

Application of Fluid Dynamics in Geotechnical Engineering

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Abstract. Nowadays there are lots of problems with a background in geotechnical engineering that cannot be separated from another important subject, fluid dynamics. Such problems include, for example, leaking problems with ground foundations, turbulent water in groundwater, and so on. This passage organized basic knowledge of two subjects that directly help to understand complex problems and introduced some advanced solutions to solve the problems of these complex problems. Darcy's Law is the key to working out all the leaking problems under earth because of the low speed and rate of flow. Turbulent water is a hot topic to talk about and there are no such overall equations as Darcy's Law to understand different problems but it's possible to combine the half-rational equations and the data of the field survey together and concluded a new formula. To understand more such complex problems, using simulating software is a good choice and there will be more and more topics containing interdisciplinary knowledge in the future.

Keywords: Geotechnical engineering; Fluid dynamics; Turbulent water.

1. Introduction

There are many problems covered by the knowledge of both geotechnical engineering and fluid dynamics. It's very common to see fluids in the geotechnical area, such as water and air which are the most important studying objects for fluid dynamics. So, how to appropriately use the application of fluid dynamics is essential to a geotechnical engineer. In this passage, there will be introduced three very significant applications, which are rather very common in daily life or contain high value to be researched.

Before introducing the three applications, we will have an eye on the history of both two research areas. It's interesting and beneficial to understand the developing conditions and some meaningful mathematical or physical formulas that have been classified or created by different scientists. And then we can introduce the three applications or problems with a specific area of knowledge. For leaking problems with ground foundations, the first thing that needs to understand is how severe the load has the water created for the whole ground foundations. For groundwater turbulence, there are some advanced calculating methods that can be introduced which are summarized by some scientists. The hydrology of surface drainage and runoff is a big research area, which nowadays is a hit for environmental fluid mechanics.

In all, these three applications represent the combination of two research areas and there are still many problems in these two areas that need to be solved in the future. Applications of fluid dynamics in geotechnical engineering are gradually becoming the most crucial parts in geotechnical engineering.

2. History of fluid dynamics and geotechnical engineering

2.1 Development of the fluid dynamics

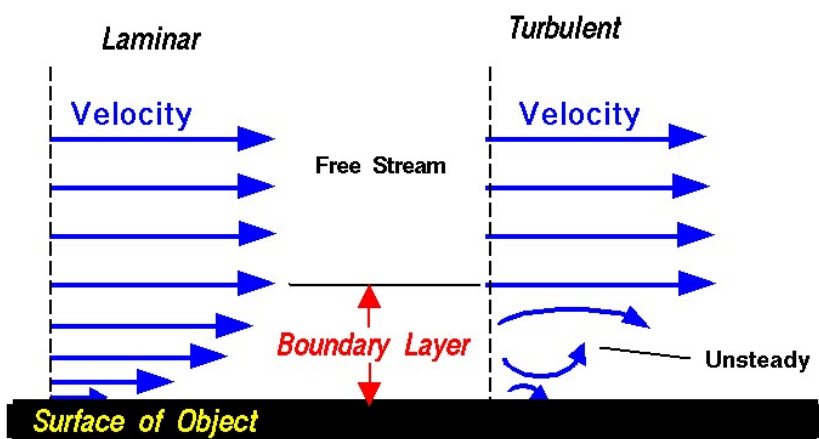
Fluid dynamics is a part of Mechanics, which mainly focus on the state of rest and moving of the fluid itself and the law of interaction and flow between a body and a solid boundary wall in relative motion. Specifically, the fluid here mainly refers to water and air. Research on fluid dynamics developed from production practice and struggling of human beings against natural hazards such as flooding. Archimedes laid the groundwork for hydrostatics by implying the physical law of buoyancy. There are many different stories in the world saying that our ancestors paid much attention to the management of water in the river. For example, in ancient China, there are stories of Yu the Great,

who successfully dredged the river so that farmers could regularly plant without damage from flooding.

The mathematical mechanics of the nineteenth century began to study new theoretical models. Navier first added a viscous force term to the fundamental equations of ideal fluid mechanics, and Stokes finally obtained the fundamental equations of viscous fluid mechanics known as the Navier-Stokes equations (Figure 1). The emergence of viscous fluid mechanics is of great theoretical and practical significance. Later Reynolds found that there are two flow states of viscous flow, laminar flow, and turbulent flow (Figure 2), and subsequently derived the mean N-S equation, which is called the Reynolds equation. The theory of viscous fluid dynamics correctly explains the contradictions between the results of ideal fluid dynamics theory and many practical flow phenomena, which makes it possible to analyze the real flow in the real world.

$$\rho \frac{\partial \vec{v}}{\partial t} + \rho(\vec{v} \cdot \nabla) \vec{v} = -\nabla P + \vec{\gamma} \rho + \mu \nabla^2 \vec{v}$$

Fig. 1 Navier-stoke equations



Velocity is zero at the surface (no - slip)

Fig. 2 Flow states of viscous flow

Aerodynamics was greatly enhanced by the advent of aircraft in the early 20th century. With the development of the aviation industry, it is expected to reveal the pressure distribution around aircraft, the force condition, and the resistance of aircraft, which promotes the development of fluid mechanics in experimental and theoretical analysis. Scientists such as Rutkowski and Capeskin developed the wing theory, which was based on the potential flow theory of incompressible and incompressible fluid, and explained how the wing would be subjected to an upward force so that air could lift a heavy aircraft into the sky. The correctness of the wing theory makes people re-understand the theory of invisible fluid and confirms its great significance in guiding engineering design.

From the 1950s, the continuous improvement of electronic computers, so that the original use of analytical methods difficult to study the subject, can be carried out by numerical calculation method, computational fluid dynamics (CFD) this new branch of the discipline (Figure 3). At the same time, due to the needs of civil and military production, fluid dynamics and other disciplines have also made great progress. In the 1960s, according to the needs of structural mechanics and solid mechanics, the finite element method for the calculation of elastic problems appeared. After more than ten years of development, finite element analysis (FEA), a new computational method, has been applied in fluid

mechanics, especially in the low-velocity flow and the complex shape of the fluid boundary. In recent years, the finite element method has been used to study the problem of high-speed flow, and the interpenetration and fusion of the finite element method and difference method have also appeared.

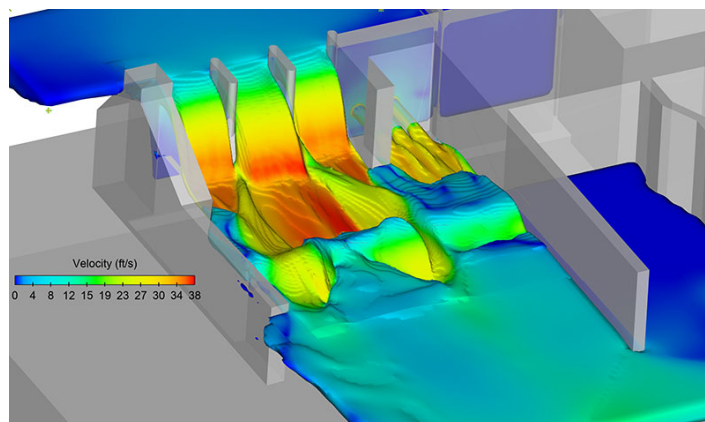


Fig. 3 Example for CFD method

Since the mid-1960s, some experimental results have slowly begun to change conventional wisdom. In recent decades, a new understanding has been growing, that is, the transport properties of most turbulent shear flows are controlled by large-scale eddy motions, which are not random or disordered, but organized quasi-order structures, which may be described by chaotic processes with seemingly random structures. It seems that traditional research ideas will give way to new ones.

2.2 Development of geotechnical engineering

Geotechnical engineering is a subject mainly created in modern society, which is inevitably developed for more and more complicated construction works. The research on geotechnical engineering focuses on the environment of the local earth and the necessary needs for constructing the projects such as buildings and bridges. This subject provides the basic theories and plans for planning, designing, and constructing specific projects. So, the geotechnical engineers need to make sure that the projects are safe, convenient, and economically usable from the prospect of the earth and ground.

Because that geotechnical engineering takes the earth as the materials for the ground or as a medium for the projects. Engineers for this subject need to consider the strength and deformation of the earth under loads in different situations such as in different temperatures and humidity. In all, the calculation of the strength and deformation of the earth is the basic theory for this subject.

Before the 18th century, geotechnical engineering hasn't developed theoretically so many problems can only be solved by experience. From 1773 to 1776, French Coulomb put forward the theory of shear strength, earth pressure, and sliding soil based on tests. Soil mechanics entered the classical theory period in 1857, Rankine established a new theory of earth pressure based on plastic stress field. In 1885, Roussinesq of France obtained the theoretical solutions of all six stress components and three deformation components of elastomeric bodies in semi-infinite space under the action of vertical concentrated forces, which established the theoretical basis for future calculation of foundation deformation. Darcy (1856) established Darcy's formula through the seepage test of water in the sand, which laid a foundation for the study of seepage and consolidation theory in the future (Figure 4). In 1922, Fellenius of Sweden put forward the analysis method of soil slope stability when dealing with railway landslides. In 1925, the American soil mechanic Terzaghi (Terzaghi) "soil mechanics" (Erdbaumechanik), soil mechanics entered a new period, making soil mechanics an independent discipline.

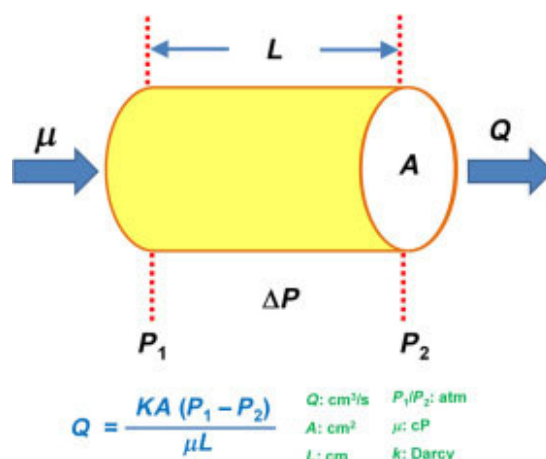


Fig. 4 Darcy's law

1956 was the first year of the modern theory of geotechnical engineering. This is marked by the academic conference on the shear strength of clay held in Boulder, Colorado, USA, and the ongoing work on the stress-strain properties of soil in the UK. In the following time, due to the popularization of computer applications, soil mechanics in the basic theory, calculation methods, indoor and field test equipment, and many other aspects have made a revolutionary development.

3. Applications of two theories

3.1 Leaking problems with ground foundations

Almost every project underground has the problem of leaking water, not only those projects existing for hundreds of years or experiencing some natural hazards such as earthquakes and flooding but also those new projects. If we cannot solve the problem of leaking properly, we may face more severe questions such as surface subsidence and erosion of the structure of the buildings.

In Geotechnical engineering, leaking problems with ground foundations are very common to see and there are some strict technical solutions to solve the problems. For example, If it is a small range of water seepage, basically should be able to find the approximate position of the water seepage, can follow the wall to the side of the soil to waterproof after hitting concrete backfill, and then should also be cleaned after the wall waterproof, to avoid water seepage damaging wall structure again.

However, as an engineer, we should consider the problem in advance, which means that if we construct the concrete plate not only hard enough that can resist the load and erosion of the water seepage but also obey the rules that lessen the waste of money and time, we can reduce the consumption of materials and other resources to a minimum. And to achieve this goal, we must use the knowledge of fluid dynamics, especially Darcy's law and other formulas.

When water is flowing through the earth, as long as there is a hydraulic gradient between different locations, water will flow at a speed and thus, creating the amount of leaking quantity of water. But also, because of the diversity of different rocks and earth (their different shapes and voids), the speed of the water and the leaking quantity will be very different. According to the speed, leaking area, and leaking quantity of the water, we can easily calculate the force of the underground water and choose the appropriate number of concrete plates to resist the load for a long period. To calculate the seepage speed and so on, as shown in Figure 5, we can use some software to draw a cross-section of one area and investigate all the information about the earth and water such as permeability. Then according to all the information, we get, we can use Darcy's law whether in one dimension or more dimensions to calculate the seepage speed and seepage amount, which finally relates to the hitting force of the water to the ground foundation.

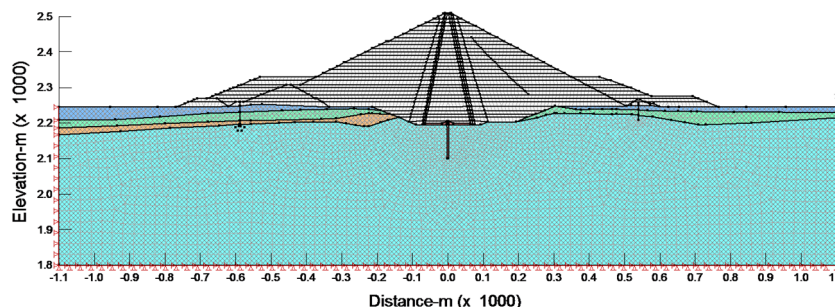


Fig. 5 Cross-section of different rocks in one area

With the input of all the information from field surveys and the flow net for the whole area. Thus, it's convenient to simulate other dynamic problems such as the landslide, which contains both fluids and solids. It's more and more common to use such software to prevent natural disasters in advance which obviously, needs the knowledge of two main subjects mentioned in this passage.

3.2 Groundwater turbulence

Ground turbulence is a popular topic these days, which basically starts from the question of laminar flow and turbulence flow. More and more cases tell us that there is not only laminar flow in our life, but we need to consider the turbulence flow whose Reynold's number is higher than 4000 in many situations.

First, groundwater is an important concept in geotechnical engineering, Groundwater is widely distributed and closely related to people's production and life and engineering activities. He is one of the important sources of water supply and so on, on the one hand, is a precious natural resource, on the other hand, it interacts with stone, can reduce the soil and rock mass strength and stability, produce all kinds of the bad geological phenomenon of nature and of engineering geological phenomena, such as collapse and landslide erosion foundation road frost heaving, has a harmful effect on the normal use of engineering.

For most constructions such as dams and underground structures, it's most important to know the flow rate of the groundwater. We know that, for laminar flow, we can use Darcy's law to calculate the flow rate just as I mentioned above for the leaking problems. However, for most constructions, the flow speed and flow rate of the fluid are really high which should be classified as turbulence flow. For turbulence flow, we still haven't created a unified formula as Darcy's law for laminar flow. So, for different constructions, we need to use different semi-rational formulas.

For example, Carl Hector dam, Chinese scientists Chengxian, Li, and his partners concluded that compared to Darcy's law, a semi-rational formula based on the Krasnopolsky formula is a better fit to the real observing data and should be used for this dam when estimating future flow rate for this dam:

$$Q = K (H_1^3 - H_2^3)^{0.515} B / (3L)^{0.515} \quad (1)$$

Where H_1 and H_2 represent the water head upstream and downstream. B represents the penetration of the bandwidth and L represents the length of the penetration zone.

4. Discussion

By using the basic knowledge of fluid dynamics and geotechnical engineering, many problems can be solved. As talked about before, Darcy's Law can be used to solve the problem of laminar flow, which occurs more at a low speed of fluids, such as flowing water inside the earth. Thus, leaking problems with ground foundations, penetration problems inside dams, and so on can be solved in this way. To estimate the flow rate of turbulence flow such as groundwater and river rapids, a semi-empirical method needs to be considered in different situations. Also, problems cannot be solved only depending on the formulas from fluid dynamics, we need to investigate the nature of different

locations such as the properties of the earth, and the constructions (hardness, compressibility, permeability...).

There are more cases proving that the future of mixing these two subjects is meaningful and many universities around the world have set up such research organizations to push the fusion forward. For example, the University of Dundee has set up research about exploring the area of mixing geotechnical engineering and fluid dynamics. Their research concluded decommissioning of offshore oil & gas, low-carbon geotechnical engineering, and so on. The University of British Columbia and Cornell University have research areas named Environmental Fluid Mechanics which concluded many specific cases in the geotechnical area. To sum up, it's more and more popular to study hydrology and geology from an interdisciplinary view.

5. Conclusion

In all, Geotechnical Engineering and Fluid Dynamics are two subjects that cannot be separated. Fluid Dynamics is more like a tool, and it can be used everywhere in the geotechnical field. N-S equation, Darcy's Law, and equations for all turbulence flow are all very basic knowledge for geotechnical engineering. Nowadays, it's also very common to use computer methods to simulate real questions in advance which can lower the risk of different constructions. For example, as I mentioned before, CFD is widely used in different software for different fluids. Also, Finite Element Analysis is very popular in geotechnical engineering to solve coupling problems such as for the settlement of the ground. These concepts are individually but also will be mixed to use in today's real problems. These two subjects now create many interdisciplinary solutions for all real questions. There are more we can search or find in these areas.

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