OPĆA RAZMATRANJA GIBANJA PODZEMNE VODE

GENERAL CONSIDERATIONS OF GROUNDWATER MOVEMENT

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REZIME

Gibanje podzemne vode je specifičan slučaj gibanja fluida u poroznoj sredini i zove se filtracija. Takvo gibanje se susreće u najrazličitijim područjima tehnike: u hidrotehnici i melioracijama, u vodosnabdijevanju i kanalizaciji, u eksploataciji nafte, u livnicama (filtracija plinova kroz materijal kalupa) i sl. Filtracija ima posebnu važnu ulogu u hidrotehničkim građevinama. Poznavanje gibanja podzemnih tokova omogućuje rješavanje takvih pitanja kao što su, na primjer, stabilnost zemljanih, betonskih i drugih pregrada (brana), filtracija iz kanala, položaj podzemnih voda nakon izgradnje kanala, navodnjavanje i odvodnjavanje tla pomoću otvorenih kanala, drenaža, doticanje u arteške i obične bunare itd. U radu je prikazan hidraulički pristup razmatranja bez hidrogeološkog osvrta na ovu problematiku.

Professional paper

SUMMARY

Groundwater motion is a specific case of fluid motion in a porous medium and is called filtration. Such movement is encountered in the most diverse fields of technology: in hydrotechnics and land reclamation, in water supply and sewerage, in the exploitation of oil, in foundries (gas filtration through mold material) and the like. Filtration plays a particularly important role in hydraulic structures. Knowledge of the movement of subsurface flows makes it possible to address such issues as, for example, stability of soil, concrete and other barriers (dams), filtration from canals, groundwater position after canal construction, irrigation and drainage of soil by open channels, drainage, inflow into artesian and ordinary wells etc. The paper presents the hydraulic approach of consideration without hydrogeological consideration of this problem.

1. UVOD

Istraživanje tipskih i za praksu važnih gibanja podzemnih voda, utvrđivanje općih zakona i metoda za proračun takvog gibanja, spada u posebnu granu hidraulike – teoriju gibanja podzemnih voda (teorija filtracije). Osnovne jednačine prve teorije dao je N. E. Žukovski 1889. godine. Nakon toga, on je dao još niz radova, na temelju kojih su N. N. Pavlovskij i L. S. Lejbenzon izgradili teoriju savremenog pristupa problemu filtracije, koja i danas zauzima vodeći položaj u toj oblasti nauke. U hidrotehničkoj praksi se često susrećemo s problemima vezanim za tok podzemne vode.

Najčešće je potrebno odrediti nivo ili gibanje podzemne vode. Veličina prostora u kojem se promatra gibanje podzemne vode može varirati od regionalnog mjerila (čija veličina se izražava u kilometrima), u kojem se promatra bilans podzemne vode te promjene smjera gibanja u vodonosnicima do prostora veličine molekula.

1. INTRODUCTION

The study of typical and important groundwater movements, the establishment of general laws and methods for calculating such movements, is a special branch of hydraulics - groundwater motion theory (filtration theory). The basic equations of the first theory were given by N. E. Zhukovsky in 1889. Subsequently, he gave a number of papers, based on which N. N. Pavlovsky и L.S. Leibenzon built a theory of the modern approach to the problem of filtration, which still holds a leading position in the field of science. In hydrotechnical practice, we often encounter problems related to groundwater flow. Most often it is necessary to determine the level or movement of groundwater.

The size of the area, in which groundwater movement is observed, can vary from a regional scale (its size is expressed in kilometres), in which the groundwater balance is observed, and changes in the direction of movement in aquifers to the size of the molecule.

2. PODZEMNA VODA I OBLICI NJENOG GIBANJA

U običnom tlu i u poroznim vodopropusnim slojevima u brdu voda se može nalaziti u različitim stanjima.

1. Pri najmanjoj vlažnosti voda je upijena u zrnca tla i može se odstraniti samo zagrijavanjem tla do 100°C. Pri takvoj vlažnosti, koja se zove higroskopska, gibanje vode u tlu nije moguće.
2. Pri povećanju vlažnosti voda u obliku filma omotava zrnca tla i može se gibati samo pod djelovanjem sila uzajamnog molekularnog djelovanja između čestica vode i tla; u tom slučaju je to tzv. *filmska voda*.
3. Pri daljnjem povećanju vlažnosti voda zapunjuje najuže pore i može se gibati samo pod djelovanjem sila kapilarnog pritiska; to je kapilarna voda. U ova tri stanja, molekularne sile toliko su važne da se u poređenju s njima sila teže zanemaruje.
4. Pri daljem povećanju sadržine vode u tlu, ona zapunjuje sve pore u tlu i postaje sposobna za gibanje pod djelovanjem sile teže, pa se zbog toga zove *gravitaciona voda*.

U daljem izlaganju će se posmatrati gibanje samo gravitacione vode i samo ta voda će se zvati podzemna voda.

Područje u kojem se voda procjeđuje kroz pore tla i stiže u podzemni tok zove se područje infiltracije. U području infiltracije, tok podzemne vode se mijenja uzduž toka na račun pridolaska novih količina vode u podzemni vodotok na svakoj jedinici dužine njegovog gibanja. Izvan područja infiltracije (koje se može nalaziti i neograničeno daleko od promatranog presjeka podzemnog toka) podzemni tok nastavlja gibanje stalnim protokom uzduž nepropusnog sloja.

Ako se posmatrani proces ne mijenja u toku vremena, onda nastaje stacionarno gibanje podzemne vode koje će se dalje promatrati.

Ako se iznad podzemnog vodotoka u poroznoj sredini nalazi također porozna sredina s atmosferskim pritiskom u njenim porama, onda se podzemni tok zove gravitacioni ili tok sa slobodnom površinom. Gravitacioni tok će biti, na primjer, pri filtraciji kroz tijelo zemljanog nasipa. Kada podzemni tok ulazi u vodopropusni sloj, koji je ograničen nepropusnim slojem odozdo i odozgo i pri tome ispunjuje sve pore propusnog sloja, stvara se pritisak veći od atmosferskog i nastaje gibanje podzemne vode pod pritiskom.

2. GROUNDWATER AND FORMS OF ITS MOVEMENT

In ordinary soil and in porous water-permeable layers in the hill, water may be found in different states.

1. At the lowest humidity, water is absorbed into the soil grains and can only be removed by heating the soil to 100°C. With such humidity, called hygroscopic, no movement of water in the soil is possible.
2. In increasing humidity, water in the form of a film wraps the soil grains and can only move under the influence of forces of mutual molecular action between the water and soil particles; in this case, it is so called *film water*.
3. As the humidity increases further, the water fills the narrowest pores and can only move under the action of capillary forces; it is capillary water. In these three states, molecular forces are so important that compared to them the force of gravity is ignored.
4. Finally, as the water content of the soil increases, it fills up all the pores in the soil and becomes capable of moving under the influence of gravity, which is why it is called gravitational water. In the following exposition, only gravity water will be observed and only that water will be called groundwater. The area where water flows through the pores of the soil and reaches the underground stream is called the infiltration area. In the area of infiltration, groundwater flow changes along the flow due to the arrival of new quantities of water into the groundwater at each unit of its length. Outside the infiltration area (which may be located infinitely far from the observed cross-section of the underground watercourse), the underground watercourse continues to move with a constant flow along the impermeable layer. If the observed process does not change over time, then a steady groundwater movement is created which will be observed further. If there is also a porous medium above the groundwater in a porous medium with atmospheric pressure in its pores, then the underground flow is called gravity or free flow. The gravitational flow will be, for example, when filtered through the body of an earth embankment. When an underground stream enters a water-permeable layer bounded by an impermeable layer from below and below and thus fills all pores of the permeable layer, a pressure greater than atmospheric pressure is created and groundwater is pressurized.

Kao primjer gibanja podzemne vode pod pritiskom može se uzeti gibanje arteških voda između nepropusnih geoloških slojeva i filtracija vode ispod betonske pregrade odnosno brane.
Kako kod betonske tako i kod zemljane brane, u početku će filtracija biti nestacionarnog karaktera i samo nakon nekog vremena postat će stacionarno gibanje s nekim povremenim okolnostima (na primjer kod velike vode). Kroz pore takvog tla voda se procjeđuje veoma sporo, s malim Reynoldsovim brojevima, pa je zbog toga strujanje podzemne vode laminarno (laminarna filtracija).
Pri filtraciji kroz krupnozrno tlo (šljunak), kroz raspucane naslage ili nabačen kamen brzina strujanja može postati znatno veća od brzine u sitnozrnom tlu, te režim strujanja podzemne vode postaje turbulentan. Turbulentna filtracija u ovome radu se ne razmatra.

3. FIZIČKA KARAKTERISTIKA TLA I NJEGOVA KLASIFIKACIJA PREMA NEPROPUSNOSTI

Svako prirodno tlo sastoji se od elementarnih čestica koje su nastale kao produkt raspadanja osnovnih brdskih masa (stijena) djelovanjem vode, leda, vjetra i temperature, ili raslinskih ostataka (na primjer, tresetno tlo). U zavisnosti od oblika i dimenzije tih čestica, prirodna tla imaju različita filtraciona svojstva. Zbog toga je veoma važno poznavati sastav tla u kojem se zbiva tečenje vode.
Zbog nepotpunog nalijeganja u tlu jedne čestice na drugu između njih ostaju praznine (pore), koje sačinjavaju veoma sitne vijugave prolaze (porne cijevi), kroz te pore se giba podzemna voda. Neka je V volumen tla, a ω volumen pora u tome volumenu tla. Odnos volumena pora prema ukupnom volumenu tla:

$$m_\omega = \frac{\omega}{V} \qquad (1)$$

zove se *koeficijent volumenske poroznosti* ili *poroznost*, koja bitno utječe na gibanje podzemne vode.
Kad bi tlo bilo sastavljeno od čestica u obliku kuglica istog pomjera, njegov koeficijent poroznosti zavisio bi samo od relativnog položaja (rasporeda) tih kuglica, a ne i od njihovog promjera, pa bi se mijenjao u granicama od 0,259 do 0,466. Takvo tlo se zove *fiktivno*.

As an example of groundwater movement under pressure can serve the movement of artesian waters between impermeable geological layers and the filtration of water under the concrete barrier or dam**.** For both concrete and earthen dams, initially the filtration will be of a non-stationary character and only after a while it will become a stationary motion with some occasional circumstances (for example, in large water). Through the pores of such soils the water is drained very slowly, in other words, with small Reynolds numbers, and therefore the flow of groundwater is laminar (laminar filtration). When filtered through coarse-grained soil (gravel), through cracked deposits, or folded rock, the flow velocity can become much higher than the velocity in fine-grained soil, and the groundwater flow regime becomes turbulent. Turbulent filtration is not considered here.

3. PHYSICAL CHARACTERISTICS OF SOIL AND ITS CLASSIFICATION BY IMPERMEABILITY

Each natural soil is composed of elemental particles that have been created as a product of decomposition of basic mountain masses (rocks) by the action of water, ice, wind and temperature, or saline debris (for example, peat soil). Depending on the shape and size of these particles, natural soils have different filtration properties. Therefore, it is very important to know the composition of the soil in which water flows. Due to incomplete settling in the soil of one particle to another, gaps (pores) remain between them, consisting of very small meandering passages (pore tubes); groundwater flows through these pores. Let V be the volume of soil and ω the volume of pore in that volume of soil. Ratio of pore volume to total soil volume:

$$m_\omega = \frac{\omega}{V} \qquad (1)$$

called *the volume porosity coefficient* or *porosity*, which significantly affects groundwater movement.
If the soil were composed of particles in the shape of beads of the same displacement, its porosity coefficient would depend only on the relative position (arrangement) of these beads and not on their diameter, and would vary in the range from 0.259 to 0.466.

Stvarno tlo sastavlja se od čestica raznolikih oblika i dimenzija, pa može imati i mnogo veći koeficijent poroznosti.

Tabela 1. Orijentacioni podaci o veličini koeficijenta poroznosti m_ω za neke vrste tla. [3]

Naziv tla	m_ω
Šljunak (2 < d < 20mm)	0,30 - 0,40
Pijesak (0,06 < d < 2 mm)	0,30 - 0,45
Pijesak (sa 12-3% glinenih frakcija)	0,35 - 0,45
Glina (sa 33-12% glinenih frakcija)	0,35 - 0,50
Glinovito tlo	0,40 - 0,50
Tresetno tlo	0,60 – 0,80

Osim po koeficijentu m_ω, filtraciona svojstva tla se mogu klasificirati i na temelju razmatranja osobina tla po njegovom poprečnom presjeku. Neka je Ω neka ravna površina u promatranom tlu, a ω ukupna površina pora u granicama promatrane ravne površine Ω. Što je veći odnos:

$$m_{\omega_p} = \frac{\omega}{\Omega} < 1 \tag{2}$$

koji se zove *koeficijent površinske poroznosti*, to je veća filtraciona sposobnost promatranog tla. Volumenska poroznost i površinska poroznost tla određuju se eksperimentalno [1].

Ako su filtraciona svojstva tla ista u svim njegovim tačkama, tlo se zove *homogeno*, u protivnom je tlo *nehomogeno*.

Kod homogenog tla koeficijent volumetrijske poroznosti m_ω i koeficijent površinske poroznosti m_{ω_p} su brojčano jednaki. Ako filtraciona svojstva tla ne zavise od smjera gibanja podzemne vode, tlo se zove *izotropno*; u protivnom je *anizotropno*.

Tako je na primjer fiktivno tlo sastavljeno od kuglica istog promjera homogeno izotropnog tla. Ako bi se tlo sastavilo od paralelopipeda istih dimenzija i iste orijentacije, takvo bi tlo bilo homogeno, ali i *anizotropno*. Osim toga, u prirodi se susreću slojevite vrste tla, koje se sastoje od niza slojeva s različitim filtracionim svojstvima u svakom sloju.

Uporedo s navedenim vrstama vodopropusnog tla postoje i druge vrste, koje su vodonepropusne. U nastavku rada pretpostavka je da se filtracija zbiva u homogenom izotropnom tlu koje leži na ravnom vodonepropusnom sloju.

Such soil is called *fictitious*. Real soil is made up of particles of various shapes and dimensions, so it can have a much higher porosity ratio.

Table 1 Orientation data on the magnitude of the porosity coefficient m_ω for some soils. [3]

The name of the soil	m_ω
Gravel (2 < d < 20mm)	0,30 - 0,40
Sand (0,06 < d < 2 mm)	0,30 - 0,45
Sand (with 12-3% clay fractions)	0,35 - 0,45
Clay (with 33-12-% clay fractions)	0,35 - 0,50
Clay soil	0,40 - 0,50
Peat soil	0,60 – 0,80

In addition to the $m_\omega$coefficient, soil filtration properties can also be classified based on consideration of soil properties by its cross-section. Let Ω be some flat surface in the observed soil, and ω be the total pore area within the boundaries of the observed flat surface Ω. The higher the ratio:

$$m_{\omega_p} = \frac{\omega}{\Omega} < 1 \tag{2}$$

called the *surface porosity coefficient*, the higher the filtration capacity of the observed soil. Volume porosity and surface porosity of soil are determined experimentally [1]. If the filtration properties of the soil are the same at all its points, the soil is called *homogeneous*, otherwise the soil is *inhomogeneous*. For homogeneous soil, the volumetric porosity coefficient m_ω and the surface porosity coefficient m_{ω_p} are numerically equal. If the filtration properties of the soil do not depend on the direction of movement of the groundwater, the soil is called *isotropic*; otherwise it is *anisotropic*. Thus, for example, a fictitious soil made up of balls of the same diameter is a homogeneous isotropic soil. If the soil were composed of parallelopipeds of the same dimensions and orientation, such soil would be homogeneous but also *anisotropic*. In addition, layered soil types are encountered in nature, consisting of a series of layers with different filtration properties in each layer. In addition to these types of waterproofing soil, there are other types of waterproofing. Further, it will be assumed that the filtration takes place in a homogeneous isotropic soil lying on a flat watertight layer.

4. BRZINA FILTRACIJE, ZAKON LAMINARNE FILTRACIJE

U laminarnom režimu gubici pada na jedinicu dužine (hidraulički pad I_h) proporcionalni su prvoj potenciji srednje brzine strujanja. Brzina strujanja u pojedinoj *pornoj cijevi* sa živim presjekom Δ_ω bit će:

$$u_p = \chi I_h \quad (3)$$

a protok kroz "pornu cijev" bit će:

$$\Delta Q = \chi I_h \Delta\omega \quad (4)$$

gdje je χ koeficijent proporcionalnosti, kojim se uzimaju u obzir svojstva promatranog tla.
Da bi se odredio ukupni protok podzemnog toka kroz neki poprečni presjek s ukupnom površinom filtera:

$$\Omega = \omega_{por} + \omega_{sl} \quad (5)$$

trebalo bi izračunati i zbrojiti elementarne protoke kroz sve porne cjevčice, koje idu kroz svu površinu filtera. Takav postupak praktično nije izvodiv, pa se zbog toga koristi drugi postupak.
Sva površina filtera Ω se dijeli na elementarne površine ΔΩ, u koje su uključeni živi presjeci pora Δ_ω i površine skeleta koje otpadaju na njih. Dijeljenjem izraza (4) sa ΔΩ i uzimanjem u obzir relacije (2) dobije se:

$$\frac{\Delta Q}{\Delta\Omega} = \chi\, I_h \frac{\Delta\omega}{\Delta\Omega} = \chi\, I_h m_\omega \quad (6)$$

Lijevi dio dobivenog izraza ima dimenziju brzine koja će se zvati *brzina filtracije* u_F. Koeficijent χ i m_ω u (6) izražavaju osobitost promatranog tla, pa se zbog toga mogu sažeti u jedan *koeficijent filtracije k*, koji će biti različit za različita tla. Tako će se dobiti:

$$u_F = kI_h \quad (7)$$

gdje se u_F može smatrati (smanjujući površinu ΔQ) lokalnom brzinom filtracije u posmatranoj tački.
Iz priloženog se vidi da je brzina filtracije u_F manja od stvarne brzine procjeđivanja kroz pore u_p i u stvari je neki apstraktan pojam. *Brzina filtracije je zamišljena brzina, koju bi imale čestice tekućine kad bi se ona procjeđivala ne samo kroz pore već kroz svu*

4. FILTRATION VELOCITY, LAMINAR FILTRATION LAW

In laminar mode, the losses fall on the unit of length (hydraulic fall I_h) are proportional to the first potency of the mean velocity of the streams. The velocity of flow in a single pore tube with a live cross-section Δ_ω will be:

$$u_p = \chi I_h \quad (3)$$

and the flow through the "pore tube" is:

$$\Delta Q = \chi I_h \Delta\omega \quad (4)$$

where χ is a coefficient of proportionality, which takes into account the properties of the observed soil.
To determine the total flow of an underground stream through a cross section with the total filter area:

$$\Omega = \omega_{por} + \omega_{sl} \quad (5)$$

elemental flows through all pore tubes, which pass through the entire filter surface, should be calculated and summed. Such a procedure is practically not feasible and therefore a different procedure will be used.
All filter surface Ω is subdivided into elementary surfaces ΔΩ, which include living pore sections Δ_ω and skeletal surfaces that fall on them. By dividing expression (4) by ΔΩ and considering relation (2), we obtain:

$$\frac{\Delta Q}{\Delta\Omega} = \chi\, I_h \frac{\Delta\omega}{\Delta\Omega} = \chi\, I_h m_\omega \quad (6)$$

The left-hand side of the resulting expression has a velocity dimension, which will be called the *filtration rate* u_F. The coefficient χ and m_ω in (6) expressing the characteristics of the observed soil, and therefore can be summarized in one *filtration coefficient k*, which will be different for different soils. So you will get:

$$u_F = kI_h \quad (7)$$

where u_F can be considered (by reducing the surface ΔQ) the local filtration rate at the observed point. From the above stated, it can be seen that the filtration rate is u_F lower than the actual velocity of sifting through the pores u_p and is, actually, an abstract term.

površinu filtera, kao kroz neku fiktivnu neprekidnu sredinu.

No za praksu je veoma bitno da proizvod brzine filtracije (7) i površine filtera Ω daje stvarni protok ΔQ. Kod veoma malih brzina, svojstvenih laminarnoj filtraciji, veličina brzinske visine se može zanemariti, a hidrodinamički pritisak H (specifičnu energiju) predstaviti sa:

$$H = z + \frac{p}{\gamma} \tag{8}$$

dok se hidraulički pad I_p može uzeti da je jednak pijezometarskom padu I. Zbog toga će se dalje primjenjivati (7) (ispuštajući indeks h) u obliku:

$$u = kI = u(x, y, z) \tag{9}$$

odnosno:

$$u = -k\frac{dH}{dl} \tag{10}$$

gdje je dH pad pritiska na dužini dl (negativna veličina). Ako se uzme linearna zavisnost gubitaka pritiska po dužini, onda će pijezometarski pad biti:

$$I = \frac{\left(z_1 + \frac{p_1}{\gamma}\right) - (z_2 + \frac{p_2}{\gamma})}{l} = \frac{H_1 - H_2}{l}. \tag{11}$$

Formulu (11) prvi je predložio *Darcy* (1855) na temelju preciznih ispitivanja laminarne filtracije i zbog toga se ona zove *Darcyjeva formula* [1].

5. KOEFICIJENT FILTRACIJE

Kako se iz (9) i (10) vidi, koeficijent filtracije ima dimenziju brzine i prikazuje brzinu filtracije pri hidrauličkom padu jednakom jedinici.

Određivanje brojčane vrijednosti koeficijenta filtracije provodi se nizom postupaka, koji se obično opisuju u specijalnim slučajevima [2,3]. Ovdje će se razmotriti jedan od postupaka određivanja koeficijenta k, uz pomoć posebnog Darcyjeva uređaja, shematski prikazanog na slici 1. To je vertikalan, odozgo otvoren cilindar A, površine poprečnog presjeka ω, koji ima otvore za priključivanje pijezometara P. Voda dolazi odozgo kroz cijev a; preljevna cijev b održava stalan nivo vode u cilindru.

Filtration rate is the imaginary rate that fluid particles would have if they were leaking not just through the pores, but through the entire surface of the filter, as through some fictitious continuous medium.

But for practice, it is very important that the product of the filtration rate (7) and the filter surface Ω give the actual flow ΔQ. At very low velocities inherent in laminar filtration, the magnitude of the velocity elevation can be neglected and the hydrodynamic pressure H (specific energy) represented by:

$$H = z + \frac{p}{\gamma} \tag{8}$$

while the hydraulic drop I_p can be taken to be equal to the piezometer drop I. Therefore, (7) (dropping index h) in the form will be further applied:

$$u = kI = u(x, y, z) \tag{9}$$

respectively:

$$u = -k\frac{dH}{dl} \tag{10}$$

where dH is the pressure drop over the length dl (negative size). If one takes the linear dependence of pressure losses along the length, then the piezometric drop will be:

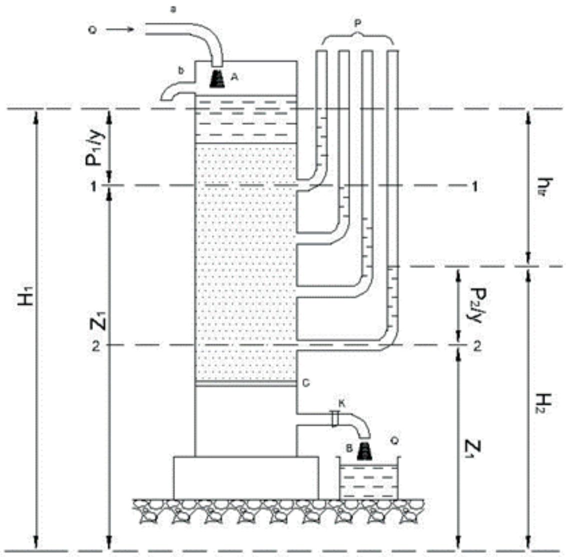
$$I = \frac{\left(z_1 + \frac{p_1}{\gamma}\right) - (z_2 + \frac{p_2}{\gamma})}{l} = \frac{H_1 - H_2}{l}. \tag{11}$$

Formula (11) was first proposed by Darcy (1855) on the basis of precise laminar filtration tests and that is why it's called *Darcy's formula* [1].

5. FILTRATION COEFFICIENT

As can be seen from (9) and (10), the filtration coefficient has a dimension of velocity and shows the filtration rate at a hydraulic fall equal to one.

The numerical value of the filtration coefficient is determined by a series of procedures, which are usually described in special cases [2,3]. Here will be considered one of the methods for determining the coefficient k, using the special Darcy device shown schematically in Figure 1. It is a vertical, cylindrical opening A, of cross-sectional area ω, which has openings for connecting piezometers P. Water comes from above through pipe a; overflow pipe b maintains a constant water level in the cylinder.



Slika 1. *Shema Darcyeva uređaja* [1,7]
Figure 1 *Scheme of Darcy's device* [1,7]

U dnu cilindra je mreža što pridržava tlo koje se istražuje, dolje ispod mreže je cijev C s ventilom K za ispuštanje filtrirane vode u posudu B.
Pri eksperimentu treba postići stacionarno gibanje vode kroz tlo, odrediti sekundarni protok Q i fiksirati podatke pijezometra. Tada se može odrediti brzina filtracije.

$$u = \frac{Q}{\omega} \tag{12}$$

i hidraulički pad:

$$I = \frac{h_{t\tau}}{l} \tag{13}$$

Gdje je $h_{t\tau}$ nivo dva međusobno povezana pijezometra koji su priključeni na međusobnoj udaljenosti l.
Upotrebom formula (9) i (10) nalazi se veličina koeficijenta filtracije k.
U tabeli 2. navedene su orijentacione vrijednosti koeficijenta filtracije za različite vrste tla [5,6].

At the bottom of the cylinder is a grid that holds the examined ground, down below the grid is a pipe C with a valve K to drain the filtered water into the vessel B.
In the experiment, stationary water movement through the soil should be achieved, the secondary flow Q should be determined and the piezometer data fixed. The filtration rate can then be determined.

$$u = \frac{Q}{\omega} \tag{12}$$

and hydraulic fall:

$$I = \frac{h_{t\tau}}{l} \tag{13}$$

Where $h_{t\tau}$ is the level of two interconnected piezometers connected at a distance l.
Using formulas (9) and (10), the magnitude of the filtration coefficient k is determined.
Table 2 lists the orientation values of the filtration coefficient for different soil types [5,6].

Tabela 2. Orijentacioni podaci o veličini koeficijenta filtracije. [1]

Naziv i kvalitet tla	Srednja vrijednost filtracije $k\ cm/s$
Glina	$(1\div6)10^{-6}$
Glinovito tlo	$(1\div6)10^{-5}$
Pješčano gusto tlo	$(1\div6)10^{-4}$
Pješčano rahlo tlo	$(1\div6)10^{-3}$
Sitnozrnasti pijesak	$(1\div6)10^{-3}$
Krupnozrnasti pijesak	$(1\div6)10^{-2}$

Iz tabele 2. se vidi da se veličina koeficijenta filtracije za isto tlo mijenja u širokim granicama. Treba imati u vidu da je koeficijent filtracije veličina koja se mijenja u vremenu zbog promjene temperature, sastava tla, disperznosti i drugih faktora.

6. SPECIFIČNOST POSTEPENOG I NAGLO PROMJENJIVOG GIBANJA PODZEMNE VODE

U općem gibanju podzemne vode, hidraulički pad I je neprekidna funkcija koordinata prostora, koji zauzima promatrani tok vode.

U pojedinim slučajevima hidraulički pad postaje stalan za određenu skupinu tačaka prostora, pa čak i za sve tačke toka u cjelini. Takvo izravnavanje hidrauličkog pada nastaje pri postepeno promjenjivom podzemnom toku [1,3].

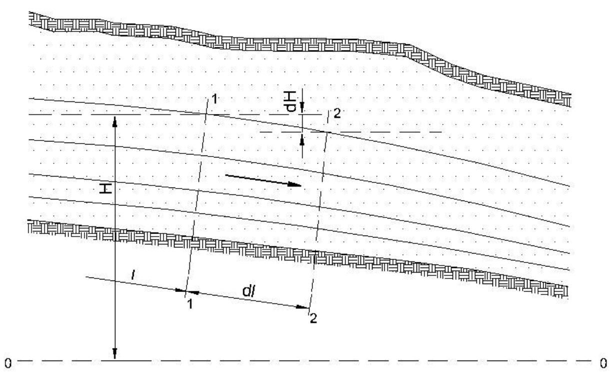
Table 2 Orientation data on the magnitude of the filtration coefficient. [1]

Name and quality of soil	Mean filtration value $k\ cm/s$
Clay	$(1\div6)10^{-6}$
Clay soil	$(1\div6)10^{-5}$
Sandy dense soil	$(1\div6)10^{-4}$
Sandy light soil	$(1\div6)10^{-3}$
Fine grained sand	$(1\div6)10^{-3}$
Coarse-grained sand	$(1\div6)10^{-2}$

Table 2 shows that the magnitude of the filtration coefficient for the same soil varies widely. It should be kept in mind that the filtration coefficient is a variable which changes over time due to changes in temperature, soil composition, dispersion and other factors.

6. SPECIFICITY OF GRADUAL AND FAST CHANGING MOVEMENT OF GROUNDWATER

In the general groundwater movement, the hydraulic drop I is a continuous function of the coordinates of the space occupied by the observed water flow. In some cases, the hydraulic fall becomes constant for a certain group of points of space and even for all points of flow as a whole. Such leveling of hydraulic fall occurs at a gradually changing underground flow [1,3].



Slika 2. *Prikaz dva presjeka toka vode na maloj udaljenosti* [3]
Figure 2 *Two cross sections of water flow at a short distance* [3]

U postepeno promjenjivom toku (slika 2.) promatraju se dva živa presjeka na međusobno maloj udaljenosti dl. Pri postepeno promjenjivom toku može se uzeti da su živi presjeci ravni i da se pritisak u

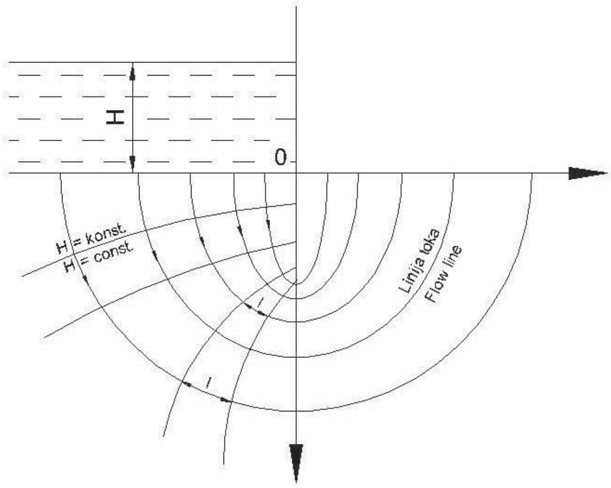
In a gradually varying flow (Fig. 2), two live sections are observed at a short distance dl. With a gradually varying flow, it can be assumed that the live sections are straight and that the pressure ravnini živog presjeka raspoređuje po hidrostatičkom zakonu. Sve tačke živog presjeka imat će jednu te istu visinu pritiska:

$$H = z + \frac{p}{\gamma} + \frac{\alpha v^2}{2g} = z + \frac{p}{\gamma}. \quad (14)$$

Zbog toga će pad pritiska na svakoj liniji toka između dva susjedna živa presjeka (idući u smjeru filtracije) biti jedan te isti $-dH$.
in the plane of the live section is distributed according to the hydrostatic law. All points in the live section will have the same height of pressure:

$$H = z + \frac{p}{\gamma} + \frac{\alpha v^2}{2g} = z + \frac{p}{\gamma}. \quad (14)$$

Therefore, the pressure drop at each flow line between two adjacent live sections (going in the filtration direction) will be the one and same - dH.



Slika 3. *Strujne linije procjeđivanja ispod pregrade (brana, talpi)* [1]
Figure 3 *Straining current lines below the barrier* [1]

S druge strane, zbog postepene promjenjivosti gibanja toka može se uzeti da će udaljenost dl između dva veoma bliska presjeka, mjerena uzduž svake linije toka, biti opet ista.
Na temelju toga može se stvoriti veoma važan zaključak: *pri postepeno promjenjivom gibanju podzemnog toka hidraulički pad za čitav živi presjek je konstantna veličina, pa su prema tome lokalne brzine u homogenom tlu u svim tačkama jednog živog presjeka jednake:*

$$u = -k \frac{dH}{dl}. \quad (15)$$

Dijagram raspodjele brzine u živom presjeku podzemnog toka, za razliku od otvorenih tokova, oblikom je pravougaonik. Zbog toga je srednja brzina filtracije v u živom presjeku postepeno promjenjivog podzemnog toka jednaka brzini u:

$$u = -k \frac{dH}{dl} = kI. \quad (16)$$

On the other hand, due to the gradual variability of the flow, it can be assumed that the distance dl between two very close sections, measured along each flow line, will again be the same.
A very important conclusion can be drawn from this: *in the case of gradually changing subsurface flow, the hydraulic fall for the whole live section is a constant magnitude, so that the local velocities in the homogeneous soil at all points of one live section are equal*:

$$u = -k \frac{dH}{dl}. \quad (15)$$

The velocity distribution diagram in a live section of an underground stream, unlike open streams, is a rectangle**.** Therefore, the mean filtration rate v in a live cross section of a gradually changing subsurface flow is equal to the velocity u:

$$u = -k \frac{dH}{dl} = kI. \quad (16)$$

gdje je I pad slobodne površine, koji se mijenja samo uzduž toka. Jednačina (16) je specijalan slučaj Darcyjeve formule, nju je dao Dupuit (1863), pa se ona i zove njegovim imenom.
Srednju brzina filtracije u Dupuitovoj formuli (16) treba shvatiti kao neku zamišljenu brzinu, kod koje kroz poprečni presjek čitavog filtera prolazi stvarni protok Q. Umjesto realnog gibanja određenog protoka Q podzemne vode kroz sumarnu površinu pora filtera promatra se apstraktno gibanje s istim protokom nekog kontinuuma koji zauzima čitav prostor pora i skeleta toga tla [2,4].
Temelj proračuna za srednju brzinu filtracije pri postepeno promjenjivoj laminarnoj filtraciji je jednačina (16).
Pri jednolikom gibanju, kao specijalnom slučaju postepeno promjenjivog gibanja, hidraulički pad bit će stalna veličina ne samo u granicama nekog živog presjeka već po čitavoj dužini toka, jer pri jednolikom gibanju sve su linije toka paralelene dnu, pa je zbog toga pad slobodne površine I na čitavoj dužini toka jednak padu nepropusnog sloja i. Formula (16) u tom slučaju poprima oblik :

$$v_0 = ki. \tag{17}$$

Proračun gibanja podzemnog laminarnog postepeno promjenjivog toka po formuli (17) je veoma jednostavan zbog međusobne jednakosti brzina u svim tačkama živog presjeka.

7. ZAKLJUČAK

U svim slučajevima koji ne odgovaraju uslovima postepene promjenjivosti gibanja, na primjer kod filtracije pod pritiskom, ispod građevina, procjeđivanja ispod brana (slika 3.), linije toka imaju određenu zakrivljenost, udaljenost između susjednih živih presjeka uzduž različitih linija tokova više nisu jednake. Zbog toga veličina hidrauličkog pada više nije konstantna u granicama živog presjeka, a živi presjek prestaje biti ravan.
Hidraulički pad, a zajedno s njim i lokalne brzine filtracije po formuli (16), bit će različite u različitim tačkama prostora koji zauzima podzemni tok.
U vezi s tim moraju se promatrati hidrauličke karakteristike stacionarnog podzemnog toka kao neke neprekidne funkcije koordinata, tj. moraju se koristiti opće jednačine hidromehanike, a to u velikoj mjeri komplikuje tehniku proračuna u poređenju sa gore navedenim

where I is the free surface drop, which changes only along the flow. Equation (16) is a special case of Darcy's formula, given by Dupuit (1863), and so it is called by his name. The mean filtration rate in Dupuit formula (16) should be understood as some imaginary rate at which the actual flow Q passes through the entire filter cross-section. Instead of the real motion of a certain flow Q of groundwater through the summarized surface of the filter pores, an abstract motion with the same flow of a continuum, which occupies the entire pore space and skeleton of that soil, is observed [2,4].
Therefore, the equation (16) for the mean filtration rate is taken as the basis of calculation for gradually changing laminar filtration.
In the case of uniform motion, as a special case of gradually varying motion, the hydraulic fall will be a constant magnitude not only within the limits of a live cross section, but over the entire length of the flow, because in a uniform motion all the flow lines are parallel to the bottom and, therefore, the free surface drop I, over the entire flow length equals to the drop of the impermeable layer i. Formula (16) in this case takes the form:

$$v_0 = ki. \tag{17}$$

The calculation of the motion of an underground laminar gradually varying flow by the formula (17) is very simple because of the mutual equality of speeds at all points of the live section.

7. CONCLUSION

In all cases that do not correspond to the conditions of gradual variability of motion, for example, filtration under pressure, under buildings, draining under dams (Figure 3), the flow lines have a certain curvature, the distance between adjacent live sections along different flow lines is no longer equal. As a result, the magnitude of the hydraulic fall is no longer constant within the limits of the live cross section, and the live cross section ceases to be straight.
The hydraulic drop, and with it the local filtration rates by formula (16), will be different at different points in the space occupied by the underground flow.
In this regard, the hydraulic characteristics of a stationary underground flow must be considered as some continuous

specijalnim slučajem postepeno promjenjivog gibanja.

functions of coordinates, ie. must be used the general equations of hydromechanics, what greatly complicates the calculation technique compared to the above mentioned special case of gradually variable motion.

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