同济大学“十二五”规划教材

Groundwater Dynamics Problem Sets

Edited by YE Weimin ZHAO Qian CHEN Yonggui YE Bin XU Long

同济大学出版社
TONGJI UNIVERSITY PRESS

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内 容 提 要

本教材是同济大学“十二五”规划教材，也是《地下水动力学》国家级双语示范课程配套教材。

本书根据《地下水动力学》教学大纲要求，按照“渗流理论基础”、“地下水向河渠运动”、“地下水向完整井的稳定运动”、“地下水向完整井的非稳定运动”、“地下水向附近井的运动”、“地下水向不完整井的运动”和“若干专门问题”等7章内容要求，搜集整理了“名词解释”、“填空”、“判断”、“作图”和“计算”等类型的习题。

本书可作为《地下水动力学》双语或全英语教学的补充教材，也可供从事地质工程、水利、给排水等相关专业的技术人员参考。

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Groundwater Dynamics Problem Sets

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Preface

Groundwater hydrology is the science that treats the occurrence, distribution and movement of water below the surface of the earth. *Groundwater Dynamics* addresses the principles that govern the groundwater movement in the pores, fissures and karst fissure cracks.

As a compulsory course for undergraduate students majoring in geological engineering, *Groundwater Dynamcis* has been taught in bilingual classes at Tongji University for more than ten years. It was awarded as one of the National Bilingual Demonstration Courses by the Ministry of Education of China in 2009.

This book is intended for a supplementary textbook of the course Groundwater Dynamics taught in English. It also can be used as a reference book for graduate students, engineers who study and work in relevant fields.

Problems are reorganized in 7 chapters according to the syllabus of *Groundwater Dynamics*. Some of them are adapted and edited from other textbooks, which are listed in the reference of this book. Many thanks should be given to the authors of these books. In each chapter, problems are presented in sections such as "Words and phrases explanation", "Fill in the blanks", "True-false questions", "Construction problems" and "Analysis and calculation", in order to help readers understand the fundamental principles, problems and methods in the relevant fields.

The authors are grateful to the Project National Bilingual Demonstration Courses: "*Groundwater Dynamics*" for the financial support.

Thanks are given to professor CHI Baoming for his kind review and helpful suggestions. Appreciations are also given to some of our former students, Mr. ZHANG Wenxiang and Mr. ZHANG Xingya, who once examined the manuscript and provided constructive feedbacks. Senior editor Ms. YANG Ningxia at Tongji University Press is also appreciated for her contributions to the preparation and editing of this book.

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Contents

Chapter 1

Fundamentals of Seepage Theory

1.1 Words and phrases explanation

1. Porous media
2. Seepage
3. Darcy velocity (v)
4. Laminar flow
5. Turbulent flow
6. Hydraulic gradient (J)
7. Critical hydraulic gradient
8. Hydraulic conductivity (K)
9. Storativity / Storage coefficient (S)
10. Specific storage
11. Permeability
12. Coefficient of transmissivity (T)
13. Uniformity coefficient
14. Effective grain size
15. Porosity (n)
16. Effective porosity
17. Pendular water
18. Specific yield (S_y)
19. Specific retention (S_r)
20. Specific discharge
21. Intrinsic permeability
22. Aquifer
23. Aquitard
24. Aquifuge
25. Aquiclude
26. Unconfined aquifer
27. Confined, or artesian aquifer
28. Reynolds number
29. The law of mass conservation

1.2 Fill in the blanks

1. Groundwater hydrology can be defined as a science of ________, distribution and ________ of water below the surface of the earth. While groundwater dynamics is a discipline that deals with the principles of the groundwater movement in ________, ________ and ________.
2. Secondary interstices developed after the rock was ________; examples include joints, ________, ________ and openings formed by plants and animals.
3. The major forms of existence of groundwater in porous media are ________, ________, ________ and ________.
4. In porous media, ________ are the pores that do not interconnected, they have ________ contribution to the groundwater movement. However, they are ________ for

the water storage. ________ refers to those interconnected pores that are not occupied by bound water, consequently, they are available for fluid flow.

5. An aquifer may be defined as a ________ that contains sufficient permeable materials to yield significant quantity of water to wells or springs.
6. According to Darcy's law, the flow rate through porous media is proportional to ________ and inversely proportional to ________.
7. The cross-sectional area of flow for a porous medium is actually much ________ than the dimensions of the aquifer. The actual velocity (interstitial velocity) is a velocity of ________; in contrast, the Darcy velocity is the average velocity of ________.
8. In Darcy's law, the factor $q = Q/A$ is called the ________, which has the dimensions of ________. It is also sometimes called the ________ velocity, which is not a true velocity as the ________ is partially blocked with soil materials.
9. The intrinsic permeability of geomaterial is considered to be independent of the pore fluid but only a function of ________, the units of the intrinsic permeability can be ________ or cm^2.
10. When the hydraulic head in a saturated aquifer or confining formation changes, water will be ________ or ________. The storage coefficient, or ________, is the volume of water that a permeable unit will absorb or ________ from the storage per unit ________ per unit change in ________.
11. Based on the relationship between properties and locations, aquifers can be divided into ________ and ________ formations; based on the relationship between properties and directions, they also can be considered as ________ or ________.
12. A homogeneous formation is one that has the same properties at all ________, while in a heterogeneous unit, hydraulic properties changes ________.
13. The continuity equation of seepage flow represents ________ and ________ of groundwater movement.
14. Water passes from one aquifer to another aquifer with different hydraulic conductivity, the direction of the flow path will ________.
15. Adjacent flow lines will be ________ to an impervious boundary and equipotential lines will ________ it at ________.
16. The larger value of the leakage factor B indicates that the ________ thickness of the aquitard, ________ hydraulic conductivity, ________ amount of leakage.
17. Groundwater models can be classified in several ways, steady state or ____________; confined, ____________ or a combination of ____________; one-dimensional, ____________, ____________, or ____________.
18. In Figure 1-1, based on the shape of groundwater depression cone, we can conclude that: for case (a), K_0' ________ K; for case (b), K_0 ________ K.

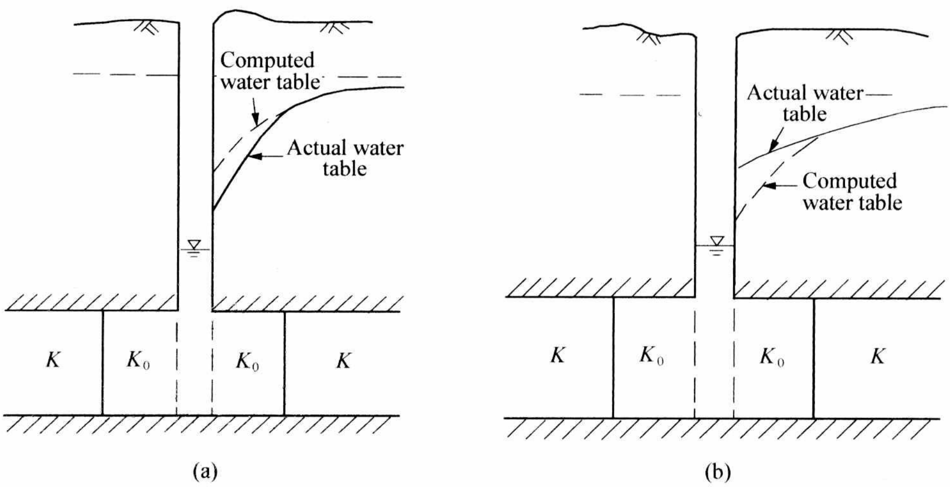


Figure 1 - 1

1.3 True-false questions

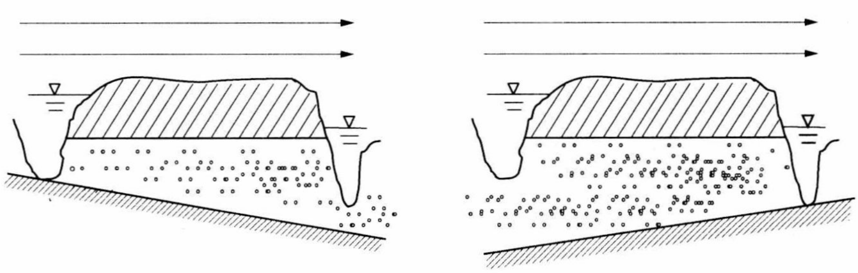
1. The uniformity coefficient of a sediment is the ratio of the grain size that is 50% finer by weight to the grain size that is 10% finer by weight, that is, $C_u = d_{50}/d_{10}$.
2. An aquifer should have ability to store and transmit significant water.
3. Storativity is a concept that also can be applied to an unconfined aquifer.
4. For an unconfined aquifer, specific yield and coefficient of storage are different concepts.
5. Practically, hydraulic head can be recognized as the driving impetus behind groundwater flow.
6. Darcy's equation is valid only when conditions are such that the resistive forces of viscosity predominate, which corresponds to a Reynolds number less than 1 to 10.
7. Generally, the constant-permeameter can be employed for measuring hydraulic conductivity of geo-materials with low permeability.
8. The intrinsic hydraulic conductivity of an aquifer remains constant no matter how much the salinity of the fluid changes.
9. Transmissivity is the amount of water that can be transmitted horizontally through a unit width of an aquifer under a hydraulic gradient equals to 1.
10. A homogeneous and anisotropic aquifer has constant hydraulic conductivity everywhere.
11. When flow refraction occurs, larger difference of the hydraulic conductivities of the two mediums results in smaller difference of incident angle and refraction angle.
12. For an aquifer formed by horizontal sub-layers, the equivalent hydraulic conductivity in the horizontal direction is always larger than that in the vertical

direction.

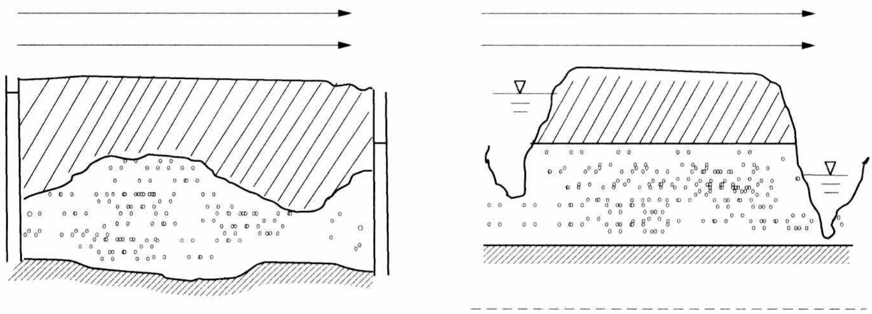
13. Groundwater cannot pass a no-flow boundary, while equipotential lines will intersect it at angles.
14. In deriving the equations for groundwater flow, the laws of mass conservation and energy conservation should be employed.
15. According to the law of mass conservation, any change in mass flowing into a small volume of the aquifer must be balanced by a corresponding change in mass flux out of the volume, or change in the mass stored in the volume, or both.
16. In seepage domain, intersection of flow lines could happen at certain places.
17. In a water-table aquifer, if there is recharge or discharge across the water-table, flow lines will be at an angle to the water table. If not, the flow lines can be parallel to it.
18. For groundwater flow, streamline is considered as drainage boundary and equipotential line is considered as impervious boundary.
19. In a homogeneous aquifer, flow lines and equipotential lines are always orthogonal.
20. In an isotropic medium, the flow lines are parallel to grad h, while in an anisotropic medium they are not.
21. Continuity equation and fundamental differential equation for groundwater flow are based on the law of mass conservation.
22. Leakage factor and leakage coefficients are parameters that indicate the leakage capacity of an aquifer.
23. Neumann boundary can be stream surface or equipotential plane. In some cases, it is also treated as Dirichlet boundary.
24. Practically, the boundary with known flow rate and hydraulic head can be treated as either Neumann boundary or Dirichlet boundary.
25. Surface water, such as streams or lakes, can be treated as Dirichlet boundary.

1.4 Construction problems

1. For each case in Figure 1 - 2, draw the hydraulic head profile for flow passes through aquifer.



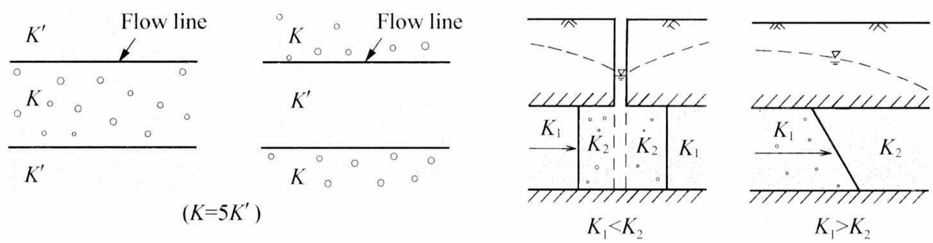
(a) (b)



(c) (d)

Figure 1 - 2

2. Draw the streamlines of the flow systems in Figure 1 - 3(a) and (b), respectively.



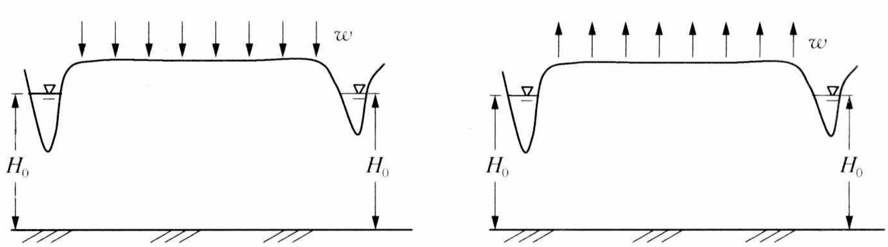
(a) (b)

Figure 1 - 3

3. An unconfined aquifer locates between two streams, which have same water heads, as shown in Figure 1 - 4. Draw:

(1) The water table of the aquifer in Figure 1 - 4(a) and (b), respectively;

(2) The schematic flow net.



(a) (b)

Figure 1 - 4

1.5 Analysis and calculation

1. A sand sample has a median pore radius of 0.12 mm. The fluid density is 1.02×10^3 kg/m^3 and the fluid viscosity is 1.16×10^{-3} N·s/m^2. If the flow rate is 0.006 m/s, is Darcy's law valid in the sample?

2. A confined aquifer with a thickness of 30 m has specific storage of 2.51×10^{-5} m^{-1}. Determine how much water can be released when the piezometric surface is lowered by 1 m over an area of 0.8 km^2.
3. A confined aquifer has a specific storage of 5.4×10^{-4} m^{-1} and a thickness of 25 m. How much water would it yield if the water declined an average of 4.0 m over a circular area with a radius of 150 m.
4. According to the falling-head permeameter in the Figure 1 - 5.
   (1) Derive the equation of calculation of the hydraulic conductivity of the geo-materials (sample) tested.
   (2) This method generally employed for measuring hydraulic conductivity of geo-materials with lower or higher values?

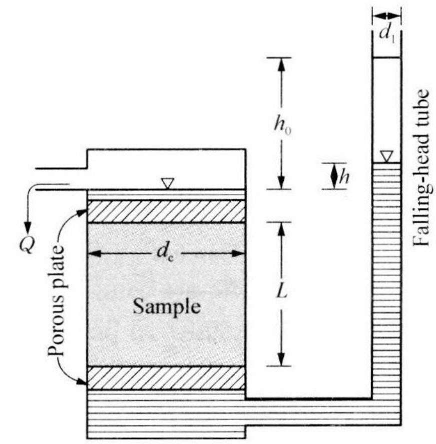


Figure 1 - 5

5. Consider groundwater flows through a confined aquifer with uniform thickness of 40 m, the discharge per unit width is 42 m^2/h, find the specific discharge (Darcy velocity) and the actual velocity of the flow when the effective porosity of the aquifer is given as 0.24.
6. The hydraulic conductivity of a confined aquifer is 30 m/d. There are two cross-sections A and B 4,200 m apart, the thickness of the aquifer linearly changes from 110 m in cross-section A to 70 m in B. When given H_A = 123.8 m, H_B = 150 m; Calculate the unit discharge q and the hydraulic head midway between A and B.
7. A confined aquifer locates on top of horizontal impervious bedrock; it has a varying thickness as shown in the Figure 1 - 6. Assuming the hydraulic conductivity of the aquifer K changes along x axis: $K = 10 + 0.004x$ (m/d), where $x = 0$ at section (A). If the piezometric heads at section (A) and (B) are 125 m and 118 m, respectively.

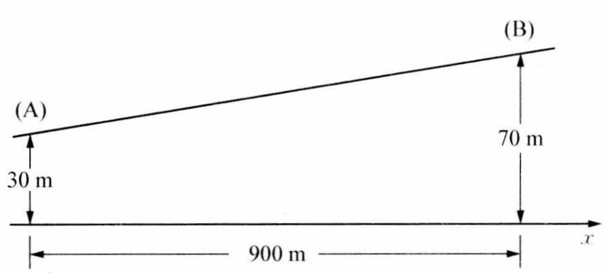


Figure 1 - 6

(1) Determine the flow rate per unit width.

(2) Plot the piezometric head between points A and B.

8. A falling head permeameter has a 10 cm diameter cylinder. The specimen tested is 30 cm long and the diameter of the tube is 12 mm. The initial water level in the tube is 25 cm above the outlet level and drops to 20 cm after 3 hours of operation. Determine the hydraulic conductivity of the specimen.

9. A confined aquifer has a thickness of 50 m and coefficient of storage 4.4×10^{-4}. The porosity of the aquifer is 0.24.

(1) Determine the fractions of the expansibility of water and compressibility the aquifer skeleton in making up the storage coefficient of the aquifer.

(2) Determine the compressibility of the aquifer skeleton, assuming that the compressibility of water is 4.2×10^{-10} m^2/N.

10. An unconfined aquifer has a porosity of 0.25 and a specific retention of 0.13. When groundwater level drops an average of 4.0 m over an area of 1.5 km^2, find the specific yield of the aquifer and the volume change of pore water.

11. A homogeneous and isotropic confined aquifer has a hydraulic conductivity of 18.5 m/d and a porosity of 0.24. The elevations of the piezometric head at two observation wells 800 m apart are 25.8 m and 22.5 m, respectively. Determine the specific discharge and actual velocity of the one dimensional steady flow.

12. An aquifer consists of three horizontal, homogeneous and isotropic layers, from top to bottom are labled as A, B and C, with hydraulic conductivity equals to K_A; K_B; K_C, respectively. Given $K_A = 2K_B$, $K_C = 2K_A$, if flow approaches the boundary of layer A and B with an incident angle of 40°, calculate the refraction angle in layer C.

13. A confined aquifer has three different horizontal formations. Formation 1 has a thickness of 6.0 m and a hydraulic conductivity of 5 m/d. Formation 2 has a thickness of 1.5 m and a hydraulic conductivity of 30 m/d. Formation 3 has a thickness of 8.0 m and a hydraulic conductivity of 8 m/d. Assume that each formation is isotropic and homogeneous.

(1) Determine both the overall (equivalent) horizontal and vertical hydraulic conductivities.

(2) If a hydraulic gradient of 5 is applied, find the flow rate.

14. An unconfined aquifer consists of four horizontal layers, each individually homogeneous and isotropic. From top to bottom, the four layers have their thickness and hydraulic conductivity of 10 m and 10.3 m/d; 8 m and 7.8 m/d; 4.5 m and 5.0 m/d, as well as 12 m and 3.0 m/d, respectively.

(1) Determine the equivalent horizontal and vertical hydraulic conductivities.

(2) Compare the equivalent hydraulic conductivities in (1).

15. A well penetrates a homogeneous, isotropic, infinitely extended unconfined aquifer. The initial groundwater table is at $H_0(x, y)$ above the impermeable bedrock. Derive the mathematical expression that describes the transient flow towards the well for each of the following conditions:

(1) The well pumps water at constant rate Q_w.

(2) The water table H_w remains constant in the well.

16. An aquifer is composed of n layers of identical strata, as shown in Figure 1 - 7. Each stratum has two alternating sub-layers with thickness of M_1 and M_2 and hydraulic conductivities of K_1 and K_2, respectively.

(1) Find the equivalent hydraulic conductivity: K_h in horizontal direction and K_v in vertical direction.

(2) Prove $K_h > K_v$ (Adapted from CHI Baoming et al., 2005).

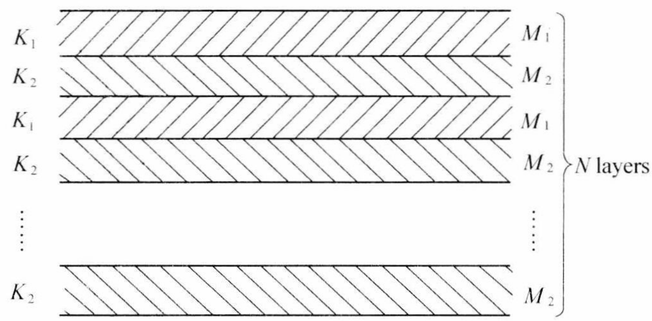


Figure 1 - 7

17. Based on the refraction of flow lines described in Figure 1 - 8, find out the relationship between K_1 and K_2.

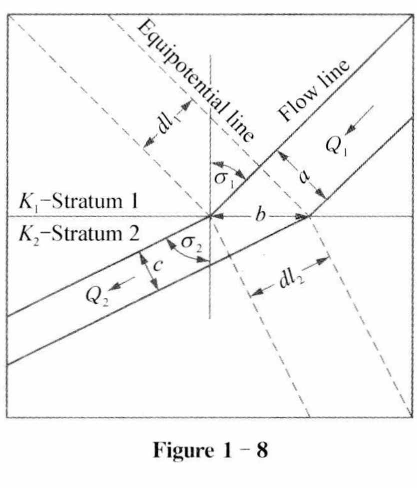


Figure 1 - 8

18. There is a leaky confined aquifer has a horizontal hydraulic conductivity of 0.8 m/h, which is overlain by an aquitard with a vertical hydraulic conductivity of 2.4×10^{-3} m/d. Given the flow in the aquitard is in the downward direction with an angle of 6° with the vertical (the incident angle), determine the refraction angle.

19. A confined aquifer has a constant thickness of 30 m and is stratified between two observation boreholes as shown in the following Figure 1 - 9.

(1) Derive the equation for calculation of the equivalent horizontal hydraulic conductivity of that section of the confined aquifer between the observation boreholes.

If $K_1 = 12$ m/d, $K_2 = 9$ m/d, $K_3 = 35$ m/d; $L_1 = 80$ m/d, $L_2 = 120$ m/d, $L_3 = 240$ m/d.

Determine the equivalent horizontal hydraulic conductivity.

(2) Given the piezometric surface elevations as indicates in the Figure, determine the flow per unit width of the aquifer. Plot the potentiometric surface between the two observation boreholes.

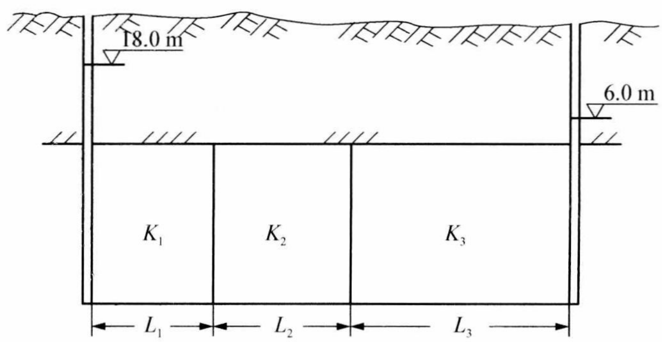


Figure 1 - 9

20. Figure 1 - 10 is a profile of a uniform, horizontal confined aquifer. There are two observation boreholes A and B, with elevations of the piezometric head readings of $H_A = 50.2$ m and $H_B = 45.8$ m. The thickness of the aquifer is 45 m, along the flow direction there are 3 sub-layers with the length of $L_1 = 300$ m, $L_2 = 600$ m and $L_3 = 100$ m, corresponding hydraulic conductivities are given as $K_1 = 35$ m/d, $K_2 = 15$ m/d and $K_3 = 20$ m/d, respectively.

(1) Calculate the equivalent horizontal hydraulic conductivity and the discharge per unit width.

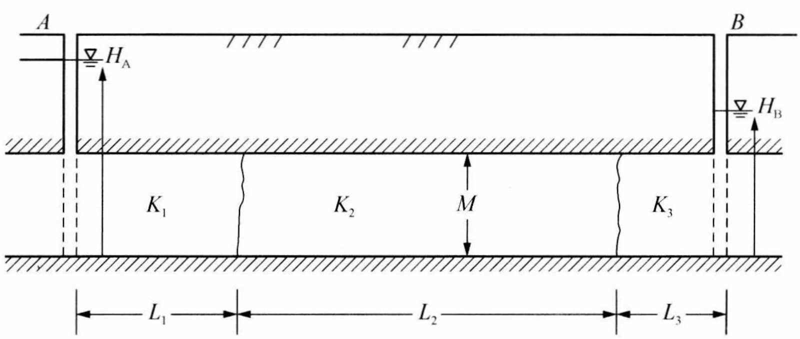


Figure 1 - 10

(2) Plot the profile of piezometric head.

(3) Rework on (1) and (2) if $H_B = 43.8$ m.

21. Figure 1 - 11 is a horizontal homogeneous and isotropic unconfined aquifer with an impervious boundary on left and a recharge boundary (river) on the right. Groundwater flow in the aquifer can be recognized as two-dimensional horizontal unsteady flow. Given the hydraulic conductivity K(m/h) and an average precipitation rate of e (m/h). Nine fully penetrating wells pump at a same constant rate of Q (m^3/h). Derive the mathematic model for description of the groundwater flow.

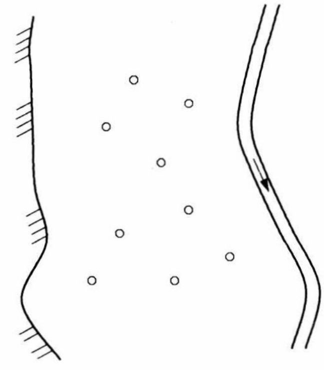


Figure 1 - 11

22. A homogeneous, isotropic earth dam is built on top of an impervious bedrock layer (Figure 1 - 12). Derive a mathematical model that describes the 2D transient flow in this flow domain.

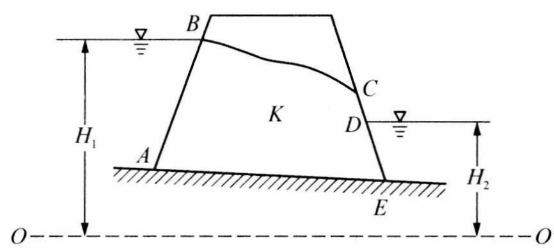


Figure 1 - 12

23. Figure 1 - 13 includes the topography and hydrogeological profile of a groundwater resources area. The amount of groundwater extraction is given as e; derive the mathematical equation that describes the transient flow in this region.

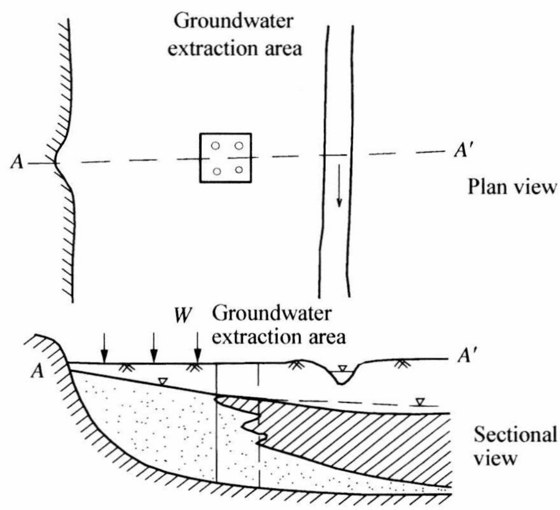


Figure 1 - 13

24. For the confined-unconfined aquifer system shown in Figure 1 - 14, derive the equation that describes the natural discharge q per unit length; also plot the phreatic surface between H_1 and H_2.

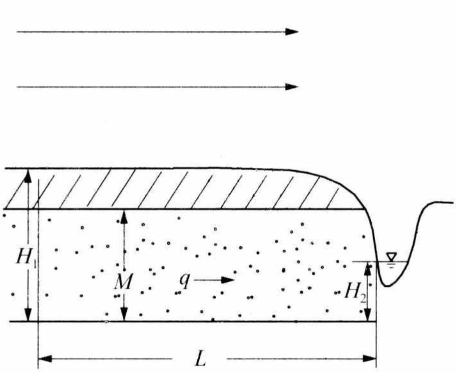


Figure 1 - 14

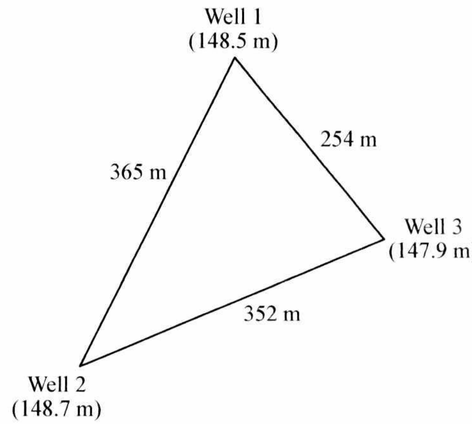


Figure 1 - 15

25. The total heads of three observation wells and distance between them in a regional aquifer are tabulated below (Figure 1 - 15). Determine the direction of groundwater flow and hydraulic gradient.

26. In Figure 1 - 16, the sand column has a length of 140 cm and a diameter of 24 cm. The sample with an effective porosity of 0.23 is tested under a constant head difference h_L = 180 cm with water at 22℃. Given the constant discharge Q to be 0.23 m^3/h, determine:

(1) The hydraulic conductivity of the sand sample.

(2) The actual flow velocity in the sample.

(3) The intrinsic permeability of the sample (Density of water at 22℃: 997.8 kg/m^3, viscosity of water at 22℃: 0.009 61 g/(s · cm)).

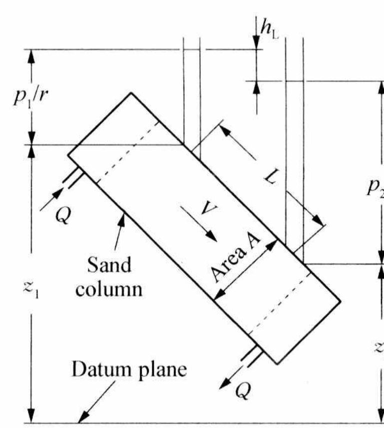


Figure 1 - 16