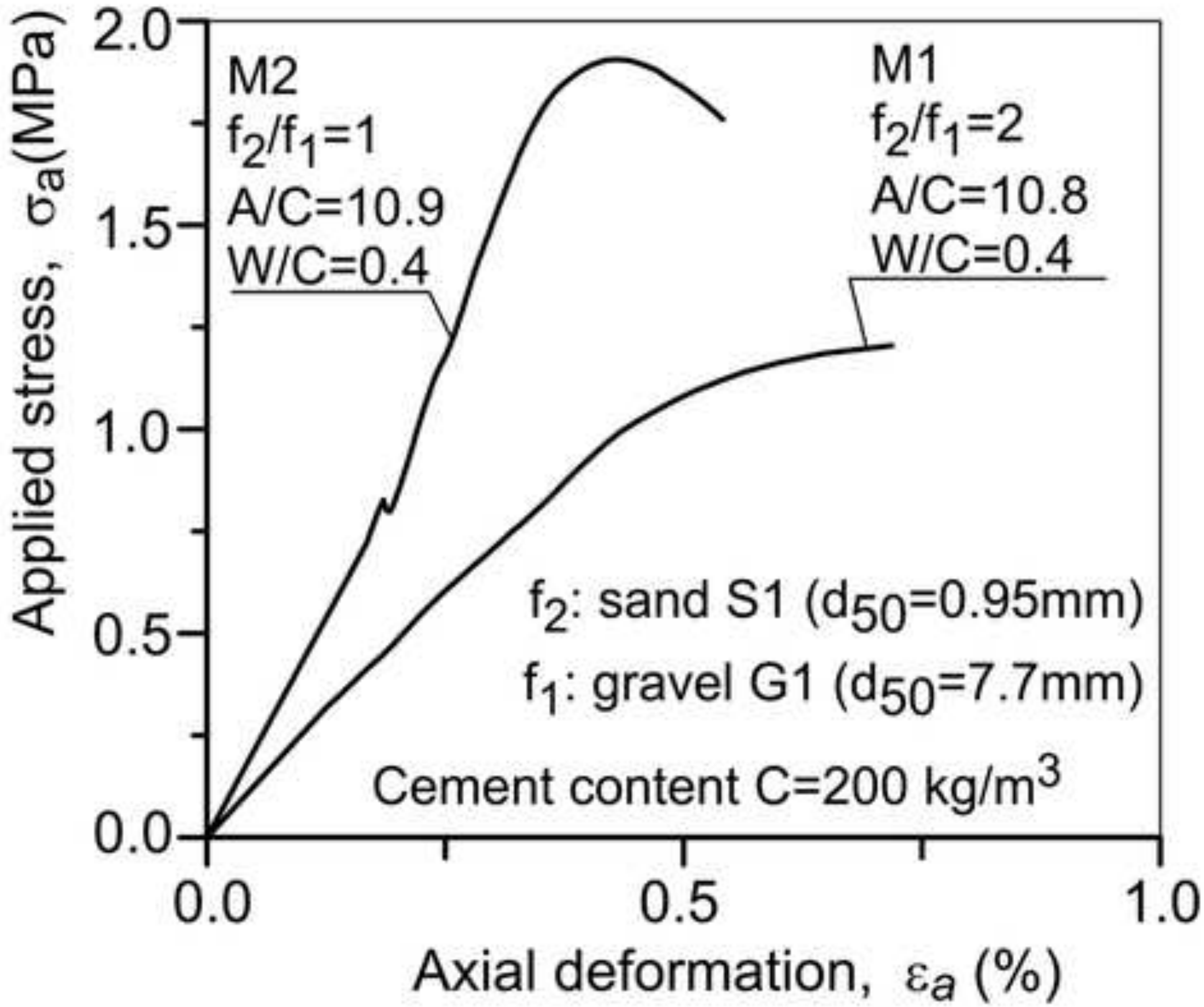
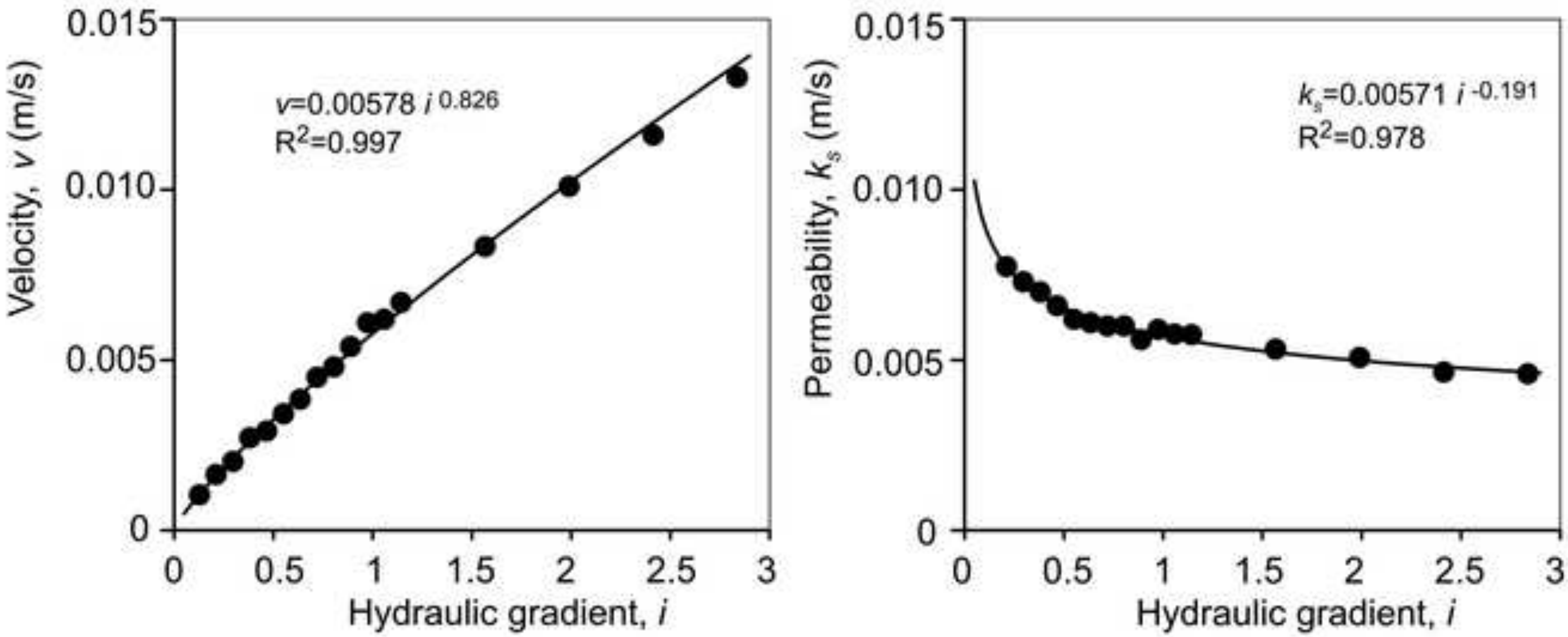


Figure 5



v=0.00578 i 0.826
R2=0.997
Velocity, v (m/s)
0.015
0.010
0.005
0
0
0.5
1
1.5
2
2.5
3
Hydraulic gradient, i
ks=0.00571 i -0.191
R2=0.978
Permeability, ks (m/s)
0.015
0.010
0.005
0
0
0.5
1
1.5
2
2.5
3
Hydraulic gradient, i

Figure 6

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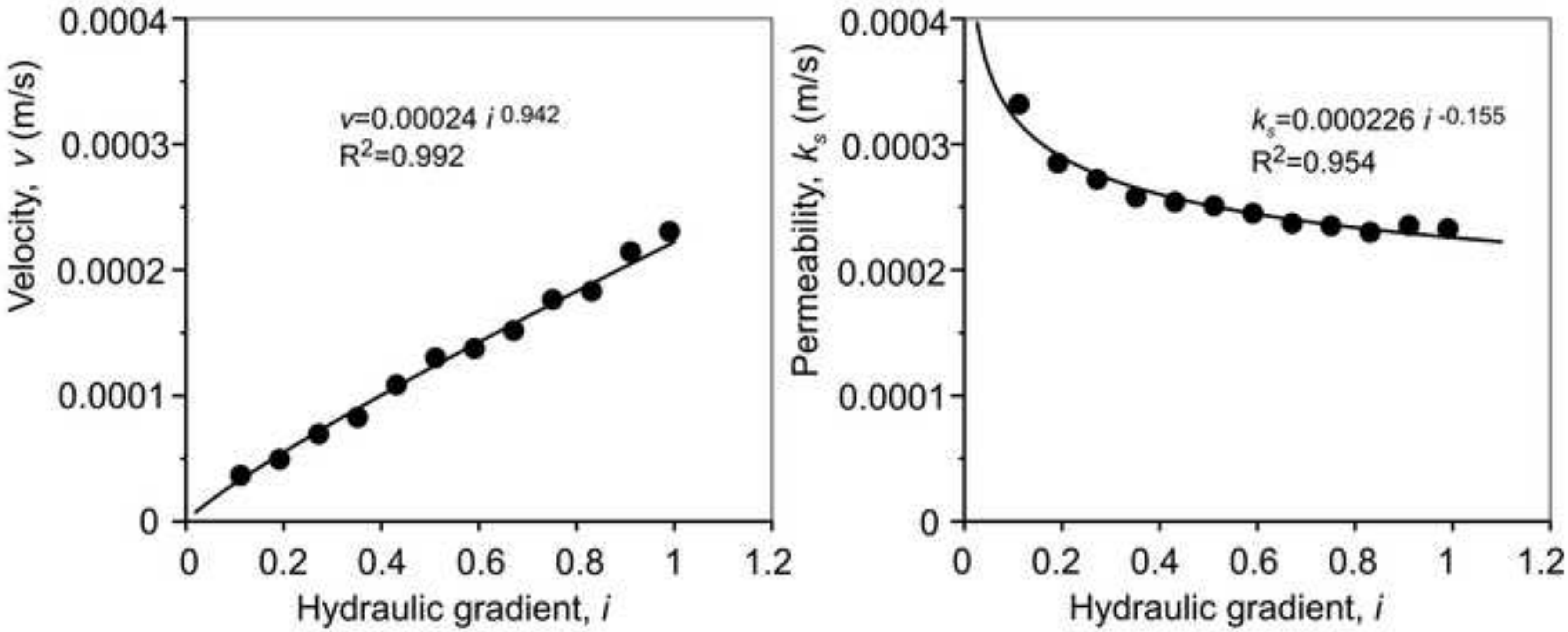

Figure 7

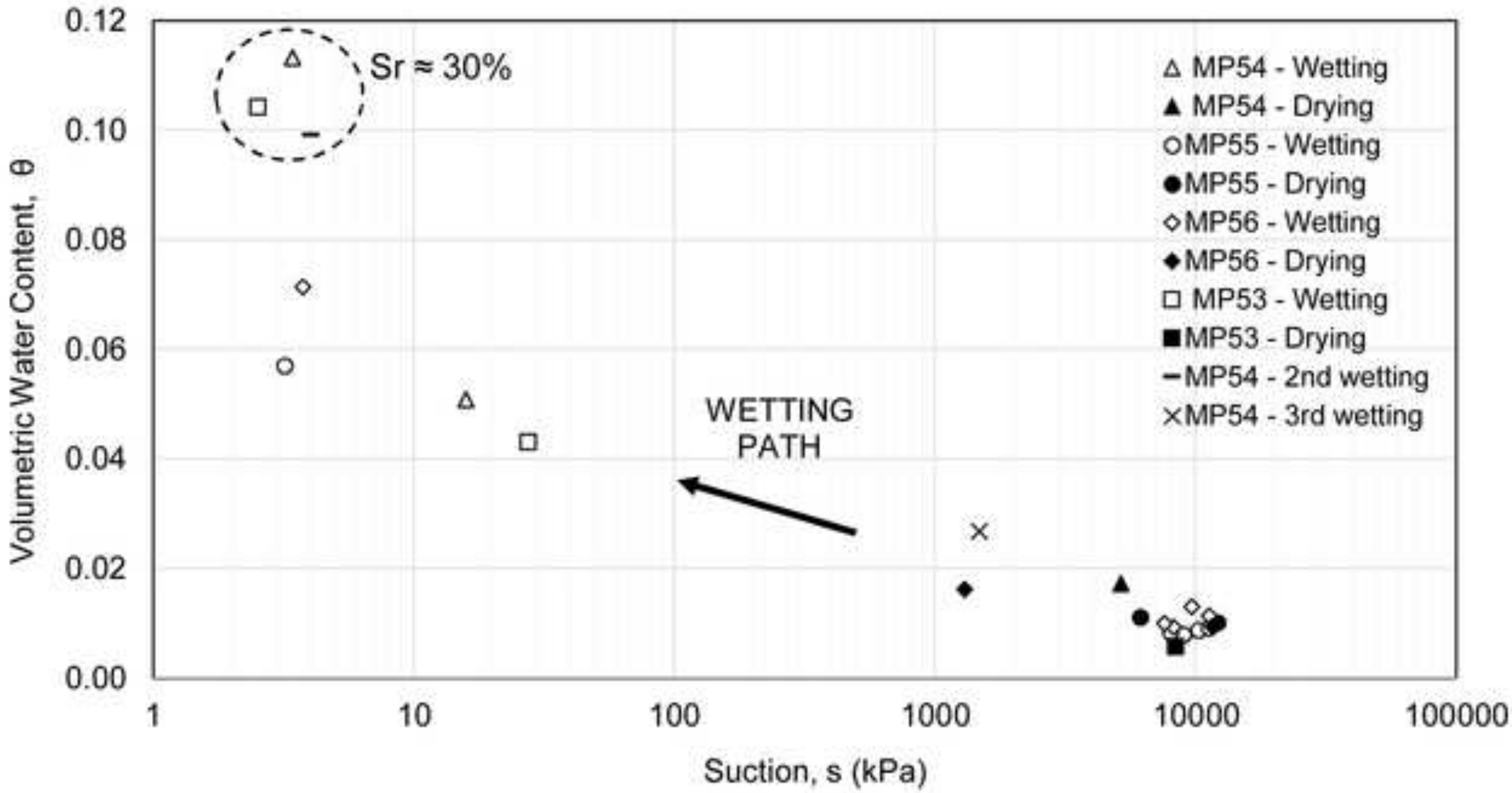
0.12
0.10
0.08
0.06
0.04
0.02
0.00
Volumetric Water Content, θ
Sr ≈ 30%
WETTING
PATH
MP54 - Wetting
MP54 - Drying
MP55 - Wetting
MP55 - Drying
MP56 - Wetting
MP56 - Drying
MP53 - Wetting
MP53 - Drying
MP54 - 2nd wetting
MP54 - 3rd wetting
1
10
100
1000
10000
100000
Suction, s (kPa)

Figure 8

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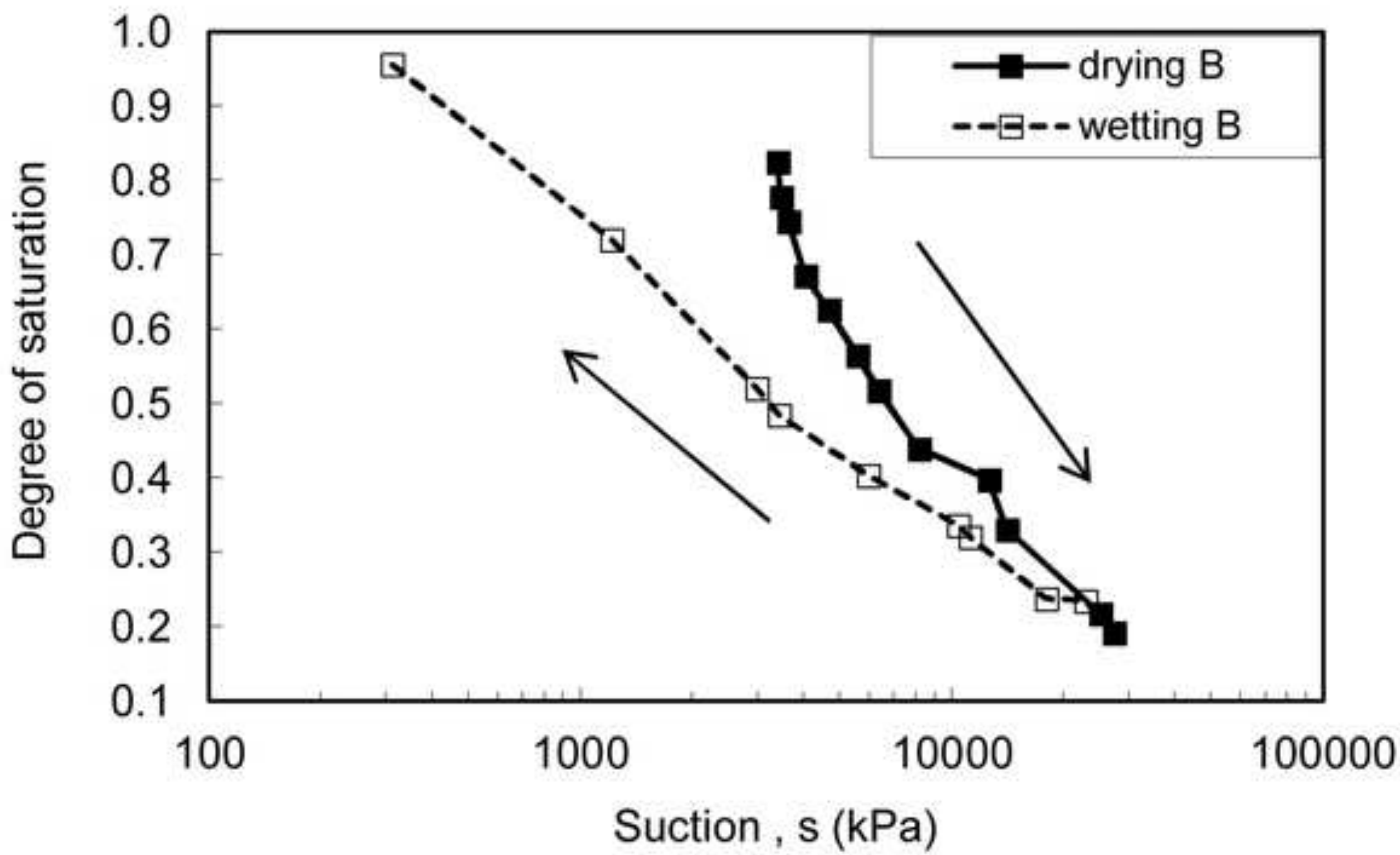
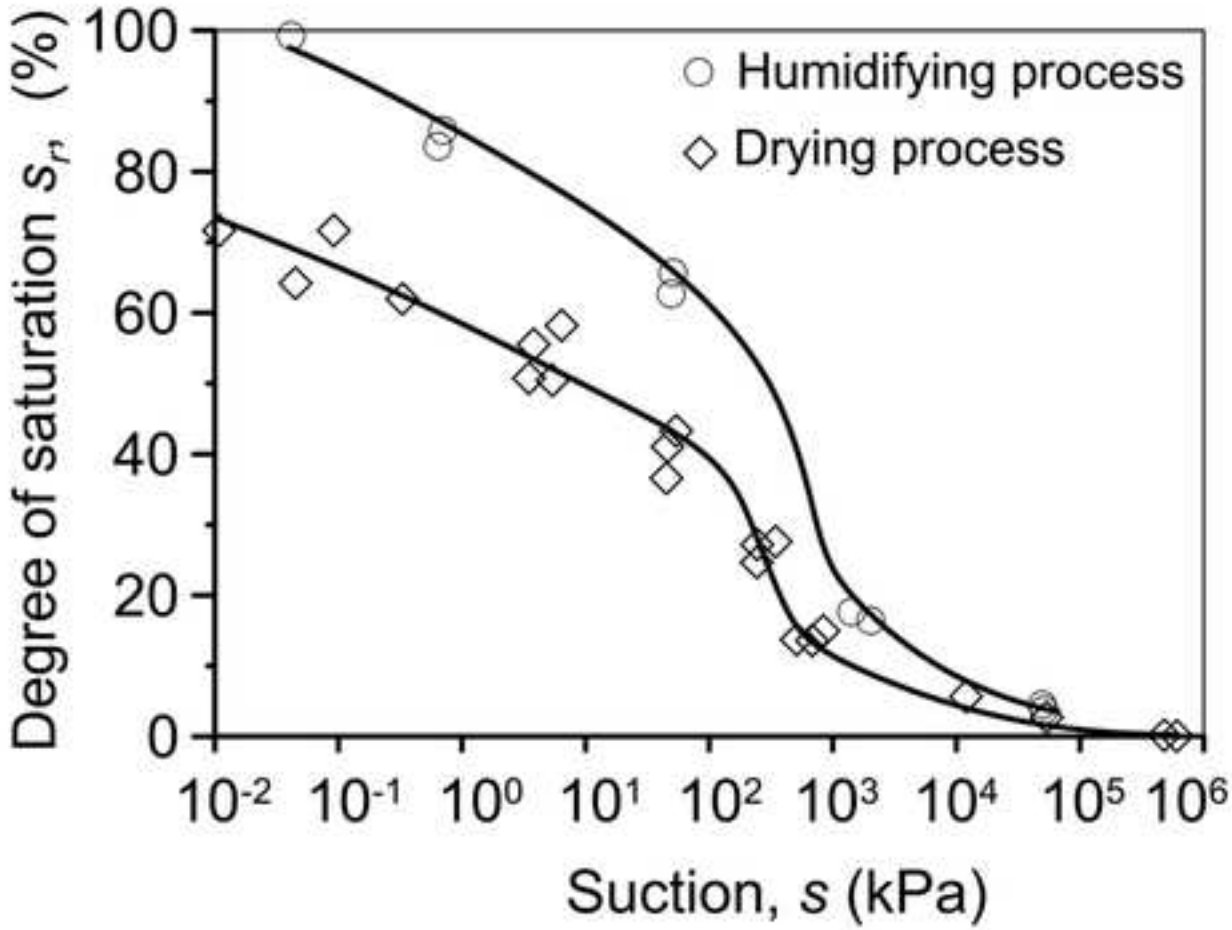




Humidifying process
Drying process
Degree of saturation s_r, (%)
100
80
60
40
20
0
10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3} 10^{4} 10^{5} 10^{6}
Suction, s (kPa)

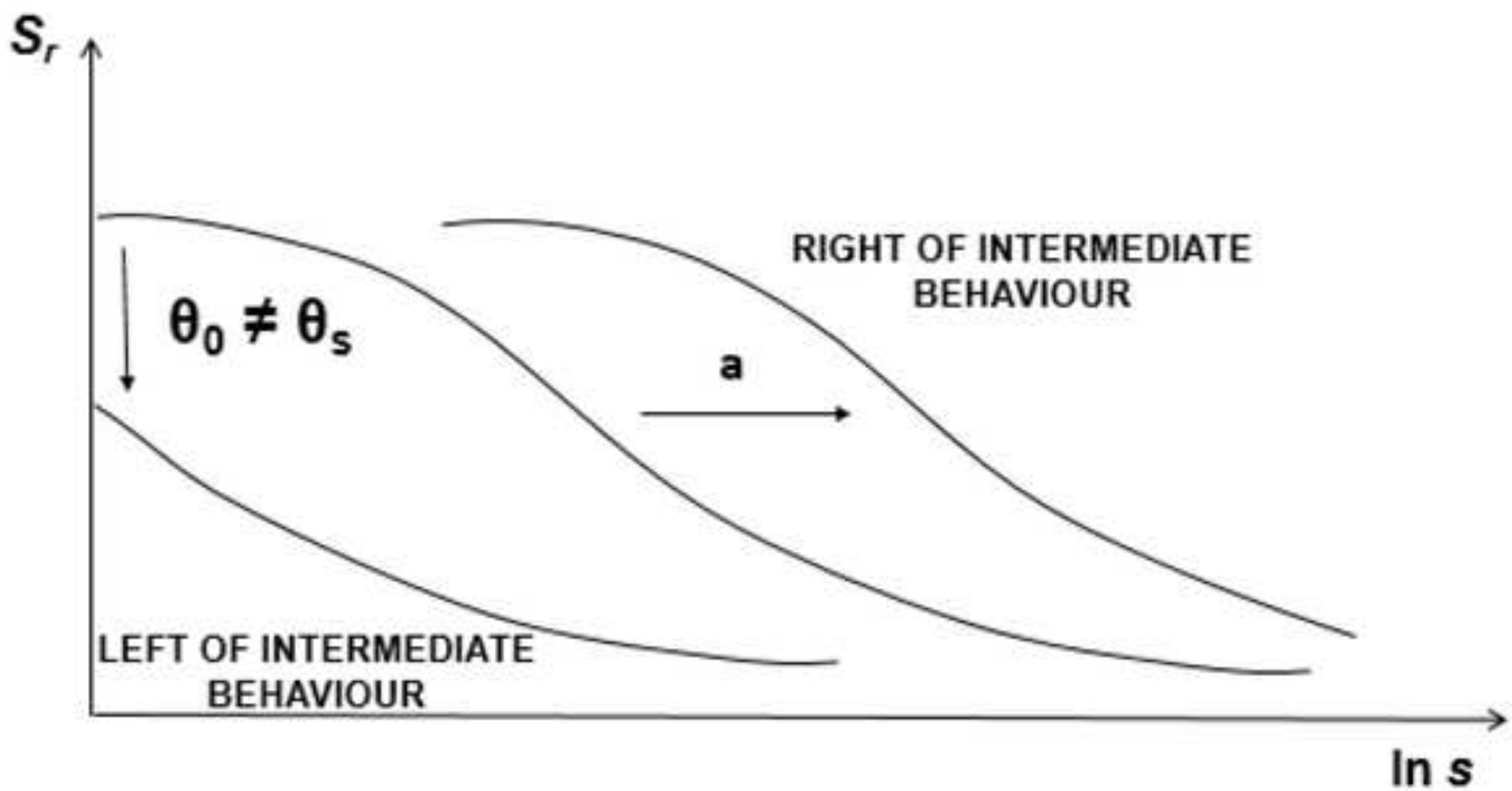
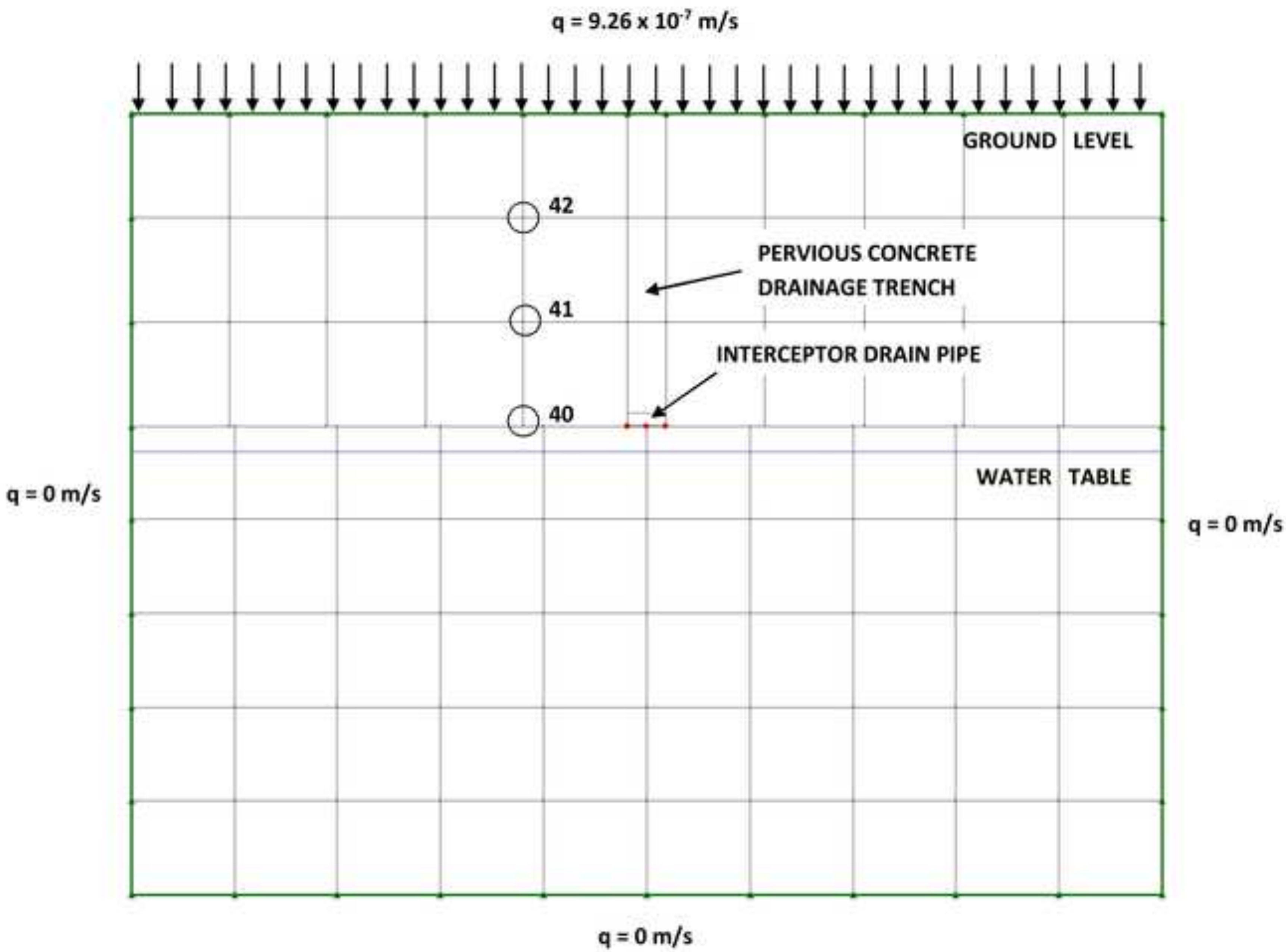

S_r
$\theta_0 \neq \theta_s$
a
RIGHT OF INTERMEDIATE BEHAVIOUR
LEFT OF INTERMEDIATE BEHAVIOUR
ln s

Figure 11



q = 9.26 x 10-7 m/s
GROUND LEVEL
42
41
40
PERVIOUS CONCRETE
DRAINAGE TRENCH
INTERCEPTOR DRAIN PIPE
WATER TABLE
q = 0 m/s
q = 0 m/s
q = 0 m/s

Figure 12

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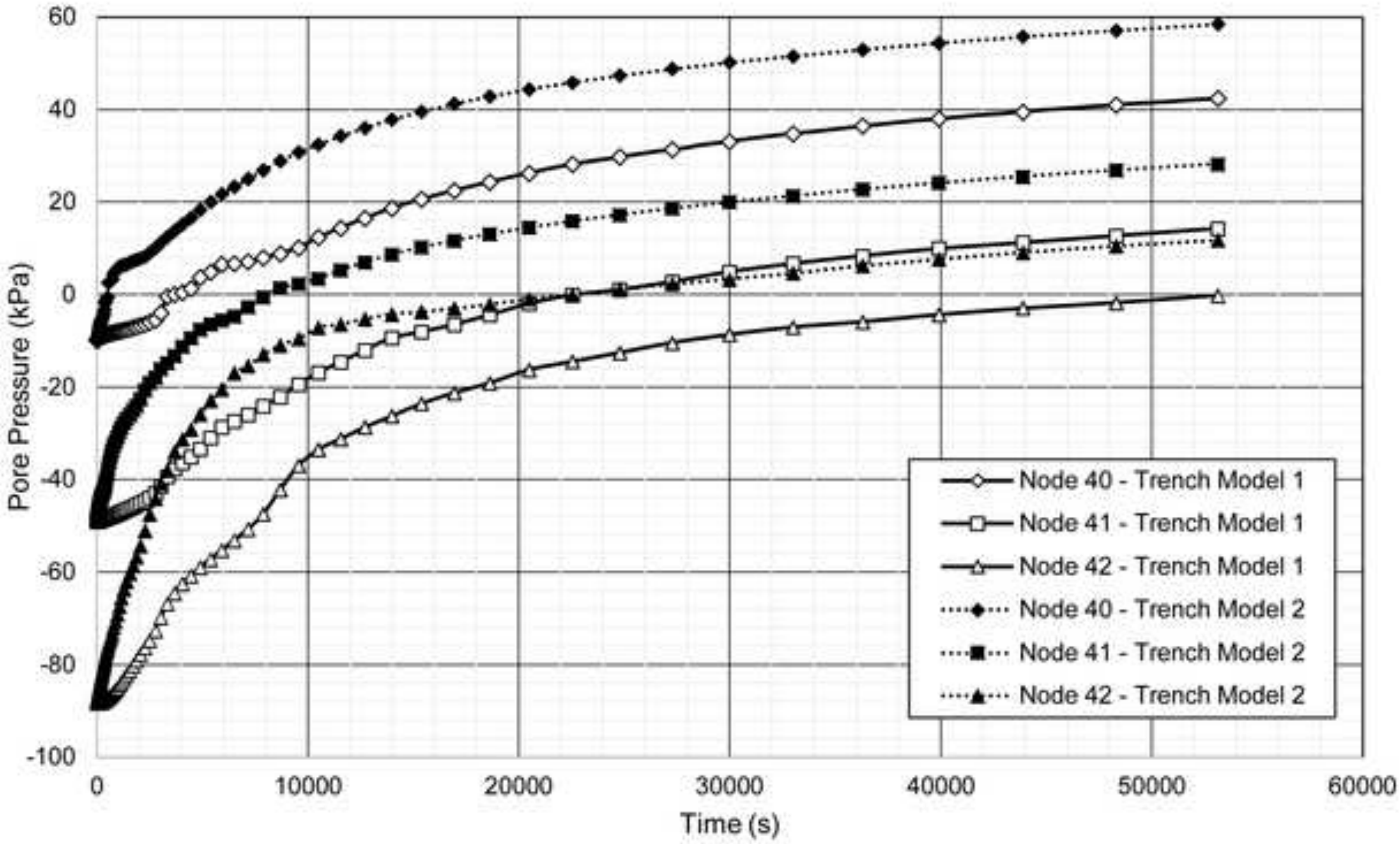

Figure 13

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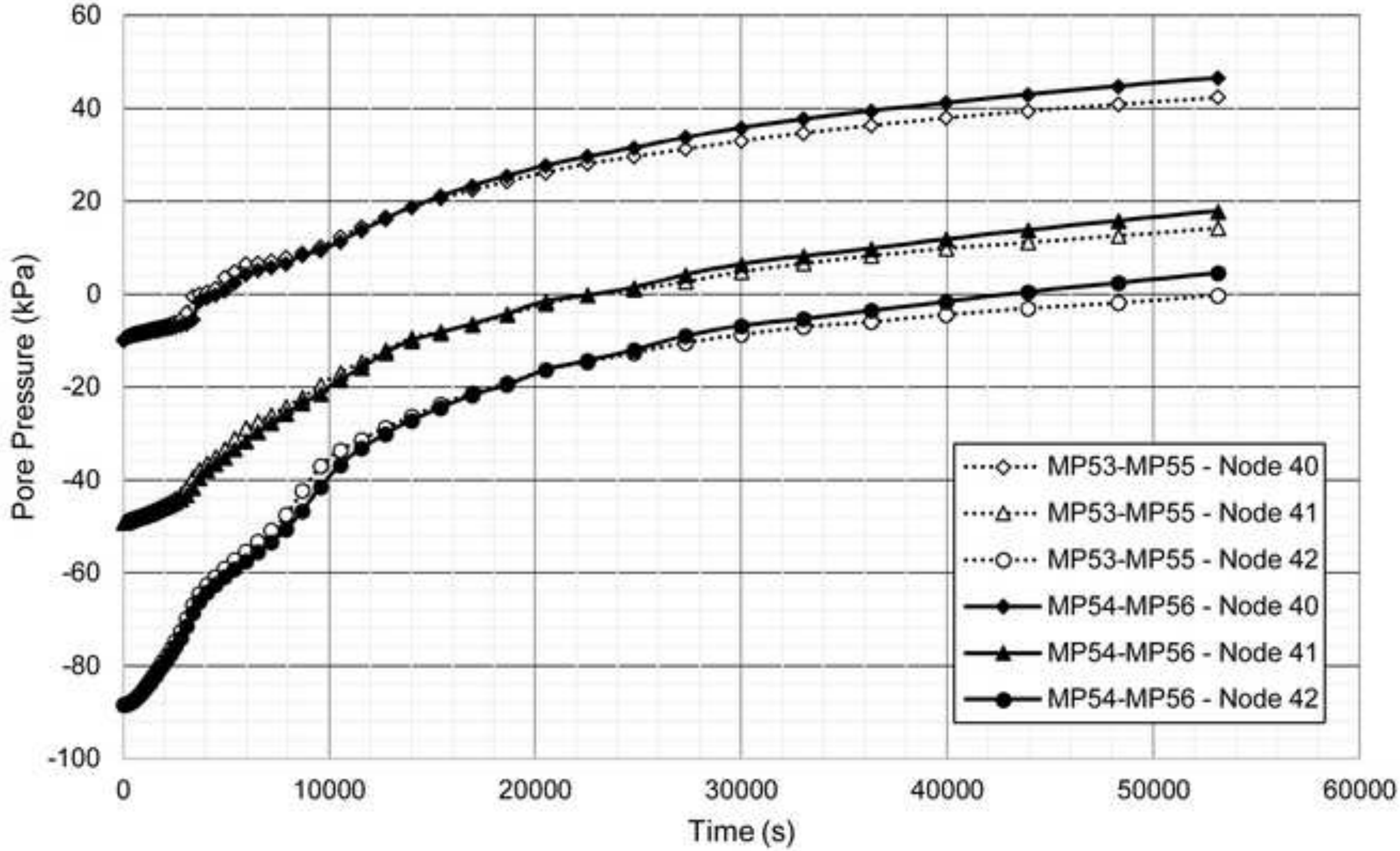

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