The Maturity of Analytic Element Ground-Water Modeling as a Research Program (1980-2003)

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ABSTRACT: Activity of the analytic element method research program for ground water flow modeling was investigated through the publication record from 1980 to 2003. Citation information was obtained from SCI Journal Citation Reports and the Web of Science databases maintained by the Institute for Scientific Information (ISI), and total publications by year are presented in a histogram, showing an increasing trend. A classification of ground water flow publications by numerical solution technique to date is shown in a pie chart: finite elements (55%), finite differences (37%), boundary elements (5%), and analytic elements (3%). In addition, a scientific genealogy was researched and a "family tree" drafted, starting with analytic element founder Professor Otto D.L. Strack of the University of Minnesota. It is concluded that that while the analytic element method is still a young and small research program, it is still in a progressive phase.
KEY WORDS: analytic element method, research program, historical analysis, citation record

1 Introduction

It is interesting to assess the development of scientific and technical research programs in the perspective of the Hungarian philosopher of science Irme Lakatos. A research program is recognized by its hard core (e.g., assumptions, methods, acceptance criteria) and protective belt. The strength of a research program is the extent to which it leads to natural predictions or solving new problems. A research program can be in a progressive phase, or in a degenerating phase.

The *analyic element method* (AEM) is a computational method based on the superposition of analytic expressions to represent any three-dimensional or two-dimensional vector field. For the purposes of this paper, the discussion will be restricted to the application of the AEM to regional groundwater flow modeling. The emergence of the AEM is relatively recent in comparison to more mature methods, such as finite differences (first journal reference 1969) and finite elements (first journal reference 1971). AEM is closely related to boundary elements (first journal reference 1981). It is difficult to assign the definitive first publication of the analytic element method. However, it is universally recognized that Professor Otto D.L. Strack of the University of Minnesota was the inventor. For a historical perspective on the emergence of the AEM, the reader is guided to the autobiography sketch by Dr. Strack [*Strack*,2003a].

The essentials of the theory began to come together in a series of journal articles [*Strack,Haitjema*,1981a], [*Strack,Haitjema*,1981b], [*Strack*,1982],[*Strack*,1984], [*Haitjema*,1985], [*Strack*,1985], [*Haitjema*,1987a], [*Haitjema,Kraemer*,1988], reports [*Strack et al.*,1980], [*Strack*,1982b], [*Haitjema,Strack*,1985], and theses [*Haitjema*,1982], [*Curtis*,1984], [*Fitts*,1985], [*He*,1987], [*Zaadnoordijk*,1988]. A definitive and comprehensive publication was the book Groundwater Mechanics by *Strack* [1989b].

A formal and mathematical definition of the hard core of the AEM in its current form is available [*Strack*,2003b]. In layman's terms, and in order to be recognized as part of the AEM research program as presented in this paper, the technique must be based on the superposition of closed-form analytic functions in an infinite domain, with these functions representing some expected hydrologic (ground water) performance, either in two dimensions (Dupuit assumption) or three dimensions, with internal or external boundary conditions being met approximately at control points, maintaining water balance and continuity of flow, and showing lineage to Strack either through a direct or indirect education pathway or through citation/nomenclature.

It has been observed at a past conference that the AEM is considered a "cult" by outsiders based on the passion of its participants. This is further evidence that the AEM is a Lakatosian research program. Is this passion being translated into a progressive research program? Or are the adherents clinging to a degenerating program? An examination of the publication record does reveal that while the AEM has a small part of the groundwater modeling market share, the total number of annual publications continues to rise, indicating the this young research program is still progressive.

2 Methods

Citation information was obtained from SCI Journal Citation Reports and the Web of Science databases maintained by the Institute for Scientific Information (ISI), and from the Proceedings from each of the International Conferences on the analytic element method: (Indianapolis,IN, USA 1994), (Nunspeet, The Netherlands, 1997), (Brainerd, MN, USA, 2000).

In order to compare the publications related to the numerical modeling technique, the IBI database was searched with a strict Boolean requirement. For example, the search might look like “analytic element AND (groundwater OR ground water OR ground-water)”.

All other information was supplied through a collection of individual researchers curriculum vitae or from public web pages.

3 Results

The Top Ten analytic element publications are listed in Table 1 based on the number of ISI Web of Science citations as of March 2003. The two most cited works are the books, Strack’s **Groundwater Mechanics**, and Haitjema’s **Analytic Element Modeling of Groundwater Flow**.

The number of annual analytic element method publications is showing a increasing trend over the period 1980-2003, as shown in Figure 1. The publications include articles, reports, proceedings, and master theses and doctoral dissertations. The spikes in the histogram correspond to additional publications from the proceedings of the international conferences on the AEM: Indianapolis (1994), Nunspeet (1997), Brainerd (2000). The 2003 year is a partial total through September. A comprehensive AEM bibliography is presented at the end of this paper.

The total ground water modeling publications through March 2003 from the IBI database classified by numerical modeling technique are shown in Figure 2. The pie chart shows that finite element publications account for around 55%, while finite difference publications account for about 37%, and boundary element around 5% and analytic element around 3%.

The publicly available ground water flow solvers are shown in Table 2. Pubic domain software gives the model user complete freedom to change, modify, or copy the source code. Open source software may place some restrictions on the source code. And freeware does not have any cost but the source code is usually not available.

It is interesting to visualize the genealogy of the analytic element research program as a family tree, starting with the inventor, Professor Otto Strack (Figure 3.

Table 1: Top Ten analytic element publications based on the citation record.

Citation	ISI times cited as of March 2003	Description
[Strack, 1989b]	130	Groundwater Mechanics
[Haitjema, 1995a]	27	Analytic Element Modeling of Groundwater Flow
[Haitjema, 1985]	26	Modeling 3D flow in confined aquifers
[Strack, 1984]	21	3D streamlines in DF models
[Strack,Haitjema,1981b]	21	Modeling double aquifer flow using distributed singularities 2.
[Strack,Haitjema,1981a]	16	Modeling double aquifer flow using distributed singularities 1.
[Haitjema,Kraemer,1988]	14	Analytic function for modeling partially penetrating wells
[de Lange,1991]	13	A groundwater model of The Netherlands
[Bakker,Strack,1996]	12	Capture zone delineation in 2D groundwater flow models
[Haitjema,1987a]	11	Comparing 3D and DF solution to a circular recharge area

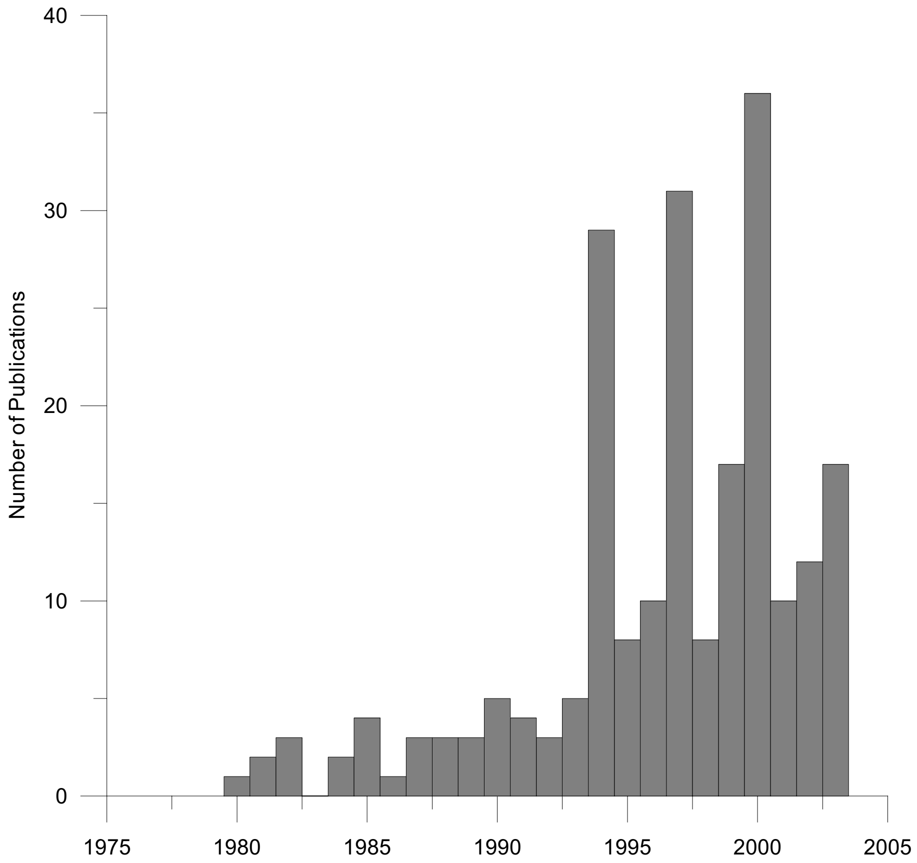

Figure 1: Analytic element publications versus time 1981-2003. Note the years associated with an international conference and the proceedings: Indianapolis (1994), Nunspeet (1997), Brainerd (2000).

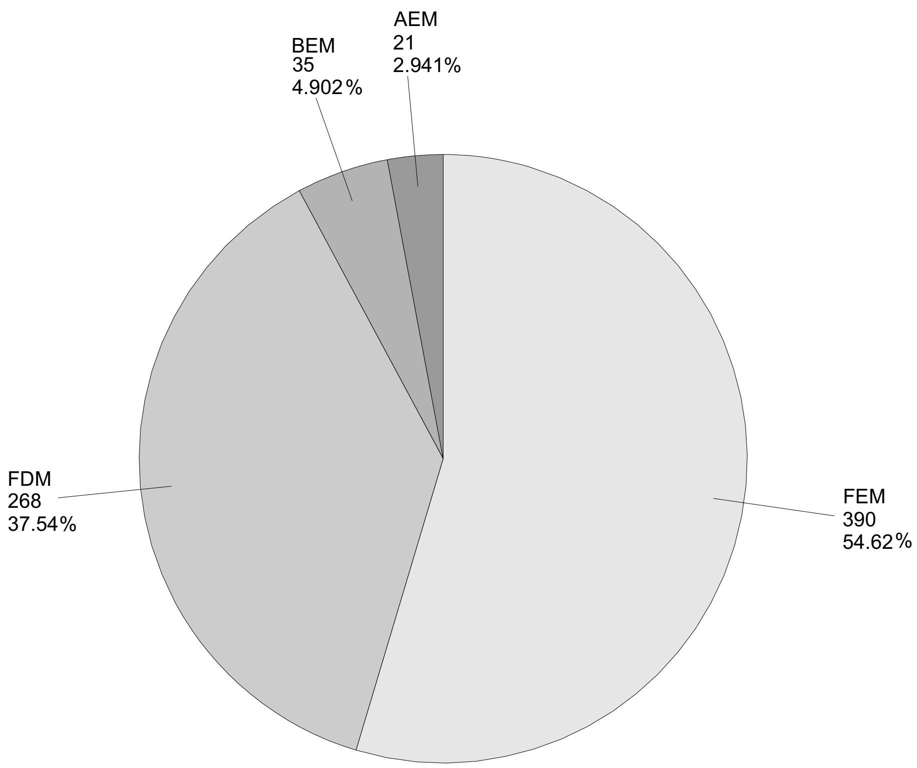

Figure 2: Total ground-water modeling publications from IBI database as of March 2003 classified by numerical modeling technique: finite element method (FEM), finite difference method (FDM), boundary element method (BEM), and analytic element method (AEM).

Table 2: Publicly available ground water flow solvers.

Software Name	Solution method	License
W*h*AEM2000/GFLOW	analytic element	open source
www.epa.gov/athens/software/whaem/index.html		
Tim^{SL}/Tim^{ML}	analytic element	open source
www.engr.uga.edu/∼mbakker/tim.html		
MODAEM	analytic element	open source
modaem.sourceforge.net/		
SPLIT	analytic element	open source
www.groundwater.buffalo.edu/software/software.html		
CZAEM	analytic element	freeware
www.epa.gov/ada/csmos/models/czaem.html		
PhreFLOW	analytic element	open source
www.groundwater.buffalo.edu/software/software.html		
3DFlow	analytic element	freeware
groundwater.ce.ksu.edu/		
MODFLOW	finite difference	public domain
water.usgs.gov/nrp/gwsoftware/modflow.html		
MODFE	finite elements	public domain
water.usgs.gov/software/modfe.html		

Figure 3: Genealogy of analytic element research program 1981-2003.

4 Discussion

The analytic element research program in ground water modeling, while small in size in comparison to finite element and finite difference research programs, is still progressive after close to 25 years.

The finite element method dominates the publication record in the ground water field. Perhaps this is because of the bias of the ISI database for journal articles and the fact that there are more academic researchers working in finite elements than in the other methods.

However, it is common understanding that the finite difference method (e.g., MODFLOW) dominates the applied modeling field. The domination by MODFLOW is likely due to a number of factors, including the US Geological Survey sponsorship and quality assurance, the user community comfort with, and understanding of, the finite difference method, and the rallying of the ground-water modeling community behind a single standard.

The emergence of a single community solver in the AEM research community has not happened. The fact that there are a number of solvers is not necessarily a bad thing in the long run. While a single community standard solver might translate into easier public adoption, the movement toward a single standard might stifle innovation.

Each of the numerical methods has its strengths and weaknesses, and the research programs will continue to improve (See Chapter 8.5 in *Fitts* [2002]). The future may see the continued development of hybrid techniques, such as embedding a finite difference grid within an infinite domain analytic element model, or using finite differences to solve for transient flow within an analytic element model. The finite element technique will likely continue to stand on its own.

It is likely that the impact of the analytic element method on ground water modeling will continue to grow. A new generation of researchers are now in place as assistant professors in the universities, forming the protective belt of Lakatos. However, unless the analytic element method meets the challenge of solving new problems, such as transient flow and representation of highly heterogeneous geology, the research program may begin to degenerate.

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