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On citation rates in earthquake engineering

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Abstract

The data on citations of 51 academics in earthquake engineering are analyzed to estimate their relative standing within the category of engineering, as used by HighlyCited.com of the Thomson Institute for Scientific Information. HighlyCited.com publishes names of up to 250 of the world's most cited researchers in each of 21 categories including life sciences, medicine, physical sciences, engineering and medical sciences. At present, there are no earthquake engineers in their category of engineering. In terms of an approximate metric used in this paper, citation threshold for engineering academics who work in related fields of mechanics and finite elements, and who are included in HiglyCited.com list, is about 6000 total citations. The most cited earthquake engineers in our sample have about half that many citations. It appears that the absence of earthquake engineers from the engineering category of HighlyCited.com is mainly the consequence of 2 facts, that (1) near 80% of journal papers in civil engineering are not cited within 5 years after publication, and (2) that the cohort of earthquake engineers is very small relative to the membership of all other engineering disciplines combined.

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Motto:

> There is something still worse, however, than being either criticized or dismantled by careless readers: it is being ignored. Since the status of a claim depends on later users' insertions, what if there are no later users whatsoever? This is the point that people who never come close to the fabrication of science have the greatest difficulty in grasping. They imagine that all scientific articles are equal and arrayed in lines like soldiers, to be carefully inspected one by one. However, most papers are never read at all. No matter what a paper did to the former literature, if no one else does anything with it, then it is as if it never existed at all. [1]

1. Introduction

The impact of published work of individual scientists and of their institutions is increasingly being assessed on the basis of the number of times their work is cited, and this quantitative measure, derived from the Science Citation Index database developed by the Thomson Institute for Scientific Information (ISI), is replacing the more informal system of peer recognition and esteem. By adopting the citation impact factors as a de facto measure of quality, the scientific community has turned a bibliometric measure (developed in 1963 by ISI) into a measure of scholarly performance.

Even though the journal impact factors (JIFs; [2]) cannot be equated with excellence, universities in several European countries have started to use impact factors to help determine institutional funding. Many investigators provide JIFs along with the listing of their articles in their curricula vitae. Furthermore, promotion and appointment committees are now increasingly using impact factors to assess the quality of the candidates [3].

As noted by Garfield [4],[1] research administrators need objective criteria for evaluating the past performance and

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[1] Dr. Eugene Garfield is ISI's founder and chairman emeritus. He is the editor of Science Citation Index, Journal Citation Reports—a bibliometric analysis of science journals in the ISI database, by the Institute for Scientific Information (ISI, http://www.isinet.com/), 3501 Market Street, Philadelphia, PA 19104, USA). Many of Garfield's writings have been

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the implied future potential of individuals, departments, and institutions. The traditional criterion is the subjective so-called peer review by committees that invariably have strong biases. The new and emerging trend is to use citations. Citation analysis is not perfect, but after some years of use it has achieved a level of standardization that enables one to obtain informed views of the influence or the impact of individuals, groups, and departments. By balancing the publication counts (input) with the citation counts (output) one can get a good idea of past performance.

The conventional wisdom is that citations bond a research paper to the body of knowledge in a particular field and are a measure of the paper's importance. Thus, a careful analysis of the ISI data can offer academics, university administrators, and government officials a great deal to think about.

The quality of a researcher's performance and its quantitative evaluation in terms of citations received by each of his or her papers are but one component of an *n*-dimensional performance vector characterizing overall faculty performance. But in view of the widespread use and potential benefits from understanding the Citation Index database, it is important and timely for earthquake engineers to learn about it and to see how it can be used. To this end, this paper presents an elementary study of a subset of faculty in the civil engineering departments who specialize in earthquake engineering.

In the following, the ISI data will be used to explore how to quantify the relative significance of the contributions (output) of the faculty members who work mainly in civil engineering departments at leading universities in the USA and at a few European universities, and who specialize in earthquake engineering. To maintain confidentiality, faculty will be assigned code names, which will consist of an abbreviated code for the institution at which they work, followed by a number. The assignment of the names to this sequence will be random—that is, it will not be based on the alphabetical order of names, seniority, discipline, or gender. However, all data we present are real and correspond to the performance period ending in December 2003.

1.1. Highly cited researchers

Recently, HighlyCited.com (Thomson/ISI) started to collect and interpret data on the "world's most cited and influential researchers." It offers information about the key contributors to science and technology during the period from 1981 to 1999 and aims to serve as "a resource for researchers, scientists, and professors, to identify key individuals, departments, and laboratories that have made fundamental contributions to the development of science and technology in recent decades." It is expected that corporations and government agencies will use HighlyCited.com to locate centers of excellence, to make policy decisions, and to optimize the distribution of funding. At present, the database of HighlyCited.com includes records of about 250 "top researchers" in each of 21 categories, including the life sciences, medicine, the physical sciences, engineering, and the social sciences.

In May 2004, HighlyCited.com data had 212 members worldwide in the category of engineering.

#	%	**Country**
152	72	USA 79% at 49 universities 21% at government labs or corporations
10	5	Canada
9	4	Japan
9	4	England
7	3	Germany
5	2	Australia
3	1	India
3	1	Switzerland
2		Belgium
2		France
2		Denmark
1		Sweden
1		Israel
1		Austria
1		Italy
1		Peoples Republic of China
1		Singapore
1		Greece
1		Norway

Examples of universities with the largest number of highly cited scientists in engineering are:

Stanford University—10
MIT and Caltech—8
UC Berkeley—7
UC Santa Barbara—6
Univ. of Michigan—6
Northwestern University—5
UC San Diego—4
UC Riverside—3
Univ. of Texas at Austin—3
Univ. of Wisconsin-Madison—3
Univ. of Virginia—3

Thirty-seven other universities had 1 or 2 members. As might be expected, the above order of institutions with the largest number of highly cited engineers correlates well

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(*footnote continued*)
posted on his Web site at http://www.garfield.library.upenn.edu. Since 1992, ISI has been a Thomson Scientific Company and part of The Thomson Corporation (http://www.thomson.com), which provides Web-based information for researchers, information specialists, and administrators. More information about ISI is available at http://www.isinet.com/ISI.

with the *US News and World Report* rankings of the leading graduate schools of engineering in the US.

Perusal of the above list of 212 members of the engineering category in the ISI HighlyCited.com data shows that none of them belong to the field of earthquake engineering. There are many possible reasons for this. For example: (1) almost 80% of journal papers in civil engineering are not cited within 5 years after publication, (2) the cohort of earthquake engineers is very small relative to the membership of all other engineering disciplines combined, (3) the time window used by ISI HighlyCited.com (from 1981 to 1999) may be too restrictive, particularly for older researchers in earthquake engineering, and (4) the half-life of citations in earthquake engineering may be longer than it is in more active and rapidly growing fields like material science or computer science, so that the time window from 1981 to 1999 may be too short to capture all relevant citations in earthquake engineering. Publication rates in earthquake engineering are close to the average rates for science and engineering professors in the United States [5] and therefore may not be the reason for the absence of earthquake engineers in the HighlyCited.com list. The purpose of this paper is to quantify the citation rates for a sample of faculty in earthquake engineering and to examine factors that may contribute to an understanding of their current status.

1.2. Citations

In the early 1990s, ISI staff showed that 55% of the papers published in journals covered by the ISI database did not receive a single citation in the 5 years after they were published [6]. When the data were grouped into broad categories, it was found that physics and chemistry had the lowest rates of uncitedness—37% and 39%, respectively. Those were followed by the biological sciences (41%), the geosciences (44%), and medicine (46%). These subjects all fell below the uncitedness average of 47% for the "hard sciences" (disciplines including basic sciences and medicine but excluding the social sciences). The figure for engineering, however, was well above the average. More than 72% of all papers published in engineering had no citations at all. Within the above broad categories, there was wide variation among individual sub-disciplines.

All fields of engineering showed high rates of uncitedness, with civil engineering being the highest at 78%. Next came mechanical (77%), aerospace (77%), electrical (66%), chemical (66%), and biomedical (60%). Other applied fields had similarly high rates of uncitedness: construction and building technology (84%), energy and fuels (80%), applied chemistry (78%), materials science—paper and wood (78%), metallurgy and mining (75%), and materials science—ceramics (73%).

Even papers that do get cited are not cited very often. An ISI study of articles in the hard sciences, published between 1969 and 1981, showed that only 42% received more than one citation [7]. When asked whether this means that more than one half, and perhaps more, of the scientific literature is essentially worthless, some 20 academicians, federal officials, and science policy analysts concluded that "researchers are publishing far too many inconsequential papers in order to pad their resumes" [7].[2]

2. Data

The bibliometric indicators employed in this work to evaluate the published knowledge production have been derived from 2 sources of data.

2.1. ISI data

The first source is the ISI web of science. It consists of 5 databases containing information gathered from thousands of scholarly journals in all areas of research:

- Science Citation Index Expanded
- Social Sciences Citation Index
- Social Sciences Citation Index
- Index Chemicus
- Current Chemical Reactions.

The ISI *Science Citation Index Expanded* covers the period from 1975 to present—that is, the citing papers in this database were all published after 1975. Collecting citations from citing papers published prior to 1975 can be done manually from the old printed version of the Science Citation Index. For these older citations, only the first author is listed, and the citations are not linked to the full paper title, list of authors, journal name, volume, page numbers, year of the publication, and the full text of the abstract, while for the more recent, fully linked citations, all authors are listed, and the order of the authors can be seen from the citation record.

Self-citations can represent several to tens of percents of the total. This percentage depends upon many factors that differ for authors and thus cannot be described reliably by any simple or general empirical law. Self-citations can be

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[2] Ray Bowen, assistant director for engineering at the National Science Foundation said that this "does suggest that a lot of work is generally without utility in the short-term sense." Frank Press, the president of the National Academy of Sciences, noted that "there are obvious concerns which are worrisome—namely that the work is redundant, it's me-too type of follow-on papers, or the journals are printing too much." To J. Duderstadt, University of Michigan President, the growing number of journals and the high number of uncited articles simply confirm a suspicion that academic culture encourages spurious publication. "It is pretty strong evidence of how fragmented scientific work has become, and the kinds of pressures which drive people to stress number of publications rather than quality of publications." "The obvious interpretation is that the publish-or-perish syndrome is still operating in force," said David Helfand the chairman of the astronomy department at Columbia University, while the editor of the Journal of the American Chemical Society Allen Bard concluded that "in many ways, publication no longer represents a way of communicating with your scientific peers, but a way to enhance your status and accumulate points for promotion and grants" [7].

eliminated by detailed screening of citation data [8], but such screening is beyond the scope of this paper.

A common problem with use of ISI data is the recurrence of names. Researchers working in the same or similar fields often have same family names and same one or both initials, making it difficult to separate their citations. For example, there are 2 civil engineers, with citations listed under E. Popov. Separating these ISI citations, without analysis of their curricula vitae, with all of their known publications, becomes difficult. It was decided that such analyses are beyond the scope of this paper, even though this reduced the sample size.

Studies of 12 subject areas have indicated that the number of citations increases with the mean JIF and with the average number of authors per article [2]. Trifunac and Lee [8] studied a sample of papers for 12 faculty members who had an average number of authors per paper between 1.39 and 4.15 and showed that this effect could be significant for the relative comparison of the researchers in the present sample. In the analysis that follows, we will ignore the possible consequences from the different mean number of authors in published papers.

2.2. EEA database

The second source of data used in this work—the Earthquake Engineering Abstracts (EEA) database—is much smaller and it is focused on the subject area of earthquake engineering and the related fields—structural and geotechnical engineering, applied mechanics, engineering seismology, and engineering geology. The EEA database was developed for the NSF-supported National Information Service for Earthquake Engineering (NISEE) that has been the leading repository for all relevant published work in earthquake engineering and related fields for the past 30 years (http://www.nisee.berkeley.edu/eea.html).

At present, the EEA database has more than 100,000 abstracts and can serve as a quantitative measure of the active contributors in this field. The EEA database could be accessed free of charge until January of 2004, when it became part of Cambridge Scientific Abstracts (CSA)—a privately owned information company located in Bethesda, Maryland, that publishes abstracts and indices for scientific and technical research literature (http://www.csa.com).

3. Analysis of citations

In the following, 2 approximations will be used. The first is that the number of publications for each member of our sample can be approximated by the number of their contributions listed in the EEA database of NISEE, which includes journal papers, reports, conference papers, and workshop contributions. To demonstrate that this is a reasonable approximation, we summarize results of a detailed study for ten faculty for whom we used their curricula vitae [8]. We considered the total number of published journal papers (y_1), reports (y_2), conference papers (y_3), and the total number of abstracts in the NISEE database (x), up to and including December 2003. Fig. 1a, b, and c show y_1 versus x, y_1+y_2 versus x, and $y_1+y_2+y_3$ versus x, respectively. In these Figures, the trends $y_1=x$, $y_1+y_2=x$ and $y_1+y_2+y_3=x$, are shown by dashed lines. Light solid lines show the best fits (using least squares)

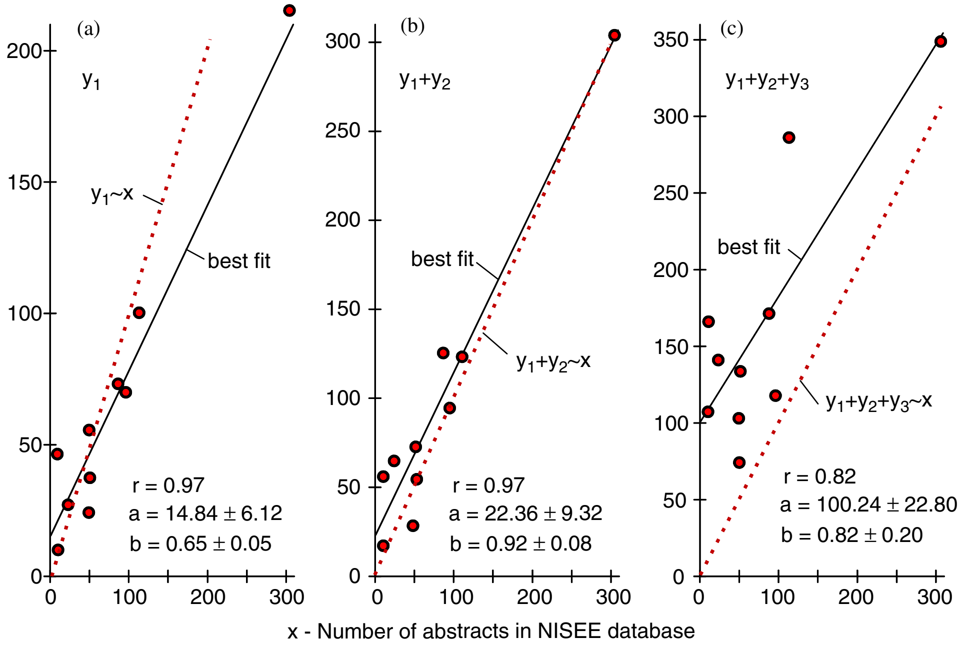

Fig. 1. (a) Number of published journal papers, y_1; (b) number of published journal papers and reports, y_1+y_2; and (c) number of published journal papers, reports, and conference papers, $y_1+y_2+y_3$. All are plotted versus the number of abstracts in the NISEE database as of December 2003. Listed in each plot are the corresponding correlation coefficient, r, and the coefficients a and b in the straight-line fit of form $y=a+bx$.

$y = a + bx$, when $y = y_1$, $y = y_1 + y_2$, and $y = y_1 + y_2 + y_3$. Coefficients a and b and the corresponding correlation coefficients, r, are also shown in Fig. 1a, b, and c. It can be seen that the NISEE database (x) can be used to predict both y_1 and $y_1 + y_2$ well.

The second approximation is that the "raw" number of ISI citations is used without corrections. These corrections are complex, labor intensive and require in-depth analyses of the curricula vitae [8] that are not available to us for all earthquake engineers chosen for this study. Fig. 2 shows examples of the total number of citations (normal count) after detailed corrections (y), versus the "raw" total number of ISI citations (x), for 4 faculty in our sample. The y/x ratios range from 0.46 (USC-4) and 0.63 (USC-8) through 0.77 (USC-6) to 0.85 (USC-7). Fig. 2 implies that the total number of corrected ISI citations can be predicted within a factor of about 2, from the raw total number of ISI citations. In the following we will assume that $y \sim x$.

3.1. Input

To maintain confidentiality, faculty have been assigned code names, which consist of an abbreviated code for the institution at which they work, followed by a number. The assignment of the names to this sequence has been random—that is, it is not based on the alphabetical order of names, seniority, discipline, or gender. Table 1 lists the adopted abbreviations (for 49 male and 2 female faculty), and it presents, for each institution, the number of the faculty members we included in this study. We made one exception to the above rule, in that we show the name of Maurice A. Biot. It was felt that his unique position in the plots would serve as a benchmark of excellence and that by showing his name the true meaning of the comparison with all other data points could thus be better understood and evaluated [9].

Table 1
Institution codes and the number of faculty (49 male and 2 female) considered in this study

Institutions	Code	No. of faculty considered in this study
American		
University of Southern California	USC	USC-1 through USC-13
University of California, Berkeley	UCB	UCB-1 through UCB-8
California Institute of Technology	CIT	CIT-1 through CIT-3
University of California, San Diego	UCSD	UCSD-1 through UCSD-3
Stanford University	SU	SU-1 through SU-2
University of California, Irvine	UCI	UCI-1 through UCI-2
University of Texas	UT	UT-1 through UT-2
Columbia University	CU	CU-1 through CU-2
State University of New York, Buffalo	SUNYB	SUNYB-1 through SUNYB-2
Rice University	RU	RU-1 through RU-2
University of Illinois, Urbana	UIU	UIU-1 through UIU-2
University of Washington	UW	UW-1
University of California, Los Angeles	UCLA	UCLA-1
University of California, Davis	UCD	UCD-1
Johns Hopkins University	JH	JH-1
Massachusetts Institute of Technology	MIT	MIT-1
Rensselaer P. Institute	RPI	RPI-1
European		
Imperial College, London, England	IC	IC-1
Tech. University of Athens, Greece	TUA	TUA-1
University of Ljubljana, Slovenia	ULJ	ULJ-1
Royal Academy of Belgium	—	M.A. Biot

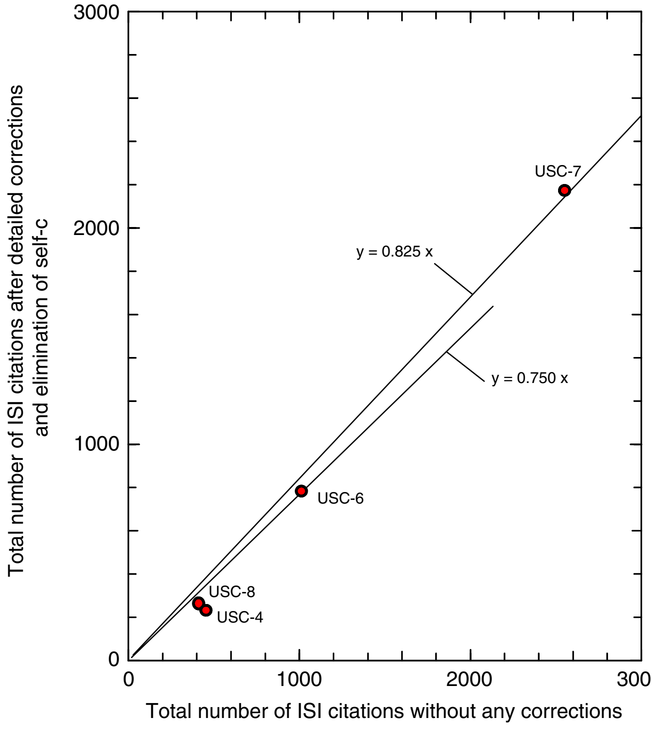

Fig. 2. Total number of ISI citations after detailed corrections and elimination of self-citations, versus total number of ISI citations without any corrections.

All of the ISI citations and NISEE data from EEA presented here are complete up to and including December 2003. Then we represent the "input" by the total number of articles recorded in the NISEE database.

3.2. Output

The distribution of total ISI citations per year for 51 faculty in earthquake engineering is shown in Fig. 3. The left part of this figure shows citation rates per year, while the right-hand side shows the corresponding histogram and the cumulative distribution function. With respect to this sample, it can be seen that Biot, UCB-1, UCI-1, and USC-7 are among the top 5%. UCB-2 and UCSD-2 are among the top 10%; UCB-8, UCSD-1, MIT-1, TUA-1, CIT-2, and USC-4 are in the top 20%, and so on.

Fig. 4 shows the total number of ISI citations (y) versus the total number of NISEE abstracts (or equivalent) (x), both plotted on a logarithmic scale. With a few exceptions,

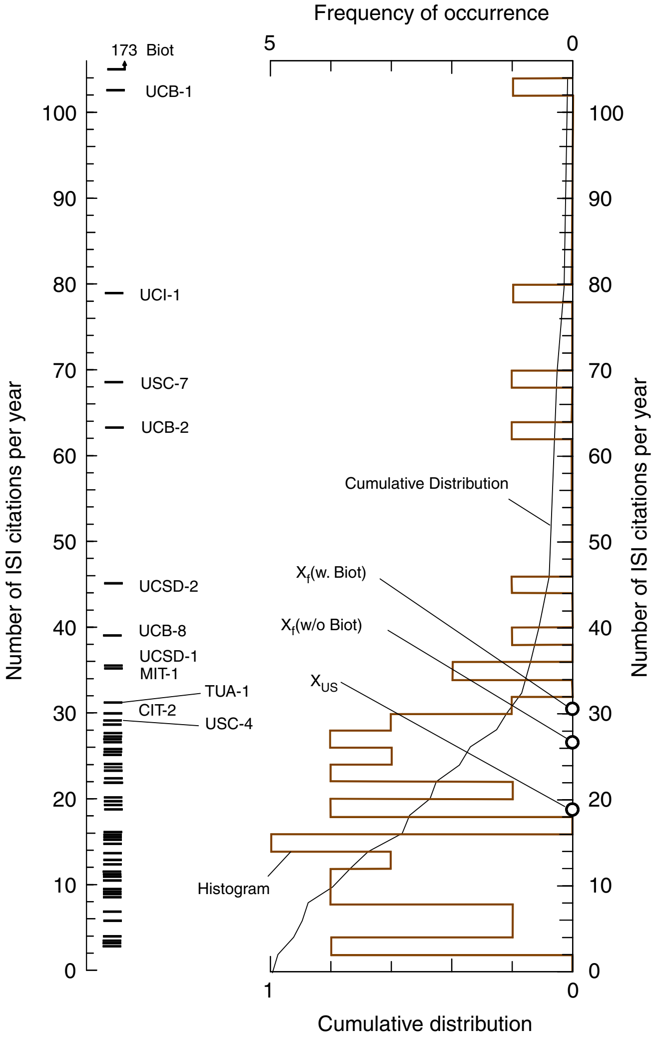

Fig. 3. (Left) Average citations per year for 51 faculty in earthquake engineering; (right) histogram and cumulative distribution of their average citations per year.

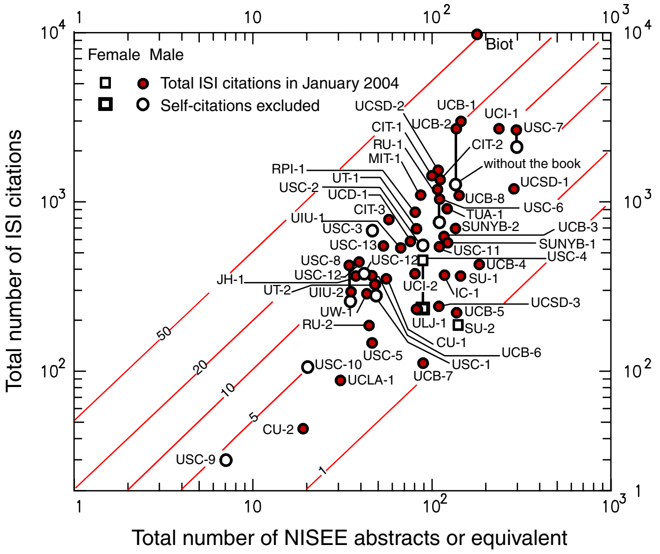

Fig. 4. Total number of ISI citations versus the total number of NISEE abstracts or equivalent.

most data points fall between 1 and 50 citations per NISEE abstract. For Biot and USC-8, the NISEE abstracts database is incomplete, and therefore the total number of papers in their curricula vitae was used instead.

Fig. 5 shows the corresponding rates. The *y*-axis displays the number of ISI citations per year since the publication of the first abstract in the NISEE database, while the *x*-axis shows the number of NISEE abstracts per year since the publication of the first abstract, both plotted on a logarithmic scale. It can be seen that, for this sample, the publication rate ranges from 0.7 to more than 8 per year, while the citation rates range from less than 3 (UCB-7) to 173 (Biot) per year.

For USC-1, USC-2, USC-9, and USC-10, the total number of citations was not computed, because of the difficulties in separating their citations from those of other researchers who share the same name. However, their corrected total citations with self-citations excluded were available from a study by Trifunac and Lee [8], and are plotted with open circles. For USC-4, USC-6, USC-7, and USC-8, both total citations and corrected total citations, with self-citations excluded, were also available from Trifunac and Lee [8] report. Both values are shown in Figs. 4 and 5, to illustrate the order of magnitude of these corrections. UCB-2 is the only member of our sample with a significant part of the total citations resulting from a textbook. For him, we show the total citations with and without the book.

Fig. 6 shows the histogram and the distribution of the average number of citations per abstract in the NISEE database. It is seen that the top 10% of authors in this group of 51 have 14 or more citations per abstract, 20% have eleven or more, 30% have 9 or more, and 50% have 7 or more.

4. Discussion

Productivity can be measured by the average publication rate (total number of publications divided by number of years since the first publication) or by author publication rate (the sum of all per-author publications divided by the number of years since the first publication). In this work, we chose to consider only the first option as a measure of the input productivity—that is, of the input into the pool of scientific and engineering literature. Using the ISI database, it is possible then to consider only those inputs that have been cited, as a measure of *recognized* productivity. The fact that a journal paper is cited does not necessarily mean that the paper is of high quality, is relevant, or contributes to the overall knowledge and understanding in the respective discipline. It is a statistical data point, contributing to the author's cumulative sums of such points, and when these sums become large enough we can consider accepting them as measures of recognized productivity, or simply as output. For example, in a sample of 12 faculty studied by Trifunac and Lee [8], the percentage of cited contributions ranged from 12% to

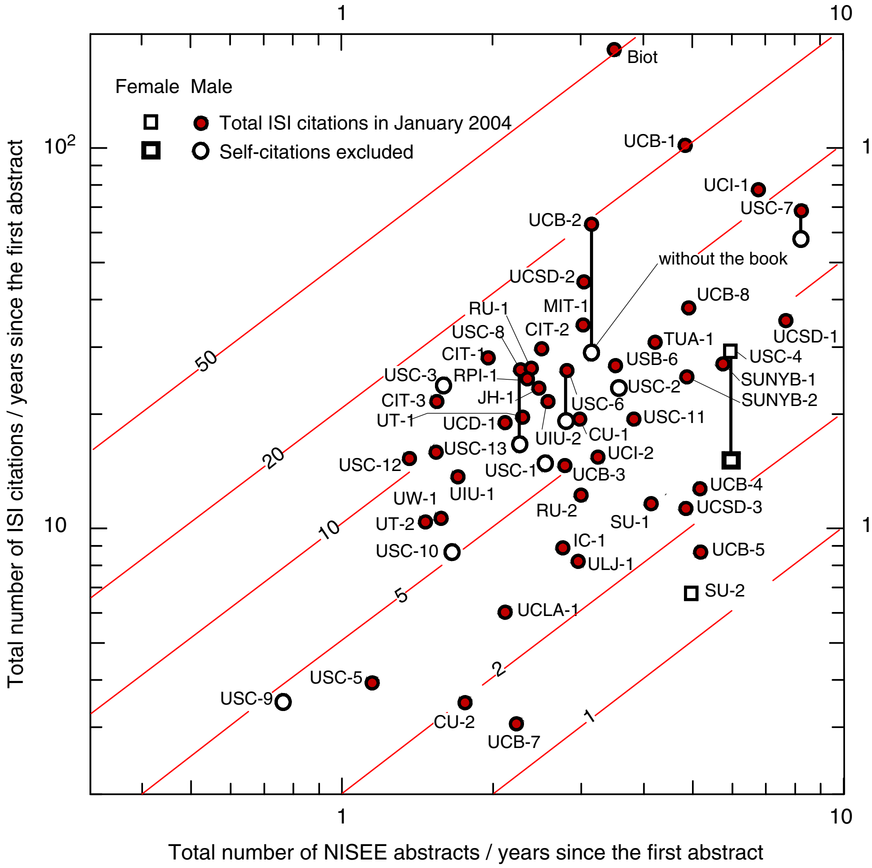

Fig. 5. Total number of ISI citations per year versus the total number of NISEE abstracts per year.

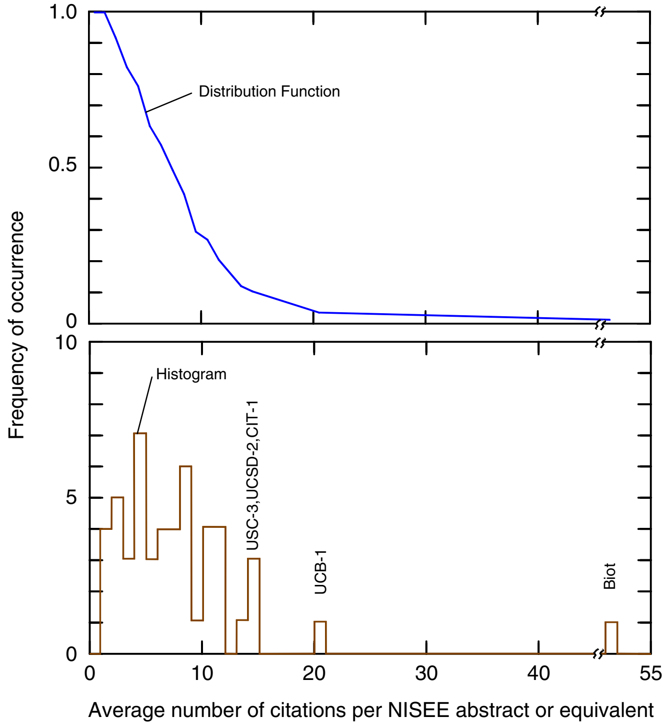

Fig. 6. Distribution (top) and histogram (bottom) of the average number of citations per abstract in the NISEE database or per published journal paper (Biot).

95%, when all publications are considered collectively (journal papers, reports, conference papers, books, book chapters, etc.).

Wanner et al. [10] argue that the important research results in the sciences are reported in refereed journals and that other journal articles, books, and other publications are less used by researchers to advance the science. Thus, weighing the publications becomes an important bibliometric issue that is only possible within the study of a particular discipline.

Another important issue is how to distribute credit among the authors of a paper. Cole and Cole [11] proposed the use of "straight count," which allocates all credit only to the first author. This method assumes that the order of authors listed on the paper reflects the levels of their contributions. The problem is that authors' names are sometimes listed alphabetically, which implies that it discriminates against those researchers whose names appear late in the alphabetic listing [12].

The second method is "adjusted count" (or "fractional count", or "per-author count") that gives each author credit equal to $1/a_i$, where a_i is the number of authors. The advantage of the adjusted count is that it eliminates the bias in overestimating production when the value of a co-authored paper is distributed among all contributors [13].

The third method is the “normal count,” or “total count,” which gives full credit to all contributors regardless of the order of the listed authors. The problem with this count is that it is not reasonable to expect that all co-authors contributed equally, especially when some publications list authors for social reasons [14], particularly in the circles where the practice of making colleagues “honorary co-authors” is common [15].

In this work, we used the “normal count” method, which may inadvertently diminish the counts for the more senior researchers in our sample. Some of their citations for publications before 1975 may be incomplete due to the use of “straight count” in the old Science Citation Index.

4.1. Sample

Our sample consists of 51 faculty in earthquake engineering (Table 1). It includes 3 (6%) deceased faculty, 9 (18%) retired professors, and 3 (6%) young faculty (1 assistant professor, 1 associate professor, and 1 research professor). Thus, it includes 48 (94%) senior faculty. Twelve (24%) are born in the USA, and 39 (76%) are foreign born (Fig. 7). Two (4%) are female, and 49 (96%) are male. Overall, this sample is representative of the senior members of earthquake engineering faculty in the United States (47 or 92% work or have worked in a university in the USA and only 4 or 8% in European institutions).

4.2. Age

The studies of Lehman [16] show that major contributions for scientists occur primarily in their 30s and early 40s, and that the production peak occurs earlier for researchers in the abstract and theoretical disciplines and later for those in the more empirical fields. Pelz and Andrews [17] found similar trends, but also observed a second peak, 10–15 years later, at age 50, and Bayer and Dutton [20] identified 2 peaks in the productivity curve, with the first peak occurring at about 10 years into the career and second near the retirement age.

Pelz and Andrews [17] considered 4 hypotheses to describe the decline of productivity with age: (1) atrophy of intellectual functioning with age, (2) migration of mature researchers into administration, (3) decrease of zeal and motivation with age, and (4) loss, through over-specialization, of breadth in knowledge, which is needed for new results. They found support only for the third and fourth hypotheses. Hammel [18] presented different results showing that productivity increases with age, but at a gradually decelerating rate.

Trifunac and Lee [8] studied variations in the number of journal publications per year versus the age of ten faculty in earthquake engineering and compared the results with the national average rates [19], assuming the average age for receiving a Ph.D. to be about 29. They found that the variation in productivity with time of 4 faculty can be described by a single peak around the late 30s and early 40s. Two faculty in their sample experienced increasing productivity [18], while 3 faculty had a peak in their late 30s and another gradual increase after the age of about 50 [20]. This range of trends is consistent with what other investigators have found, which is that the most productive period, from the point of view of publications that receive more than the average number of citations, appears to be the first 10–15 years after Ph.D. M.A. Biot, the most cited member of the sample of faculty and researchers we selected for this study (see Figs. 3–6), does not fit into this pattern. Fig. 8 shows his citations (as of January 2004) plotted versus his age at the time the cited work was published. Assuming linear growth of citations, from the publication date to January 2004, this figure also shows a lower bound of the citations he would have received at his ages of 40, 50, 60, 70, and 80. It can be seen that he was very productive throughout his life and had especially productive periods at ages 36, 51, 57, and 60.

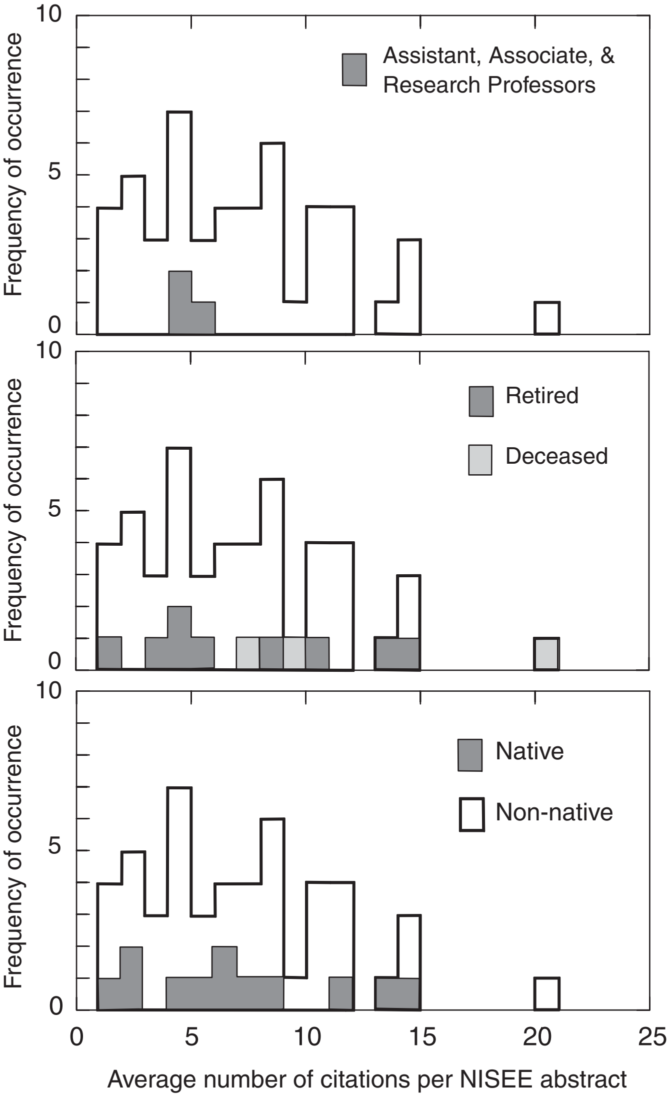

Fig. 7. Composition of the histogram of the average number of citations per NISEE abstract in terms of rank (top), present status (middle), and origin (bottom).

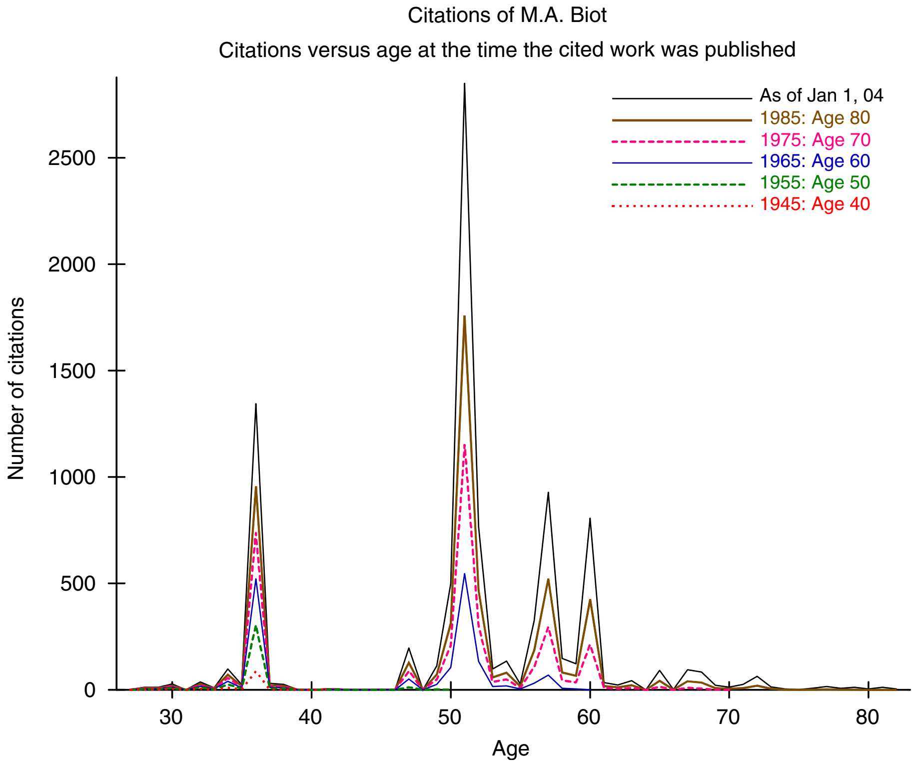

Fig. 8. Current total number of citations (as of January 2004) of M.A. Biot, and estimates of his total number of citations at ages 40, 50, 60, 70, and 80, all plotted versus his age at the time the cited work was published.

5. Collaboration

A study of Nobel laureates showed strong correlation between collaboration and productivity [21]. Nobel laureates published more and were more collaborative than a matched sample of other scientists. High-profile authors seem to collaborate most frequently, and authors at all levels tend to collaborate with other highly productive authors [19].

In an early study about motives for collaboration, Beaver and Rosen [22] identified 18 motives. They found that about half of the motives were related to the desire to enhance productivity. Similarly, Fox and Faver [23] found that division of labor is one of the main motivations for collaboration. As in business management, division of labor is expected to give mutual benefits to participants by increasing efficiency. In a recent in-depth review of research collaboration, Katz and Martin [24] articulated the following reasons why the level of research collaboration has been growing over the past 30 years: the escalating instrumentation costs of conducting fundamental science at the research frontier, the substantial fall in the cost of travel and communication, the growing importance of networking and interaction, the complexity of instrumentation, the need for interdisciplinary research, and the political factors encouraging collaboration.

Melin [25] surveyed 195 university professors about the major reasons for collaboration and the chief benefits of collaboration. The respondents' most often reported (41%) motive for collaboration was that the "co-author had special competence." Other common motives included "co-author has special data or equipment (20%)," "social reasons: old friends, past collaboration (16%)," "supervisor–student relation (14%)," and "development and testing of new methods (9%)." With respect to the benefits of collaboration, the respondents point to increased knowledge (38%)," "higher scientific quality (30%)," "contact and connections for future work (25%)," and "generation of new ideas (17%)." Based on these data, Melin concluded that scientists collaborate for strongly pragmatic reasons. Melin's "pragmatic reasons" are largely consistent with productivity-oriented collaboration.

For the ten earthquake engineering faculty studied by Trifunac and Lee [8], the average number of authors per paper was in the range from 1.40 (USC-1) to 3.10 (USC-9). One of the consequences of cooperation with other researchers, then, can be viewed in terms of the distribution of received citations among single-author papers, first-author papers, second-author papers, and so on. Trifunac and Lee [8] found that those who received the most citations in their sample group of ten faculty had a significant number of single-author papers (USC-1, USC-2, USC-7, and USC-8), while those with the smallest number of citations received more than half of all journal citations as third authors (e.g., USC-10, USC-5). Even though Bozeman and Lee [19] state that in "the Big Science era, the lonely genius working alone in the laboratory is still lonelier," and that at present working with others has become the norm, the study by Trifunac and Lee [8] shows that, in a typical civil engineering department, for the faculty who work in earthquake engineering, most significant citations still come mainly from single-author papers.

5.1. Gender

Many studies have found somewhat lower production rates for women than for men [26–28]. These studies noted that obligations to family and children, as well as sex discrimination, may make it more difficult for females to compete for resources [29], and that this in turn may limit their ability to publish. In contrast to this stereotype that women are less productive, Clemente [30] and Wanner et al. [10] found that gender does not affect productivity in terms of articles published. Long [31] and Bozeman and Lee [19] found that the differences in the number of publications and citations increase during the first decade of the career, but that the differences in lifetime productivity are later reduced. At present, a decline in the effects of gender on scientific productivity may also be due to the increasing participation of females in scientific jobs [32].

In our sample of 51 earthquake engineering faculty studied in this paper, there are only 2 female professors so we cannot make any general conclusions. Insofar as this analysis can show, their publication productivity is above the national average trends and is better than the publication productivity of many male faculty in our sample.

5.2. Citizenship

With an increasing number of foreign nationals in US research and educational institutions, it may be expected that different cultures and languages may influence productivity. As reported by Trifunac [5], the publication productivity of foreign-born earthquake engineers is higher (about 35%) than that of US born. In our sample of 51, only 12 (24%) were born in the US (Fig. 7, bottom). The average number of citations for the 12 USA-born earthquake engineers is $\bar{x}_{\mathrm{us}} = 7.08$ citations per NISEE abstract ($\sim$paper). The average citation rate for the 39 foreign-born earthquake engineers, including M. Biot, is $\bar{x}_{\mathrm{f}} = 8.24$, or about 16% higher. Excluding Biot, $\bar{x}_{\mathrm{f}} = 7.21$, or about 2% higher than $\bar{x}_{\mathrm{us}} = 7.08$. The overall average citation rate for 51 earthquake engineers in our sample is $\bar{x}_{\mathrm{overall}} = 7.97$. Without Biot, it is $\bar{x}_{\mathrm{overall}} = 7.18$.

5.3. Education

Of the 51 members in our sample, 7 (14%) have earned their Ph.D. or equivalent at a university in Europe, Australia, Japan, New Zealand, or Israel. The remaining 44 (86%) have doctoral degrees from an American institution: Caltech (CIT)—13 (25%); MIT 6 (12%); UC Berkeley—6 (12%); Univ. of Illinois—5 (10%); Univ. of Southern California (USC)—3 (6%); SUNY at Buffalo—2 (4%); and Stanford—2 (4%). Of the remaining 12, 5 have graduated (one each) from UCLA, Illinois Inst. of Technology, Rice Univ., Univ. of Michigan, and Rensselaer Poly. Inst. Finally, the remaining 7, as noted above, are foreign graduates.

Fig. 9 shows a decomposition of the histogram describing the average number of citations per NISEE abstract, according to the institution where the members of our sample of 51 earthquake engineers received their doctoral degrees. Table 2 and Fig. 9 show the average citation rates with respect to the institutions granting Ph.Ds. The samples are too small to attach significance to the computed averages, but the results suggest a range between 2 (Stanford) and about 9 (Caltech, Columbia, and MIT).

Fig. 10 shows 43 individual citation rates (citations per abstract) versus publication rates (abstracts per year). The correlation coefficient is essentially zero, and the citation rates are distributed between a few (CU–2, UCB–7) and 51 (Biot). The publication rates are distributed between 0.87 (USC–9) and 8.5 (USC–7).

Fig. 11 shows the average citation rates for institutions granting the Ph.D. versus the corresponding average publication rates. Again, the number of samples per institution (see Table 2) is too small to attach statistical significance to these results, but collectively the data suggest a decreasing trend of citation rates with increasing publication rates. Both Figs. 10 and 11 suggest that the largest citation rates occur for publication rates less than or equal to about 3 abstracts (papers) per year. In statistical terms, this might suggest that the quality, relevance, and significance of the content in the published papers in earthquake engineering may begin to diminish for publication rates beyond about 3 papers per year.

5.4. Some general observations

One of the expected observations of this study is that there is no short and direct path to glory. As the ancient Romans used to say, *per aspera ad astra* (through difficulties to the stars) is true today as it was 2000 years ago. Original and hard work and its systematic documentation in recognized journals (*per aspera*) may lead to recognition and respect. But, whether some of the published ideas will ever evolve into professional milestones and vehicles for new ways of doing things (*astra*) depends upon persistence and to some degree, upon luck.

Fig. 8 shows citations (normal count) of M.A. Biot, the father of modern earthquake engineering, plotted versus his age at the time the cited work was published [9]. From 1975 to January 2004, Biot received 9214 citations, mainly derived from 4 groups of his contributions that were published in (1) 1941, (2) 1956, (3) 1962, and (4) 1965, when he was 36, 52, 57, and 60 years old. The first group includes his papers 40 and 41 (Table 3); the second group includes papers 55, 57, 60, 61, 62, 63, 68, and 71; the third group includes papers 90, 97, and 99; and the fourth derives

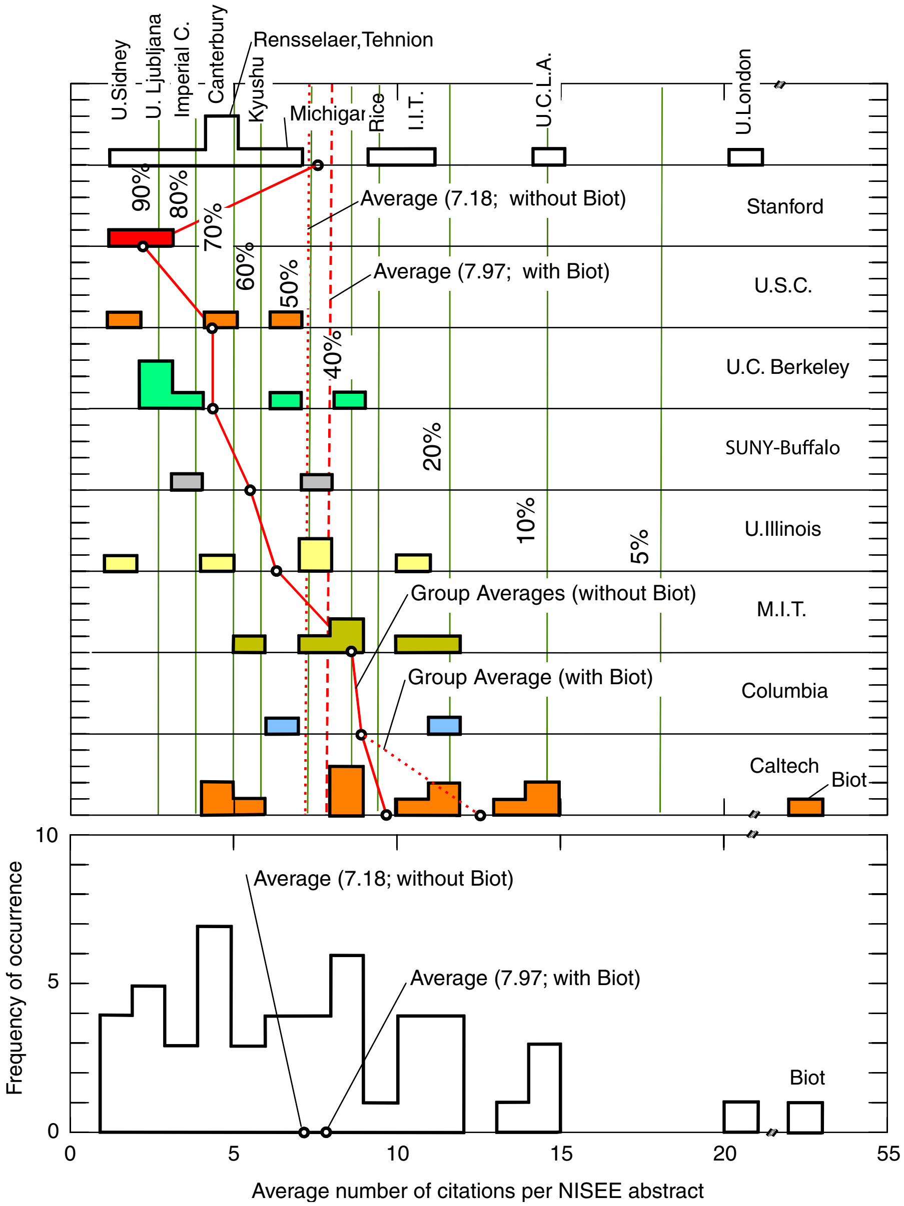

Fig. 9. Decomposition of the histogram of the average number of citations per NISEE abstract, for a sample of 51 faculty in earthquake engineering, based on the institution where they received the Ph.D. degree.

Table 2
Distribution of 51 earthquake engineering faculty among the institutions where they earned their doctoral degrees, and their group citation rates

Institution	Number	Group citation rate per NISEE abstract
Caltech	13	12.58 (with Biot) 9.67 (without Biot)
Columbia	2	9.00
MIT	6	8.67
University of Illinois	5	6.30
SUNY, Buffalo	2	5.50
UC Berkeley	6	4.33
USC	3	4.17
Stanford	2	2.00
Other 12 institutions	12	7.33

citations from his book *Mechanics of Incremental Deformations*. So far, Biot's paper no. 60, published in 1956, has received the largest number of citations (1447). It deals with the theory of propagation of elastic waves in a fluid-saturated porous solid. During all other years, Biot's papers received on average about 50 citations (Fig. 8). A remarkable characteristic of these highly cited papers is that Biot wrote them alone.

6. Conclusions

The nature of the data presented in this paper permits only rough estimates of the citation rates in earthquake engineering and describes only a small group of 51 faculty. Yet, because our sample is representative of senior faculty,

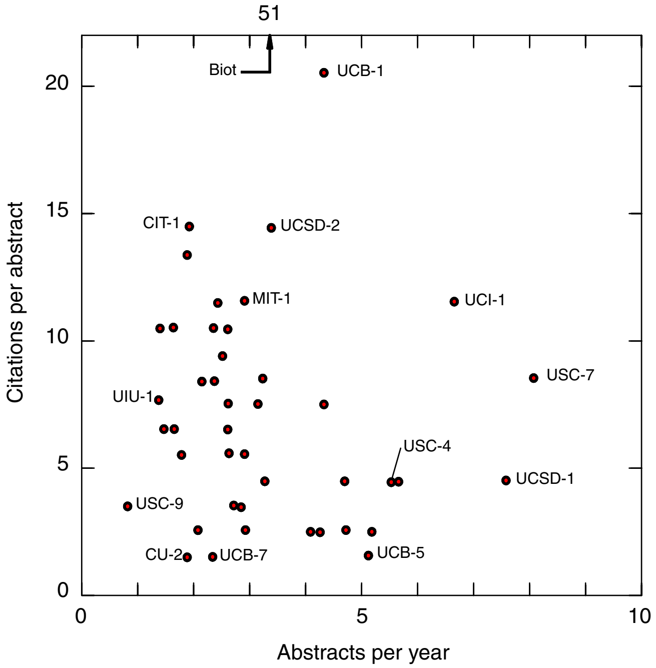

Fig. 10. Individual citation rates (citations per abstract) plotted versus publication rates (abstracts in NISEE database per year).

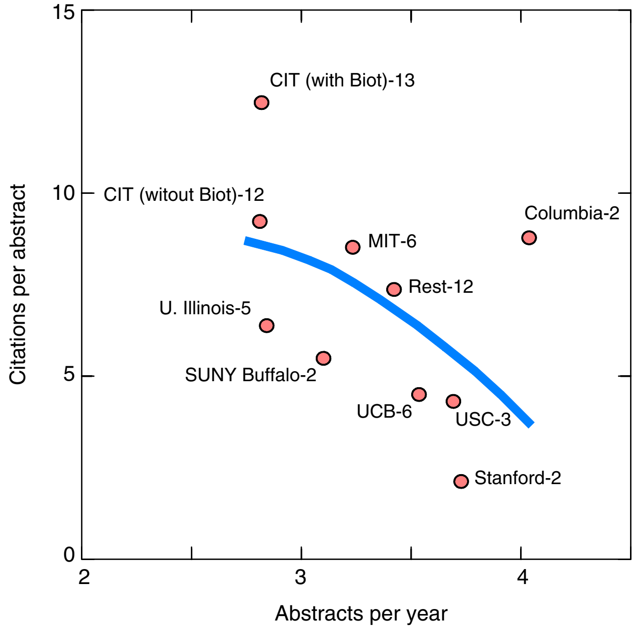

Fig. 11. Average citation rates for institutions granting Ph.D. degrees versus the corresponding average publication rates.

it provides a useful first glance at the high end of citation rate distribution in earthquake engineering. To estimate the corresponding mean rates it will be necessary to study larger samples. Nevertheless, it is hoped that this type of analysis will further motivate more detailed studies, helping us to understand and improve our standing relative to other disciplines in the field of engineering.

Our sample shows annual publication rates that range from less than 1 to more than 8, and the citation rates (total count) range between 1 and 100 per year (173 for M. Biot). With respect to the number of citations per publication, 10% of the sample have 14 or more citations per publication, 20% have 11 or more, 30% have 9 or more, and 50% have 7 or more citations per publication. The average citation rate for all 51 members of the sample is $\bar{x}_{\text{overall}} = 7.18$ citations per publication (excluding M. Biot). For 39 members of the sample (76%), who are not US born, the average citation rate is $\bar{x}_{\text{f}} = 7.21$ citations per publication. For the remaining 12 faculty, born in the USA (24%), the average is $\bar{x}_{\text{us}} = 7.08$ citations per publication.

The sample of 51 earthquake engineers has the highest cumulative rate (normal count, up to December 2003), for active faculty, approaching 3000 (about 80 citations per year for UCI-1). In terms of the total cumulative citations, this is about one half of the cumulative total citations of 6000, for the least-cited engineering members of the HighlyCited.com. It is known that group citation rates can vary considerably among different disciplines [8], but are also apparently different among sub-groups. There is no reason to expect that the earthquake engineers who primarily work in structural design, for example, will have the same citation rates as those who work in structural dynamics or in stochastic methods. The logical next step will be to partition the 21 categories, which are at present used by HighlyCited.com, into sub-categories, which will consist of smaller more homogeneous groups of researchers.

The high rate of un-cited published journal papers in civil engineering, estimated at 78% [6], may also apply to the field of earthquake engineering and may explain in part the absence of earthquake engineers from the HiglyCited.com. Our data show that there is strong correlation between the cumulative number of citations and the publication rates of individual faculty [8]. The data also suggest that the average citation rates per publication begin to decrease for production of more than about 3 publications per year (see Figs. 10 and 11). However, since the publication rates per year in earthquake engineering for our sample are almost the same as the publication rates of science and engineering faculty in the US [5], it appears that earthquake engineers do not cite the contributions in their own field.

Following the Seventh World Conference on earthquake engineering in Istanbul, Turkey, in 1980, Krishna [33] stated in his summary comments: "Earthquake engineering as such could be considered to have been born with Biot's concept of response of an idealized structure to ground motion." Yet, Biot received a relatively small number of citations for his pioneering work on the Response Spectrum Method [34–37], and for what amounts to his state-of-the-art final papers on the subject in 1941 [38] and 1942 [39] (see papers 41 and 42 in Table 3). This example suggests that earthquake engineers may not only fail to cite the work of their contemporary colleagues, but also the fundamental and seminal contributions, as those of M. Biot [9].

Table 3
Selection of seminal and highly cited papers of M.A. Biot

Paper		Citations	
No.	Title	No. in Jan. '04 (normal count)	Average/Year
40	General theory of three dimensional consolidation. Journal of Applied Physics, February 1941;12(2):155–161.	1319	45
41	A mechanical analyzer for the prediction of earthquake stresses. Bulletin of the Seismological Society of America, April 1941;31(2):151–171.	21	0.72
45	Analytical and experimental methods in engineering seismology. Proceedings of the American Society of Civil Engineers, January 1942;68:365–409.	30	1
53	Propagation of elastic waves in a cylindrical bore containing a fluid. Journal of Applied Physics, September 1952;23(9):997–1005.	153	5.3
54	Theory of stress–strain relations in anisotropic viscoelasticity and relaxation phenomena. Journal of Applied Physics, November 1954;25(11):1385–1391.	213	7.3
55	Theory of elasticity and consolidation for a porous anisotropic solid. Journal of Applied Physics, February 1955;26(2):182–185..	372	12.8
57	General solutions of the equations of elasticity and consolidation for a porous material. Journal of Applied Mechanics. Transactions of ASME, 1956;78:91–96.	145	5
60	Theory of propagation of elastic waves in a fluid saturated porous solid I—low frequency range. The Journal of the Acoustical Society of America, March 1956;28(2):168–178.	1447	50
61	Theory of propagation of elastic waves in a fluid saturated porous solid II—high frequency range. The Journal of the Acoustical Society of America, March 1956;28(2):179–191.	705	24
62	Thermoclasticity and irreversible thermodynamics. Journal of Applied Physics, March 1956;27(3):240–253.	333	11.5
63	Theory of deformation of a porous viscoelastic anisotropic solid. Journal of Applied Physics, May 1956;27(s):4S9–4G7.	93	3.2
68	The elastic coefficients of the theory of consolidation. Journal of Applied Mechanics, Transactions of ASME, December 1957;24:594–G01.	378	13
71	The influence of thermal stresses on the aeroelastic stability of supersonic wings. Journal of the Aeronautical Sciences, June 1957;24(G):418–420.	104	3.6
90	Theory of folding of stratified viscoelastic media and its implications in tectonics and orogenesis. The Geological Society of America Bulletin 72(11):159S–1G20.	233	8
97	Mechanics of deformation and acoustic propagation in porous media. Journal of Applied Physics, April 1962;33(4):1482–1498.	582	20
99	Generalized theory of acoustic propagation in porous dissipative media. The Journal of the Acoustical Society of America 34(S, Part 1):1254–1264.	279	9.6
Book	Mechanics of incremental deformations. New York: Wiley; 1965.	644	22

Paraphrasing Garfield, a positive consequence of the increasing use and interpretation of the ISI database is not only that it may help weed out the culture of appearances, but also that it will help quantify the realities. There is much to be learned from the vast ISI data on citations, and we should use it as a feed-back signal to amplify individual motivation and to calibrate an important component of our performance.

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