Investigation on the influence of permeability coefficient *k* of the soil mass on construction settlements. Cases of infrastructure settlements in Greece.

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Abstract: One of the most important problems that Civil and Geotechnical Engineers' Society faces, stand for the settlements due to inconsistent permeability of soil, not only in building projects but also in constructions in general. Settlements observed are usually a function of both the imposed load and the characteristics of the foundation soil (Kirtas, 2010). [1]

The presence of water in the soil, its flow in the pores of the soil, water removal from clay rocks as well as variations of the phreatic surface are some of the main causes of settlements.

Quantification of permeability with the use of permeability coefficient *k* is of utmost importance because it effectively aids toward a technically correct and safe design of various geotechnical projects.

The aim of this paper is to investigate the influence of permeability coefficient *k* in soil settlement, particularly in cases observed in Greece.

Keywords: permeability coefficient, settlement, hydraulic conductivity, embankment, road settlement, consolidation.

1 Introduction
All soil materials are permeable, as their pores communicate and form continuous passages. Thus, water flows through the voids in a soil which are interconnected. This flow may be called seepage, since the velocities are very small. Water flows from a higher energy to a lower energy point and behaves according to the principles of fluid mechanics.
One of the most critical properties of soil is the hydraulic conductivity or permeability, which regulates mainly, the movement of water through it. Permeability is the measure of the soil's ability to permit water to flow through its pores or voids. The following applications illustrate the importance of permeability in geotechnical design:

– Permeability influences the rate of settlement of a saturated soil under load.
– The design of earth dams is very much based upon the permeability of the soils used.
– The design of pavement in terms of the dimensioning process is affected by soil's permeability.
– The stability of slopes and retaining structures can be greatly affected by the permeability of the soils involved.
– Filters made of soils are designed based upon their permeability.

Also, the water that penetrates fillers is associated with reduction of strength parameters of continuations and gliding movements while volume changes due to absorption or removal of water from aluminates rocks lead to vertical soil movements, i.e. subsidence. Finally, frost effects can cause passive elevations or passive settling, while fluctuations in the level of the phreatic surface lead to passive settling.
From all of the above, it becomes clear that soil permeability is one of the most important soil properties of interest to geotechnical engineering and it is particularly important to investigate its influence on building settlements.

2 Hydraulic conductivity/permeability coefficient
Many scientists, mathematicians, physicists and engineers in particular, have dealt with the phenomenon of fluid movement and especially of water in the ground and have formulated relevant laws and equations, such as Darcy's law, the coefficient of permeability *k* and Bernoulli's equation as shown in the following Figures 1, 2 and 3, accordingly.

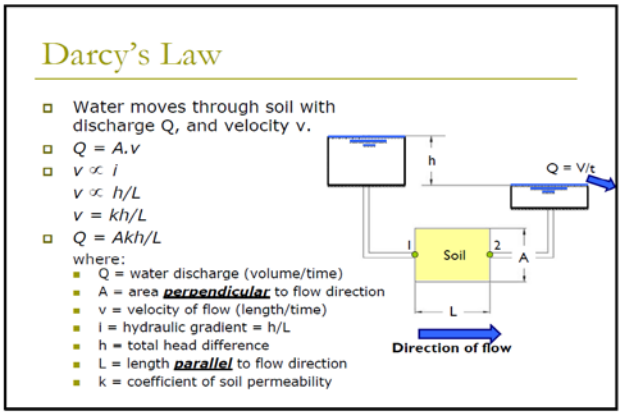


Figure 1: Darcy's Law [Source: Salem 2010-2011] [2]

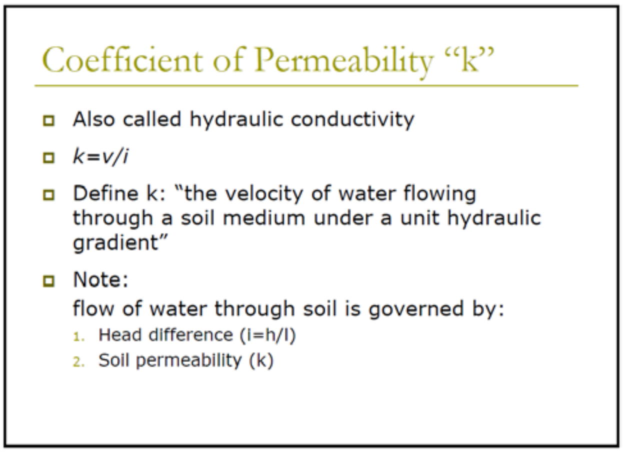


Figure 2: The permeability coefficient *k* [Source: Salem 2010-2011] [2]

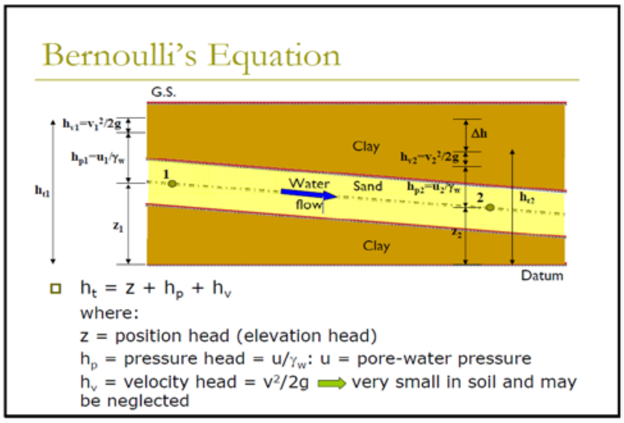


Figure 3: Bernoulli equation [Source: Salem 2010-2011] [2]

The *k* coefficient ratio that appears in Darcy's law, is also called (apart from permeability coefficient) *hydraulic conductivity* and depends on both the characteristics of the porous material and the characteristics of the moving fluid, while it has dimensions of speed. The permeability coefficient is a property of geomaterials bearing a very large range of values, as shown in Tables 1, 2 and 3, below, as well as in Figure 4.

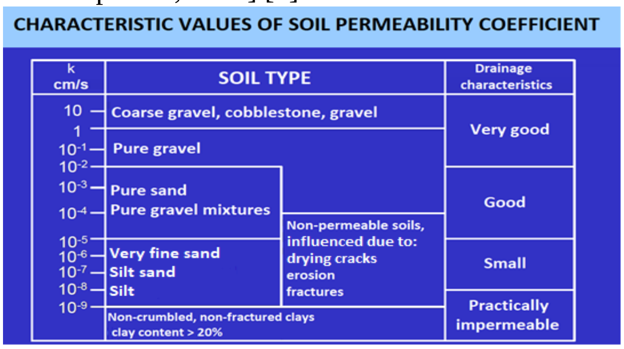
Table 1: Values of permeability coefficient *k* [Source: Kavvadas, 2005 [3]- Toubanou, 2015 [4]]

SOIL TYPE	*k* (cm/sec)
gravel	10^{2}-1
pure sand	1-10^{-3}
thin sand, silt sand	10^{-3}-10^{-6}
silt , clay silt	10^{-4}-10^{-7}
clay	10^{-6}-10^{-9}

Table 2: Hydraulic conductivity values *k* for different types of soil [Source: Theocharis, 2015] [5]

Soil	k(m/sec)	Soil	k(m/sec)
1	2	1	2
Clay	< 10^{-9}	Fine sand	10^{-5}-10^{-4}
Sandy clay	10^{-9}-10^{-8}	Coarse sand	10^{-4}-10^{-3}
Carbon clay	10^{-9}-10^{-7}	Sand with gravel	10^{-3}-10^{-2}
Silt	10^{-8}-10^{-7}	Fine gravel	> 10^{-2}
Extremely fine sand	10^{-6}-10^{-5}		

Table 3: Characteristic values of soil permeability coefficient [Source: Pelekis, Kavvadia, Xenaki, Pantazopoulos, 2009] [6]



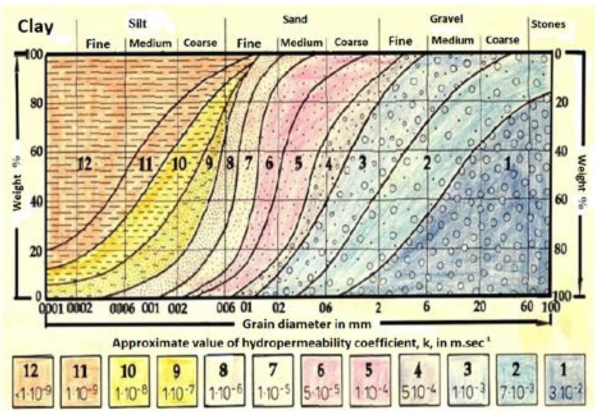


Figure 4: Typical values of the permeability coefficient *k* for various soil formations [Source: Poursaitidis, 2013] [7]

3 Determination of permeability coefficient

The ways for determining the permeability coefficient *k* are by:

1) Direct methods (Constant Load Test, Falling Load Test, Pump Field Test),
2) Indirect methods (consolidation test data, Hazen formula),

as well as by laboratory methods but also by external (on-site) permeation measurement tests as summarized below.

3.1 Laboratory methods for measuring permeability

Determination of the permeability coefficient in the laboratory is done special devices, called *permeameters*, in which the water is forced to percolate through the soil sample. Permeameters are of two types: fixed and variable load. The former is used in soils with high permeability, while the latter ones in small permeability soils. In both types, a hydraulic slope is created within the soil sample (Poursaitidis, 2013) [7].

Fixed load permeameter

In the test on the fixed load permeameter the free levels in the two tanks with an altitude difference ΔH remain constant and the constant infiltration flow (Q) is measured, so in Darcy's law the permeability coefficient is calculated from the relation (Figure 1):

$$k = \lambda H A_1 / h A_2 t = Q / i A_2 t \qquad (1)$$

where:

A1: the cross-sectional area of the final container

A2: the cross-sectional area of the soil sample

H: the height of the soil sample

h: hydraulic load

λ: the height of the water in the final container

t: drain time in seconds

i: the hydraulic gradient (i = h/H)

Q: water supply over time t.

Variable load permeameter

In this device the low free level is kept constant, whereas the high level decreases at a rate dependent on the filtered flow rate. This condition also determines the mathematical expression of the permeameter function from which the relationship used in calculating the permeability coefficient is derived:

$$k = a*L/S*t*\ln(\Delta h_o/\Delta h_1) \quad (2)$$

where:

L: sample height
S: cross sectional area of the sample
a: cross-sectional area of the load tube
Δh_o: initial difference of input-output level at time t = 0
Δh_t: difference in input-output level at time t.

3.2 In-situ permeability measurement tests

Le Frank Test (Fixed Load Test)

The Le Franc test is applied in the case of coarse soil materials. According to this method, the calculation of the permeability coefficient depends on the form of the tested part and its position in relation to the groundwater level and is given by the formula:

$$k = Q/ch \quad (3)$$

where:

Q: water flow rate in cm^3/sec
h: the height of the loading column in cm
c: the pocket coefficient that depends on the geometry of the compressed portion (pocket).

Maag test (variable load test)

This test is applied in the case of fine soil materials (materials with low hydraulic conductivity). (http://www.legah.metal.ntua.gr/pdf/tex1/2011/A23_P.pdf) [8].
The permeability coefficient is given by the following mathematical relationship:

$$k = S/ct \times \ln(h_1/h_2) \quad (4)$$

where:

S: the cross-sectional area of the test section (πr^2 in cm^2)
c: the pocket coefficient
t: the duration of the level drop step (in sec)
h_1: the initial height above the reference plane (in cm)
h_2: the final height of the level above the reference plane (in cm).

As was the case in the Le Frank test, the middle of the tested portion is taken as a reference level, when the test is performed in a dry environment, whereas the hydrostatic level is used, when the test is done below the level of the aquifer

Lugeon Test

Packer tests are used in rocky formations. (http://www.legah.metal.ntua.gr/pdf/tex1/2011/A23_P.pdf) [8].
One of the formulas that have been constructed in order to calculate water permeability is as follows: (http://www.legah.metal.ntua.gr/pdf/tex1/2011/A23_P.pdf)

$$k\ (cm/sec) = Q/2\pi LP \times \ln(2L/D) \quad (5)$$

where:

Q: the losses (in cm^3/sec or lit/min)
L: the length of the intake portion (in cm)
P: the actual test pressure applied in cm of a water column (10 m water column = 1 Atm)
D: the diameter of the drilling hole (in cm).

Pumping tests

These are tests carried out mainly on deep aquifers (free and under pressure). They are used in hydrogeological surveys and studies. For this purpose, pump tests are carried out in wells. A vertical filter tube, which is pushed into the aquifer, is used. The pump is then activated, set at a constant flow rate Q, while at the same time the drop of the water level is measured, whereupon for a free aquifer, with application of the Dupuit formula, we are able to calculate *k*:

$$k = Q(\ln r_2 - \ln r_1)/\pi(h_2^2 - h_1^2) \quad (6)$$

and for a pressurized aquifer from the Theis formulas:

$$k = Q/4\pi\pi M \times W(u) \quad (7)$$

and by Cooper-Jacob:

$$k = 2.3Q/4\pi\pi M \times \log(2.25\ Tt/r^2 s) \quad (8)$$

where:

Q: the drilling flow rate (m^3/ sec)
h_1, h_2: the height of the water level in the pressure switches P_1 and P_2
r_1, r_2: the distances of the P_1 and P_2 pressure switches from the pumping well
M: the aquifer thickness (in meters)
$s = h_2 - h_1$: the drop in water level during pumping (in meters)

From all of the above, it appears that the draining Q of an aquifer is increased or decreased if, respectively, its hydraulic slope (i) is increased or decreased. This conclusion can be used in the calculation of the water permeability coefficient.

3.3 Approach methods for determining permeability

Several approximate empirical relationships have been suggested for determining k from other soil properties. However, comparative studies showed that none are reliable enough and that estimates of *k*, which satisfactorily approaching reality, were achieved only with on-site pumping and with laboratory tests.
The approximate relation used most frequently is by Hazen, for sandy soils with:

Granulometric analysis
(http://www.geo.auth.gr/courses/ggg/ggg758y/PDF/1.pdf) [9]

$$k = C_k\,(D_{10})^2 \text{ (cm/s)} \qquad (9)$$

where:

D_{10} = the active grain size (in cm)
C_k = experimental factor depending on the nature of the soil, with values:
C_k = 45 (s/cm) for clayey sand,
C_k = 100 (s/cm) for clean and uniform sand, for which $C_u = D_{60}/D_{10} < 2$ should apply.

Consolidation Test
(http://www.geo.auth.gr/courses/ggg/ggg758y/PDF/1.pdf) [9]

$$k= C_v \cdot \gamma_w \cdot m_v = C_v \,.\gamma_{\,w}\,.\alpha_v/\,(1+ e) \qquad (10)$$

where:

C_v: the coefficient of solidification (cm^2/sec)
C_c: compression index (cm^2/kg) $C_c = \Delta e/\Delta \log p$
γ_w: the specific weight of water (gr/cm^3)
m_v: the volume change factor $m_v = \alpha_v/1+e_o$ (cm^2/kg)
α_v: the coefficient of compressibility $\alpha_v = \Delta e/\Delta p$ (cm^2/kg)
e: the void ratio of the material
p: the mean tension of the loading stage during oedometer tests $p=p_1+p_2Y_2$.

4 Settlement of soil layers associated with the presence of water

Two basic methods have been developed for detecting and determining vertical movements (settlements) in a region of interest:
1) Geotechnical methods carried out by means of instruments such as pressure gauge, gradiometer, inclinometer and elongation gauge.
2) Geodetic methods performed either by terrestrial or satellite geodetic methods. (Skouras and Tabakopoulos, 2015) [10].
The studies to date concerning the effect of the permeability coefficient on the settlements of structures gave, in general lines, the following points:
1. The change in settlements during rainfall is significantly affected by the groundwater table position near the ground surface due to changes in matric suction. In addition, higher bearing capacity in response to rainfall infiltration is observed for the soil with smaller permeability function as compared to larger permeability function (Kim et al., 2017) [11].
2. The soil permeability coefficient plays a key role in the process of numerical simulation of the liquefaction phenomenon. Liquefaction causes a considerable increase in soil permeability, due to the creation of easier paths for water flow (Rahmani et al., 2012) [12].
3. The permeability coefficient of sand may change after liquefaction. The proposed model (Wang and Song, 2017) with variable permeability coefficient allows the maximum permeability coefficient during the liquefaction several times of its initial value. The results show that the adopted variable permeability model is capable to simulate the behaviour of the sand in the free-field condition under seismic loading with an acceptable accuracy (Wang and Song, 2017) [13].
4. Liquefaction phenomenon is usually accompanied by large amounts of settlement owing to disruption of soil structure. In addition to that, significant settlement is also caused by a significant increase in soil permeability during seismic excitation. The variation of permeability coefficient during liquefaction can be expressed as a function of excess pore pressure ratio. Comparison of numerical simulation results and the centrifuge experiment measurements indicate that there is a direct relationship between the permeability coefficient and excess pore pressure ratio during build-up, liquefaction and dissipation phases. The coefficient of permeability increases significantly during

seismic excitation and excess pore pressure generation (Shahir et al., 2012). [14]
5. The problems addressed in settlement of embankments on soft clays include site exploration; solid modeling of field data; problems associated with taking, handling, and testing soil samples; efficient reduction, storage, and display of laboratory data; and analytical methods to handle such routine problems as effective-stress dependent coefficients of consolidation, large strains, nonlinear stress-strain curves, multidirectional flow, and secondary effects (Olson, 1998). [15]
6. The processing of Kremasta dam data revealed that an increase in rate of sedimentation of the crest of the dam is related to the combined effect of three parameters when they exceed their critical values simultaneously: reservoir level (270 m), reservoir level change rate (1.30 m / month) and rate of rainfall change (100 mm / month) (Pytharouli and Steiros, 2008). [16]

5 Examples of settlements in Greece

1) Catastrophic settlements appeared in the road of Preveza-Igoumenitsa in March 2013. The disaster was attributed to the severely bad weather that hit the area in the winter of the same year (Figure 5).

Figure 5: Settlement of Igoumenitsa-Preveza road [Source: mypreveza.gr, 2013 [17] -Skouras and Tabakopoulos, 2015 [10]]

2) The strong morphological relief, the presence of formations characterized by low consistency, the intense penetration of the area from source and surface waters are among the causes of the landslide movements that affected the village of Ropotos of Trikala (Figure 6).

Figure 6: Settlement in the village of Ropotos, Trikala [Source: www.moderndads.gr/?p = 928709 [18]]

It all started in 2010 when the ground began to recede in the village of Ropotos, in Trikala. Things got worse over the next two years after heavy rainfall, causing major damage to most houses. On April 12, 2012 a huge landslide took place, which dragged the whole village for about 40 meters towards the bottom of the slope. Impressive is that many of the houses and the village church moved without being destroyed, with the result that they simply stand tilted on the mountainside.
Most of the community area of Ropotos, has a geological background of the Pindos flysch, which is encountered in various lithological phases, while alternating between them. The flysch, which belongs to the geodesic zone of Pindos, occurs in two phases: sandstone and clayey. In the surface of the ground the flysch is covered by soil mantle, which is a result of the action of the agents of erosion and weathering, which contributes to the creation of an aquifer that discharges into various points within the village.
Intense rainfall and snowfall are considered the main reason for the landslides that occurred not only in Ropotos but mainly in areas of Western and Central Greece. The water of the rains that fall in a short period of time on sensitive geological highlands, infuse the ground, causing both on the surface and beneath it, large, visible or invisible cracks and settlements.
3) The Mw 6.4 earthquake of June 8, 2008 in Achaia-Ilia prefecture near the city of Patras, Greece, caused severe damage to buildings and other engineered structures in the meizoseismal area, as well as a variety of geotechnical failures within approximately 25 km from fault (Margaris et al. 2008, 2010 [19], [20]). These failures encompass soil liquefaction, with or without lateral spreading, slope instabilities, rockfalls, as well as coastal subsidence phenomena (Batilas et al. 2010 [21]) Liquefaction phenomena occurring in the event of the earthquake, in Ilia-Achaia (8^{th} June 2008) in the

eastern part of the beach of Kato Achaia, occupy an area of 150x90 m^2, at about 30 m from the shoreline and were perceived by the appearance of sand craters and cracks, with or without emergence of fine-grained silt (Kitsonidis and Kordolaimis, 2016 [22]) (Figure 7).

Figure 7: Kato Achaia-East: Sand craters with the emergence of the liquefied soil of silt composition [Source**:** ITSAK, 2008 [23]- Batilas, Athanasopoulos, Pelekis P, Vlachakis, Klimis, Mylonakis (2010) [21]]

4) On the Athens – Thessaloniki motorway, near the city of Thebes, a significant number of cracks appeared in the asphalt layer of the motorway (Figure 8). After an autopsy, it was found that similar cracks also existed in adjacent craft buildings.

Figure 8: 5 mm crack on the asphalt in the Theban field area [Source: Christodoulias and Giannaros, 2018 [24]]

From the meteorological data of these regions it was found that there are seasons with high rainfall and seasons with severe droughts every year. As a result, swelling cycles (expandable clay soil) and shrinkage of the subsoil, alternate. Under conditions of soil soak, high stresses are created on the foundation elements, resulting in the upward movement and breakage of the masonry of the houses and the cracking of the embankments. The existence of expanding clay on the ground combined with the climatic characteristics of the country leads to adverse effects on constructions (Christodoulias and Giannaros, 2018 [24]).

6 Cases of settlements in the Prefecture of Larissa

6.1 The phenomenon of cracks (Short history)

From 1990 onwards, significant cracks have appeared in the ground and houses in several villages in the region of Thessaly, mainly between Larissa and Volos, in the wider area of drained lake Karla. In many cases, these cracks presented an immediate risk to the structural integrity of the constructions and thus to the safety of the occupants. Such phenomena often occur in the SE and NW side of Eastern Thessaly and may even affect the stability of the buildings. Cracking and settlements have occurred in various regions of the Prefecture of Larissa (Niki, Armenio, Rizomylos, Halki, Platykampos, Omorfochori, Agia Sophia, Ampelonas, Falani, Farsala), while damage was observed in houses (Melia, Rizomylos, etc.), as in the Larissa-Volos railway line (Evangelopoulos, 2005 [25]). Later, the community of Stavros in Farsala joined them. Generally, the cracks were almost parallel along the longitudinal axis of the lake. It is characteristic that in some homes or warehouses intense cracking appeared, while the floor was divided into two sections, which have an altitude difference up to 6-7 cm, as shown by the following figures 9 to 15 (Source: (Source: Hatzopoulou, 2018 [26], Dakoulas, Thanopoulos, Belesis, Lazaropoulos, 2004 [27]).

Figure 9: Cracks in exterior house wall [Source: Hatzopoulou, 2018 [26], Dakoulas, Thanopoulos, Belesis, Lazaropoulos, 2004 [27]].

Figure 10: Cracking in interior house wall [Source: Hatzopoulou, 2018 [26], Dakoulas, Thanopoulos, Belesis, Lazaropoulos, 2004 [27]].

Figure 11: Cracking in house floor [Source: Hatzopoulou, 2018 [26], Dakoulas, Thanopoulos, Belesis, Lazaropoulos, 2004 [27]]

Soil cracking phenomena have also appeared in the military airport of Larissa, which reinforced the view that the phenomenon was not local but had spread in the area of the plain of Larissa. In consultation with the air force general staff, measurements were made at Larissa Airport.
According to a relevant study (Dakoulas et al., 2004 [27]) the region with the settlement belongs to the prefecture of Larissa, of the geographical sector of Thessaly and is located in the central and southeastern part of the basin of eastern Thessaly. The basin of Larissa has a NW-NE address, which is in line with the Greek-Orographic Directorate (NW-NE).

Figure 12: Cracks in a building due to rupture along the provincial road between Larisa and Volos with a N110^{o} general bearing, inclined to the south [Source: Hatzopoulou, 2018 [26], Dakoulas, Thanopoulos, Belesis, Lazaropoulos, 2004 [27]]]

Figure 13: rupture along the provincial road of Larissa-Volos, bearing N110^{o}, tilted towards S. It appears over a length of 20 m, has an opening of 3cm and a depth of about 30 m [Source: Hatzopoulou, 2018, Dakoulas, Thanopoulos, Belesis, Lazaropoulos, 2004]

The region is crossed by geological faults which have highly complex structure with precedence over the East-West (N100^{o} – N110^{o}) approximate vector which coincides with the direction of the ruptures.

Figure 14: Cracking in a courtyard wall. [Source: Hatzopoulou, 2018 [26], Dakoulas, Thanopoulos, Belesis, Lazaropoulos, 2004 [27]]

Figure 15: Cracking on road surface and a house courtyard [Source: Hatzopoulou, 2018 [26], Dakoulas, Thanopoulos, Belesis, Lazaropoulos, 2004 [27]]

The current piezometric situation with the weakened hydraulic load, mainly in the horizontal vectorial direction, due to overexploitation of the groundwater potential showed that: the drainage of the horizons in the deeper aquifers is quite weakened to nonexistent. Seasonal piezometric fluctuations of 3 - 6 m which were before the system entered full use (1970s) are converted to 40 -50 m with a continuously dropping annual water level. Water formations, which have developed in depth in the basin of Larissa, are essentially medium and fine grain sands and gravel (medium water conductivity 10^{-3}–10^{-4} and 10^{-5} m/sec) located in interplay with large clay and clay packages. As a consequence of this, we observe consolidation of fine-grained materials of the rectangular-shaped soil mass with the long side of the NW-SE direction. The alluvial granular formations attempt to adapt to the new equilibrium state created by the fall of the groundwater level by compression, i.e. by reducing the voids between the grains (Evangelopoulos, 2005 [25]).

6.2 Reason of settlements

The obvious cause of the significant settlement that ruptures soil and creates cracks in structures is the significant drop of the water horizon (Figure16), which in the last years ranged from 30 m to 50 m (while temporarily the drop reached 80 m) depending of the area (Dakoulas et al., 2004 [27]). The biggest drop of the aquifer level is in the area of Eastern Thessaly. The removal of buoyancy exerted on the soil skeleton due to the drop of the aquifer level, increases active stresses in the ground which is compressed, decreasing the volume of voids that exist between the grains. This process is slow in the case of clay soils and is described by Terzaghi's consolidation theory (Terzaghi and Peck, 1967 [28]).

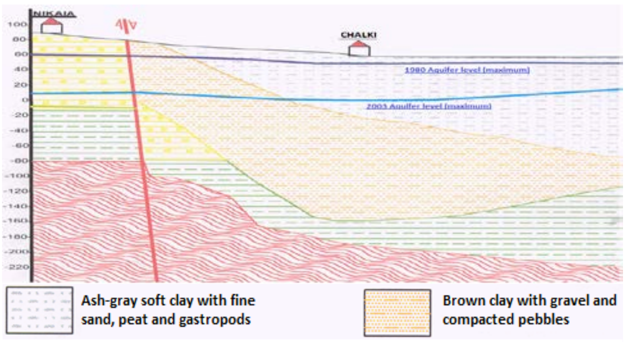


Figure 16: Soil profile and fall of the water surface in the area of Halki [Source: Hatzopoulou, 2018 [26], Dakoulas, Thanopoulos, Belesis, Lazaropoulos, 2004 [27]]

Obviously, the composition of soil material and the degree of its existing consolidation greatly affect the final size of additional settlements that would occur due to the lowering of the underground horizon (larger settlements in silt-clay, soft sediments and smaller in sandy ones). It is worth noting that a drop of the underground horizon by 50 m causes additional load on the ground which is equivalent to the construction of an embankment about 12 m high on the surface of the entire area affected by this drop of the water table. Particularly, the heterogeneity of the superposing materials in various neighbouring positions, their different depth between the boundaries, as well as the different subsoil position in each case is highlighted, resulting in the extend of settlements varying from between different positions.

7 Conclusions

The causes of soil settlements due to the presence of water, associated with the behaviour of the permeability coefficient *k*, are as follows:

1. The entry of water into fillers results in the reduction of soil strength parameters and the occurrence of sliding movements especially on slopes.
2. The change in soil volume due to absorption or removal of water from clay layers or fillers.
3. The fluctuation of the groundwater level where fluctuations in active stresses lead to passive settlements.
4. The effect of frost which can cause passive elevations or passive settlements.
5. Liquefaction of saturated sandy soils due to reversible seismic loads where there is a clear change in the values of the permeability coefficient *k*.
6. The intense infiltration of mountain volumes from source and surface waters creates landslide movements and is one of the causes of the settlements in mountain areas such as in the case of Ropotos.
7. The water of the rains that fall in a short period of time on sensitive geological highlands infuses the ground, causing both on the surface and beneath it, large, visible or invisible cracks and settlements.
8. The significant decrease of the level of the aquifer (especially in the villages of the Prefecture of Larissa) is associated with a permeability coefficient of 10^{-4} m/sec, which corresponds to medium - fine grain sands which due to the fall of the groundwater level, exhibit

compression, that is a reduction of the voids between the grains and therefore settlement.

From the data presented in this paper, the influence and in some cases the detrimental effects of the permeability coefficient *k* on the settlement of the structures become obvious. The case of the plain of Larissa is typical.

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