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DOI
10.1111/gwat.13260

Publication date
2022

Document Version
Final published version

Published in
Groundwater

Citation (APA)
Bakker, M., Haitjema, H. M., & Strack, O. D. L. (2022). Arnold Verruijt (1940-2022). *Groundwater*, *60*(6), 851-853. https://doi.org/10.1111/gwat.13260

Groundwater

Arnold Verruijt (1940–2022)

by Mark Bakker[1,2], Henk M. Haitjema[3], and Otto D.L. Strack[4]

Introduction

Arnold Verruijt (Figure 1) was a civil engineer and a professor of Soil Mechanics at the Delft University of Technology in the Netherlands from 1975 to 2002. His primary contributions were in the fields of linear elasticity and poro-elasticity, more so than in groundwater flow. He nonetheless influenced the field of groundwater flow significantly by explaining in easily understandable terms how to solve groundwater flow problems effectively using analytic solutions and complex variables and, at the other end of the spectrum, how to simulate groundwater flow with numerical methods. At a time when computer modeling of groundwater flow was in its infancy, the 1970s, numerical modeling of groundwater flow was unpopular, as both input and results of computer models were entirely in terms of numbers, often resulting in unrealistic models. Arnold demonstrated, through creating finite-element programs in BASIC on early desktop computers, how computer modeling of groundwater could be very useful. The programs were so simple, yet so useful, that students and colleagues were able to learn the basic principles of numerical modeling of groundwater flow and how to apply them.

Arnold wrote 11 books; all but 1 as sole author, and 2 on groundwater flow, 1 with Jacob Bear. He published 124 papers on a broad range of topics, from very practical to highly theoretical, but always outstanding in terms of the rigor of his work.

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Received September 2022, accepted September 2022.

doi: 10.1111/gwat.13260

Figure 1. Arnold Verruijt accepting the Maurice A. Biot medal in 2014.

Major Publications on Groundwater Flow

In 1969, Arnold published a 45-page treatise on elastic storage in aquifers (Verruijt 1969) where he discussed the topic from the physical principles of soil mechanics. He demonstrated, for example, that a pumping test on a well screened in the upper aquifer of a two-aquifer system may result in an initial increase of head in the lower aquifer. This phenomenon, first observed in the field near the village of Noordbergum in the Netherlands, is known as the Noordbergum effect.

Arnold published *Theory of Groundwater Flow* (Verruijt 1970), one of the first books dedicated to the topic, early in his career. He provided a lucid summary of the principles of groundwater flow, derived several analytic solutions for steady flow including advanced solutions using complex variables and the hodograph method; the book includes exercises with solutions. *Theory of Groundwater Flow* is a remarkably concise discussion of what Arnold later called groundwater mechanics and convincingly illustrates Arnold's unique ability to reduce complex material to its essence.

Chapter 10 of *Theory of Groundwater Flow* contains an early discussion of the finite-element method to

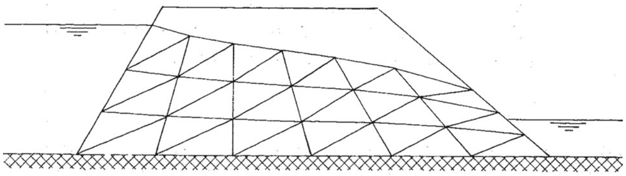

Figure 2. Flow through a dam with a phreatic surface simulated with 36 finite-elements (Verruijt 1982).

simulate groundwater flow. Results are shown for two-dimensional unconfined flow through a dam, both steady and transient. This problem is difficult to solve because the phreatic surface is a free boundary of initially unknown position. Arnold fell in love with the finite-element method and pioneered its application on a computer. The second edition of his book was published in 1982 (Verruijt 1982), the same year as the release of the Commodore 64 (one of the first home computers with 64 KB of memory). The chapter on the finite-element method was expanded to include several BASIC programs for two-dimensional groundwater flow, which could be run on a Commodore 64 or PET. For example, steady flow through a dam with a phreatic surface and sloping faces was simulated with 36 triangular elements (Figure 2). The BASIC script consisted of just 40 lines of (condense) code, including 3 lines of data, an implementation of the Gauss–Seidel method to solve the matrix iteratively, and iteration to find the position of the phreatic surface in the dam. Such a small program, and the description and derivation that preceded it, clearly shows how the method works. The results are fully reproducible, already in 1982. Conversion of such a small program to a modern language (e.g., Python) would still be a very useful method to learn the fundamentals of the finite-element method.

In 1987, Jacob Bear and Arnold Verruijt published *Modeling Groundwater Flow and Pollution* as part of the series *Theory and Applications of Transport in Porous Media* which was edited by Jacob Bear (Bear and Verruijt 1987). The first seven chapters were devoted to the mathematical theory of transport in porous media and were written by Jacob Bear. Chapters 8 through 13 are devoted to solutions of the differential equations presented in the previous chapters and were written by Arnold. Verruijt briefly discussed four numerical methods of solution: the finite-difference method, the finite-element method, the boundary element method, and the analytic element method. He then proceeded with the finite-difference and finite-element methods, referring the reader to the literature for the other two methods. He illustrated these methods with simple numerical examples and offered BASIC computer code for 39 examples, varying from snippets of a few lines to complete programs of up to 200 lines. He also offered sample input data and graphical output, and compared finite-element solutions with analytic solutions where possible, illustrating both the power and limitations of (approximate) numerical techniques. His programs provided a practical and transparent illustration of how to solve several fundamental problems of groundwater flow and solute transport, including density flow and dispersion. This hands-on computer programming approach, suitable for the then emerging personal computer (PC) market, was ahead of its time. These programs, together with those from several other books he authored, are available at https://geo.verruijt.net/

Arnold's latest book is called *Theory and Problems of Poroelasticity*, which he published on his own website (Verruijt 2016). The book is accompanied, not surprisingly, by a set of computer programs (this time in C), which are available from the same website. The book gives a state-of-the-art treatment of poro-elasticity, formerly called the theory of consolidation. Chapter 5 is of special interest for groundwater engineers, where flow to pumping wells is considered, again from the basic principles of soil mechanics. Arnold demonstrated that horizontal displacements in a pumped aquifer cannot always be neglected, as is often done. In the last chapters, he revisited the solution for flow to a well in a layered system, where he used the finite-element method to simulate the Noordbergum effect, a phenomenon that he wrote about almost 50 years earlier (Verruijt 1969).

Teacher and Mentor

Arnold taught courses in soil mechanics, groundwater flow, applied mechanics, and the theory of elasticity. Arnold's teaching style was unique. He had a relaxed demeanor and succeeded in making complex concepts easy to understand. Many alumni remember Arnold's classes fondly and tried to copy his teaching style. Arnold was elected Best Teacher by the civil engineering students on several occasions.

In his early years of teaching, Arnold's groundwater class was accompanied by a lab where the students used carbo-coated paper (Teledeltos paper) and silver-loaded paint to simulate groundwater flow in two dimensions (Figure 3). The silver-loaded paint was used to create canals and lakes (equipotentials) and a dot of paint connected to a copper wire served as

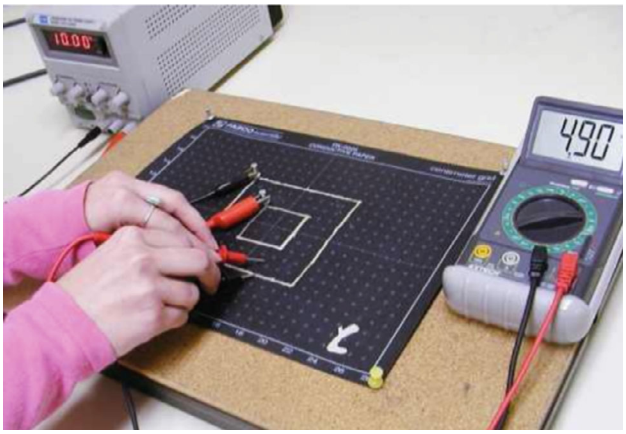

Figure 3. Simulating groundwater flow with Teledeltos paper (UCSD 2010).

a well. Equipotentials were traced on the Teledeltos paper (aquifer) using a multimeter—a trial and error procedure. The lab experience was enlightening as the groundwater formulas that were taught in class came to life in these experiments. Arnold embraced the PC early on, and moved the exams of his groundwater class to PCs in the 1980s, using software he wrote himself (Figure 3).

Outside the classroom, in a mentoring role, Arnold had an informal relationship with his students that made him very approachable and fostered learning. He encouraged his students to be on a first-name basis with him, even in the 1970s, which was quite unusual for that time, at least in the Netherlands. He was also very supportive of his students, often putting their career interests above his own. Arnold supervised 36 Ph.D. students of which 6 dealt directly with groundwater flow, on a broad range of topics varying from dispersion and non-linearity to periodic flow and the hodograph method.

Arnold Verruijt passed away on August 4, 2022, at the age of 82. Those who know his work, and especially those who attended his lectures, will remember the extreme clarity that accompanied the rigor of his explanations. Arnold Verruijt will be sorely missed by his colleagues.

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