REPORT

Supporting the Changing Research Practices of Civil and Environmental Engineering Scholars

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ITHAKA S+R

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Executive Summary

Ithaka S+R's Research Support Services Program investigates how the research support needs of scholars vary by discipline. In 2017 and 2018 Ithaka S+R examined the changing research methods and practices of civil and environmental engineering scholars in the United States with the goal of identifying services to better support them. The goal of this report is to provide actionable findings for the organizations, institutions, and professionals who support the research processes of civil and environmental engineering scholars.

The project was undertaken collaboratively with research teams at 11 academic libraries in the United States and Canada.[1] We are delighted to have the American Society of Civil Engineers (ASCE) as project partner and sponsor. Angela Cochran, Associate Publisher at ASCE, served as a project advisor. The project also relied on scholars who are leaders in the field to engage in an advisory capacity. We thank Franz-Joseph Ulm (Massachusetts Institute of Technology), Antonio Nanni (University of Miami), Anand Puppala (University of Texas at Arlington), and Roger Ghanem (University of Southern California) for their thoughtful contributions.

Many of the challenges civil and environmental engineering researchers face are shared with other STEM disciplines – a competitive funding landscape, a fraught peer review system, complex data management requirements. Yet this applied field presents unique opportunities for academic support service providers. Fundamentally focused on finding practicable solutions to real-world problems, civil and environmental engineering is highly collaborative, interdisciplinary, and close to relevant industries. Yet these synergies are largely built on old-fashioned research infrastructures. Inefficient systems for sharing data impede innovation, tools for discovering data and gray literature are inadequate, and career incentives discourage investment in the industry partnerships that shape the field's future directions. Successful interventions will need to recognize and leverage the field's strength in building personal, targeted, collaborative relationships, both within academia and between academia and industry. This report describes the distinctive ways in which civil and environmental engineering scholars conduct their research and draws out broad implications for academic libraries, universities, publishers, research technology developers, and others.

[1] See Appendix I for a full list of participating institutions.

Introduction

Through its Research Support Services program, Ithaka S+R conducts in-depth qualitative analysis of the research practices and associated support needs of scholars by discipline in order to better understand changing research methods and practices. Our previous projects in the program studied scholars in history, chemistry, art history, religious studies, Asian studies, agriculture, and public health.[2] A scholar-centered approach to understanding research in higher education is crucial to developing information services and spaces. By studying different disciplines, we gain a better understanding of how research activity functions across the academy.

An investigation of research practices in civil and environmental engineering has the potential to illuminate the complex support needs of scholars whose work is both shaped by and ultimately intended to inform engineering practitioners. Academic civil engineering departments proliferated in the late nineteenth and early twentieth centuries, when professional engineers were required to keep pace with federal infrastructure spending; the addition of "environmental engineering" to department names beginning in the 1970s reflected the broader society's changing needs and priorities.[3] The discipline is now tackling new challenges, such as the influence of private technology companies like Google and Uber on transportation, the decay of public infrastructures, and the myriad ramifications of climate change. Innovative and effective research support services will help position the field to respond to these critical issues.

Our report explores civil and environmental engineering scholars' information activities over the entirety of their research lifecycle – from information discovery and access to

[2] Jennifer Rutner and Roger C. Schonfeld, "Supporting the Changing Research Practices of Historians," *Ithaka S+R*, last modified Dec. 7, 2012, https://doi.org/10.18665/sr.22532; Matthew Long and Roger C. Schonfeld, "Supporting the Changing Research Practices of Chemists," *Ithaka S+R*, last modified Feb. 25, 2013, https://doi.org/10.18665/sr.22561; Matthew Long and Roger C. Schonfeld, "Supporting the Changing Research Practices of Art Historians," *Ithaka S+R*, last modified April 30, 2014, https://doi.org/10.18665/sr.22833; Danielle Cooper et al., "Supporting the Changing Research Practices of Religious Studies Scholars," *Ithaka S+R*, last modified Feb. 8, 2017, https://doi.org/10.18665/sr.294119; Danielle Cooper et al., "Supporting the Changing Research Practices of Agriculture Scholars," *Ithaka S+R*, last modified June 7, 2017, https://doi.org/10.18665/sr.303663; Danielle Cooper et al., "Supporting the Changing Research Practices of Public Health Scholars," *Ithaka S+R*, last modified Dec. 14, 2017, https://doi.org/10.18665/sr.305867; Danielle Cooper et al., "Supporting the Changing Research Practices of Asian Studies Scholars," *Ithaka S+R*, last modified June 21, 2018, https://doi.org/10.18665/sr.307642.

[3] Kumares C. Sinha et al., "Development of Transportation Engineering Research, Education, and Practice in a Changing Civil Engineering World," *Journal of Transportation Engineering* 128, no. 4 (2002): 301-313; Hojjat Adeli, "Vision for Civil and Environmental Engineering Departments in the 21st Century," *Journal of Professional Issues in Engineering Education and Practice* [hereafter *JPIEEP*] 135, no. 1 (2009): 1-3.

organization, preservation, and dissemination – as well as their perceptions of the key issues facing the discipline and what those issues mean for the evolution of engineering research. We share our findings and recommendations in order to highlight opportunities for a variety of stakeholders to better support their scholarship.

Methods

This project is part of Ithaka S+R's ongoing program to conduct research on scholarly information practices by discipline through collaboration with higher education institutions.[4] Participation in the project was open to any U.S. higher education institution with a civil and environmental engineering research program that was able to conform to the project specifications (e.g. timeline, research capacity). We invited all institutions that met these criteria. Appendix 1 lists the participants on the institutional research teams. We thank all the institutions that participated in the project.

The partner libraries created research teams of one to four members who, following a training workshop designed and led by Danielle Cooper, collected the qualitative data that Ithaka S+R analyzed for this report. The research teams at the participating institutions primarily comprised subject librarians but also included participants in other roles, such as assessment librarians and graduate students. Each team conducted research with approximately fifteen civil and environmental engineering scholars at their institution through semi-structured interviews that followed the arc of the research process (see Appendix 2 for the interview guide). Each team developed its own analysis from the data it collected at its respective institution with the option of either creating an internal whitepaper or a publicly available local report. The publicly available local reports, which provide a complement to this capstone report, are listed and linked in Appendix 1.

Ithaka S+R collected anonymized transcripts from the 109 interviews conducted across the participating institutions. We selected 40 of these transcripts as a representative sample based on the research subfields delineated below, academic title (assistant professor, associate professor, professor), and institution. The sampled transcripts were analyzed through a grounded approach to coding utilizing NVivo software. The interviewees remain unidentified in this report to protect anonymity. We thank the interviewees for their participation.

[4] Research for our previous reports on the research support needs of scholars in art history, chemistry, and history was conducted exclusively by Ithaka S+R staff.

Defining the Civil and Environmental Engineering Scholar

This report focuses on the practices and needs of civil and environmental engineering scholars at higher education institutions. Reflecting the project's aim to illuminate research as opposed to teaching activities, we define "scholars" as individuals who are employed by their institutions with research as a significant component of their job responsibilities, as opposed to those who primarily teach. Graduate students were not included in this study.

The field of civil and environmental engineering is characterized by its disciplinary breadth and its orientation toward applied research, often designed and carried out in close cooperation with industry partners. Broadly speaking, the field aims to scientifically understand and improve the built and natural environments for the benefit of human society, with "civil engineering" researchers focusing on the built environment and "environmental engineering" researchers on the natural environment. This means that civil and environmental engineering is especially interested in domains such as public transportation and utility infrastructure, construction methods and project management, pollution and climate change, disaster preparedness, energy consumption, and sustainability design. Geographically, researchers may focus on applications in their local areas or tackle engineering challenges worldwide.

For the purpose of creating a diverse sample, this project classed faculty members according to the following subfields, which can be grouped into "civil" and "environmental."[5]

Civil	Environmental
Construction	Air Quality
Geothermal	Coastal
Infrastructure	Geosystems
Structural	Water
Materials	
Transportation	

[5] We classed architectural engineering scholars in either the "construction" or "structural" groups depending on the focus of their work.

However, it is important to emphasize the regularity with which research in civil and environmental engineering draws on multiple subfields, often across the civil-environmental boundary. For instance, a specialist in coastal sediment might research both coastal erosion – an “environmental” topic – and coastal evacuation planning – a “civil” topic. Or, a researcher trained in microbiology might investigate the role of microbes in both water – “environmental” – and concrete – “civil.” This is in addition to significant collaboration with researchers in other disciplines, which will be discussed in the section “Working with Others.”

Another way to conceptualize the field is in relation to research methodology. Broadly speaking, scholars in this field conduct four types of research:

> *Qualitative.* Researchers investigate a community’s behaviors and preferences using tools such as surveys or questionnaires, interviews, workshops, and product trials. Formal methodologies include coding and qualitative comparative analysis.
>
> *Fieldwork.* Researchers observe processes and technologies in applied settings. They may do this either by installing and maintaining instruments that record, for instance, traffic flow or air quality. Or, they might make written, numeric, or photographic observations in person – for instance, photographing structural damage to a bridge, or counting the number of pedestrians who cross an intersection. They may also collect samples which are analyzed in the laboratory.
>
> *Experimental.* While fieldwork aims to gather data in “real world” settings, experimental research focuses on isolating processes and variables. It can occur in laboratories or in specialized testing facilities. The latter are often designed to allow experimentation in a particular domain, such as railroads, algae, or residential buildings, and might be maintained by industry groups or university departments.
>
> *Modeling and Data Analysis.* Researchers are increasingly using computerized mathematics to understand physical and chemical processes, networks, causal relationships, and probabilities associated with the built and natural environment. They also create software tools to help industry stakeholders make complex decisions.

It is important to note that a single scholar or research group will frequently make use of more than one research methodology, such as by gathering experimental data to use in modeling, or by developing a new technology in the lab before “piloting” it in the field.

Working with Others

The research of most civil and environmental engineering scholars involves working with others to a significant extent. Those “others” might include other academics, industry partners, librarians, and support staff. Working with other academics happens on several levels: within research groups; within faculties; across faculties within the same university; and with researchers at other universities. Broadly speaking, it can range from informally sharing insights – as when scholars meet to discuss common research interests – to undertaking more formal collaborative projects. Many interviewees implicitly defined "collaboration" as work resulting in a jointly-authored output, such as a grant proposal, report, or article. This report follows this distinction, considering "collaboration" to be a project-based cooperative venture and one of many ways of working with others.

Civil and environmental engineering researchers also work extensively with what this report calls "industry partners," namely government agencies, NGOs, and private companies. When interviewees were asked about how they work with industry partners, they described a variety of partner functions, including funding projects, defining research aims, supplying data, and contributing research insights. In academic-industry partnerships, these functions are often inseparable.

This report also highlights the support infrastructure that enables civil and environmental engineering researchers to work with others. Technology has enhanced scholars' ability to communicate and share information within collaborations, especially across distances, but it has not replaced the rapport and serendipity associated with in-person meetings. It is noteworthy that civil and environmental engineering scholars do not consider librarians to be collaborators in their research. However, they do turn to librarians for help with accessing published material, and are open to – though not yet widely accustomed to – working with librarians navigate the rapidly-evolving realms of data management and research dissemination.

Academics

Civil and environmental engineering faculty members lead research groups comprised of graduate students and, in some cases, postdoctoral researchers and visiting scholars. Group members usually write literature reviews, conduct research, and draft publications under the supervision of the lead faculty member. Sometimes, one group member may be given responsibility for a specialized technical function within the group, such as information management.

> The applied nature of research in this field demands that insights and methods be drawn from several disciplines in order to achieve real-world impact.

Civil and environmental engineering researchers also work extensively with academics outside their own research groups. At a fundamental level, the applied nature of much civil and environmental engineering research demands that insights and methods be drawn from several disciplines in order to achieve real-world impact – especially as technological development moves at an increasingly rapid pace.[6] The most common interdisciplinary collaborations are with researchers in materials science, chemistry, biology, geology, statistics, and other engineering fields. Other departments or schools with which civil and environmental engineering researchers collaborate include computer science, construction management, operations research, economics, urban planning, behavioral science, design, architecture, business, and even law. Some interviewees expressed pride in the interdisciplinarity of their research, suggesting that they consider the cutting edge of the field to lie outside "arbitrary" disciplinary boundaries. One explained, "we're trying to position ourselves in advance [of] different emerging fields .... We're the first group in the nation to conduct this type of research." Even within the field, collaborations can allow researchers to draw insights from methodologies that lie outside their own area of expertise. As one researcher who focuses on modeling explained, "I have never been an experimentalist; it's just one of those things that I just decided you can't do everything. So I collaborate with people who do experiments."

There are other practical reasons why civil and environmental engineering researchers work with others. Some study environments outside the United States and Canada and require the help of local experts; others need to access to specialized laboratory equipment housed at other universities. Competing for research funding can also necessitate assembling a collaborative team – "shotgun teaming," as one interviewee put it. "If I know I'm writing a proposal on X, and it requires expertise in these three things, A, B, C, I search through my mental tree of people I know to find out who to contact," another explained. Covering the needed areas of expertise is not the only consideration when selecting collaborators for proposals; when funding is being offered by a state government, an out-of-state researcher's proposal may be more competitive if they find an in-state collaborator. Finally, many collaborations start from a desire to work with someone else's data. Working with other academics to share data can be temporary and informal – providing data or contextual information over email – or long-term and formal – co-investigating on a project or jointly authoring an article. Temporary and informal data sharing exchanges will be discussed more fully in the section on "Sharing Data" below.

[6] Adeli, "Vision"; Gunnar Lucko and Jessica A. Kaminsky, "Construction Engineering Conference and Workshop 2014: Setting an Industry-Academic Collaboration Research Agenda," *Journal of Construction Engineering and Management* 142, no. 4 (April 2016).

The process of discovering and initiating potential academic collaborations is ad hoc and highly personalized. Civil and environmental engineering researchers generally network with other academics by attending conferences, leveraging existing contacts, and scheduling meetings with other researchers. "It's mostly word-of-mouth and people we know or three degrees of separation or whatever," one interviewee commented. Although some civil and environmental engineering researchers use online networking sites like ResearchGate and Twitter to make their own research profiles discoverable and stay abreast of what colleagues are working on, these services have not displaced conferences and direct communication as the most important methods for network-building. There is, however, room to improve the ad-hoc process of locating potential collaborators: "Often times we are looking for a collaborator and we don't really know ... who to go to."

Industry

The broad scope of applied research conducted in civil and environmental engineering departments means that the field collaborates with a wide variety of industry partners. These can be grouped into three categories: government agencies, non-governmental organizations (NGOs), and private companies.

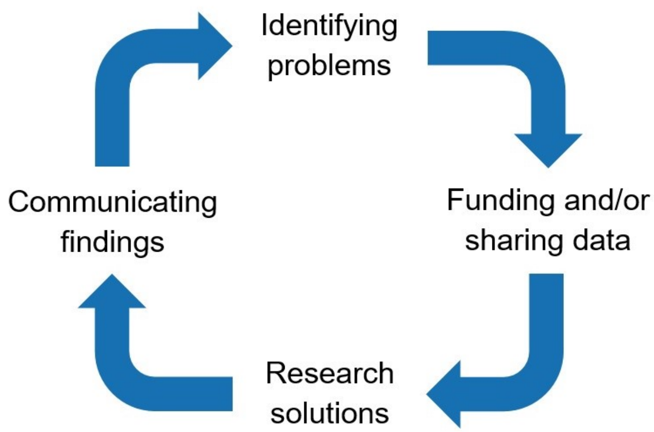
> *Government agencies*. Civil and environmental engineering researchers collaborate with government agencies including municipalities; state health and transportation departments; and federal entities such as the Environmental Protection Agency, the Department of Energy, and the Department of Natural Resources. The National Science Foundation and its subsidiaries are particularly important partners in and funders of civil and environmental engineering research. Government-funded laboratories such as the National Institute of Standards and Technology and the National Renewable Energy Laboratory are also prominent in the field. Researchers at Canadian universities collaborate with a range of local and national Canadian government agencies.
>
> *NGOs*. Researchers who tackle global environmental issues will frequently partner with inter-governmental organizations such as the United Nations and World Health Organization, or with organizations working on the ground in developing regions. Some transportation and manufacturing trade associations, such as the Association of American Railroads and the Semiconductor Research Corporation, sponsor and facilitate research; these efforts are often funded by consortia of private companies. Finally, nonprofit research organizations such as the Transportation Research Board (TRB), a subsidiary of the National Academies of Sciences, Engineering, and Medicine, facilitate collaborative research; for instance, the TRB oversees the National Cooperative Highway Research Program, which itself aims to collaborate with state-level Departments of Transportation.
>
> *Private companies*. Civil and environmental engineering researchers partner with private companies such as consulting, architecture, and engineering firms; contractors; specialized manufacturers; and energy suppliers.

Working with industry partners is fundamental to the research of many civil and environmental engineering scholars. On one level, industry partners represent the link which allows researchers to see their work applied in the built and natural environments. Just as importantly, industry partners shape the direction of civil and environmental engineering research and contribute to research processes, even as academic research opens up new strategic directions in engineering.[7] As mentioned above, the function of some industry partners as funders of research is important, but in many cases the funding role is also inseparable from other collaborative contributions.

Civil and environmental engineering researchers' working relationships with industry partners can be conceptualized schematically (see Figure 1). Successful working relationships are mutually beneficial and tend to lead to further collaboration. Starting from the top of the diagram, industry partners identify engineering challenges or opportunities. They seek an academic researcher to investigate; if the industry partner is a government agency or NGO with sufficient resources, they may advertise a request for proposals and allocate research funding. Industry partners of many types will supply the researcher with proprietary data, and may be actively involved in shaping the research process. Once the research is completed, the scholar will communicate their findings to the industry partner for implementation. Such communication – which includes reports, practitioner-facing conference presentations, and the submission of engineering standards to practitioner committees for review – frequently results in a dialogue through which further potential research avenues are brought to light; the cycle restarts.

[7] Burcin Becerik-Gerber and Karen Kensek, "Building Information Modeling in Architecture, Engineering, and Construction: Emerging Research Directions and Trends," *JPIEEP* 136, no. 3 (July 2010): 139-47; Aviad Shapira and Yehiel Rosenfeld, 'Achieving Construction Innovation through Academia-Industry Cooperation – Keys to Success," *JPIEEP* 137, no. 4 (October 2011): 223-31.

Figure 1. Academic-Industry Partnerships



Although every collaboration is different, this generalized schema can be used to understand a variety of types of industry partnerships. Larger government agencies and research organizations typically fund collaborative research projects, which may involve faculty members from different universities and/or industry consultants serving as co-investigators. Organizations working overseas will similarly shape research directions, but also play an important role in facilitating qualitative research and dialogue with local communities. State and local governments tend to contract researchers as consultants on specific environmental or infrastructure initiatives; or, a consulting firm working on such an initiative may subcontract a researcher. Several interviewees reported that they had been contracted by local governments or private energy companies to capture, store, and analyze infrastructure performance data. Others work with manufacturers to develop and test specialized equipment. All of these working relationships, if successful, involve the same core elements, in which industry partners both shape and support research, benefitting from research insights as a result.

Although industry-academia partnerships can pose ethical concerns in some fields, interviewees overwhelmingly spoke of industry partners as positive actors in their research field. Many implied that helping a government agency, company, or organization improve their engineering products or processes was a desirable end in itself. Only a few interviewees alluded to potential ethical concerns. One asserted that "in the beginning" of an industry-funded project they establish that they will not allow the industry partner to manipulate research methods or outcomes to suit their own interests, and suggested that they had seen scholars at other institutions doing this. This scholar explained, "I tell [the partner], 'Look … you're going to tell me what we are studying; I'm going to decide what to do, how to conduct [it], how to collect the data, where to collect it.'" Another interviewee acknowledged inappropriate interference by industry partners as a potential problem in theory, but said they had never encountered such a conflict in their own research. By contrast, a number of interviewees said that they welcomed the involvement of industry partners throughout the research process.

Close Reading: Motivations for Collaborating with Industry

"The majority of the collaboration[s] that I have are in the shape of funding. For example, if they have a specific problem that they want us to look at ... it is not exactly funding [in the] sense that they give us money and we solve the problem and we go back to them. It is more a collaboration in the sense that yes, they fund us, but they are very involved in the process and always have input. We want that input, right? Because we want to solve the problem that they really want [solved]."

"People come to us and say, we have a problem. What we may do is put together [a team] – find the funding somehow to get the research done. We will normally partner with other universities. … So we'll engage with them, we'll do collaborative research to generate [a solution] …. And then we help get it out into practice. One of the things we do is we host a conference every six months with engineers … where we can listen to them, go back to them, present answers."

In both examples, the interviewees are motivated by solving a problem practitioners are experiencing. Industry partners are involved in both the research design and execution processes.

Additional collaborators and third-party funders may be brought on board.

Both interviewees emphasize that they "go back to" the industry partner with answers. This also allows scholars to "listen," facilitating future cooperative work.

As with academic collaborations, civil and environmental engineering researchers tend to discover and initiate industry partnerships on a personal, ad hoc basis. They are broadly familiar with the industry stakeholders operating in their research areas, and they build relationships with these stakeholders and keep abreast of industry trends and research needs by competing for funding, leveraging existing contacts, and attending conferences and offering workshops aimed at industry practitioners. The topic of research dissemination to industry partners is discussed at length in the "Dissemination" section below.

Collaborative Technologies and Workflow Management

Although communication and collaborative technologies can facilitate collaboration among academics and industry partners, several core challenges arise and are addressed at the interpersonal level. Interviewees described difficulties managing differences in personality and work habits; coordinating efforts across large groups (more than two or three collaborators) or within groups where there are two principal investigators); and communicating across subfields which use discrepant terminologies. Language and cultural barriers can also interfere with international collaborations, to the extent that some universities have undertaken efforts to better train civil and environmental engineering graduates in working cross-culturally.[8] Collaborators prefer to hammer out agreements on the potentially thorny issues of intellectual property and order of authorship at the beginning of a project. One interviewee, however, noted that working through differences with collaborators can also be rewarding: “That’s sort of the fun part of working with other people … because people bring different things to it.”

Collaborative workflows are enabled using multi-purpose file sharing and document collaboration platforms such as Google Drive, Google Docs, Box, and Dropbox. Difficulties occasionally arise when collaborators use different citation management software, and there is some interest in having greater access to collaborative platforms that integrate seamlessly with citation management tools. Working with others can also compound the challenges of managing research data discussed in the next section.

Many civil and environmental engineering researchers maintain collaborations over significant distances. They communicate using video conferencing services such as GoToMeeting, Zoom, and Skype, in addition to phone and email. Nevertheless, in-person meetings remain essential to maintaining strong professional relationships. “If you don't occasionally get together face to face the basis of your understanding and your mutual understanding and support gradually diminishes,” one interviewee explained. Traveling significant distances to meet with a colleague communicates intentionality: “It’s a total difference if someone makes the effort, from England, to travel over here to meet with me. That means someone is really committed to build up this network.”

> “So much still relies on running into your colleague in the hallway.”

[8] Lucio Soibelman et al., “Preparing Civil Engineers for International Collaboration in Construction Management,” *JPIEEP* 137, no. 3 (July 2011): 141-50.

The importance of meeting in person extends even to working relationships within the same university. Yet some researchers find it easier to connect with colleagues from other institutions through conferences than with colleagues from different departments on their own campus. "So much of [working with others] still relies on running into your colleague in the hallway," one interviewee explained, and researchers believe that the physical location of their departmental building has a real effect on how frequently they encounter colleagues from other departments. Departmental siloing may be particularly problematic for civil and environmental engineering, a highly interdisciplinary field in which jointly-affiliated researchers sometimes have their offices in other departments. In the absence of "a teleportation system around campus," interviewees noted that research seminars are a good venue for facilitating inter-departmental, as well as inter-institutional, meetings.

Librarians

Civil and environmental engineering researchers tend to work with librarians on an as-needed basis, and this means that they require a comprehensive understanding of what services their libraries offer in order to take full advantage of them. This is because they view the librarian's role as passive and reactionary rather than proactive. As one interviewee put it, "my general sense is if I ever have issues … the library is there to help, and it's really more my deciding when I want help." This is not necessarily a negative thing in researchers' eyes: "When you go there and talk with them, you know that the goal is trying to help you." However, a common refrain was that scholars are ill-informed about the range of ways in which libraries might support their research.

Researchers' tendency to work with librarians on an as-needed basis means that they require a comprehensive understanding of what services their libraries offer.

Civil and environmental engineering researchers view the library's primary function as providing them with access to published materials, both scholarly literature and, in some cases, gray literature. This function is detailed in the "Working with Information" section below.

Interviewees also expressed an interest in obtaining librarians' help with several other research support needs. Two of the most frequently emphasized areas appear to be research data management and navigating open access requirements and options.

Although some researchers have a relatively limited vision of what support in these areas would look like – for instance, they may wish they could delegate the administrative function of organizing their research notes to someone else – others are interested in getting advice on best practices, either for themselves or for their graduate students. Research groups embarking on new, data-intensive projects would benefit from consultation with data management specialists, and bibliometrics experts could help advise pre-tenure researchers and graduate students on how to maximize the impact factors of their publications.

Skills training is another area which researchers tend to associate with their libraries: in addition to academic writing workshops for their graduate students, they are also interested in gaining new technical skills themselves, especially in computer programming. “We weren't in school when everyone was deciding [that] we needed to know how to do big data,” one interviewee explained. “And so a lot of us are trying to learn this stuff on our own.” Another described working with librarians to develop a user-friendly online platform for sharing their research data with the wider public. Finally, civil and environmental engineering researchers are interested in libraries offering in-house editorial services to help improve their journal articles and, even more importantly, their grant proposals prior to submission.

Working with Information

Civil and environmental engineering researchers discover, access, and manage information throughout the research cycle. Scholars may obtain data from others – either other researchers or industry partners – and/or collect or produce their own data. The collection or production of research data requires scholars to coordinate and archive their research groups’ work using tools such as laboratory notebooks and shared drives. Data produced by other researchers, as well as industry data and gray literature, must be located either by leveraging professional networks or searching online. Once a researcher has obtained the data they need, they make decisions about how to organize, store, or dispose of it, taking into consideration factors such as funder requirements, file sizes, the potentially limited shelf file of file formats, and the high-turnover context of a research group, in addition to convenience and cost effectiveness. Finally, many researchers code software and create computer models for data analysis, and these research products must also be stored and managed. Civil and environmental engineering researchers also work with published scholarly literature – primarily journal articles in electronic form – and with gray literature. They employ a grab-bag of techniques to identify relevant information, gain access to it, and store electronic copies and citations for future use.

Discovering Data

As described in the introduction, the research of civil and environmental engineering scholars can be roughly divided into four methodological categories: qualitative, fieldwork, experimental, and modeling and data analysis. Reflecting this methodological diversity, the data produced and used in the field takes many forms, including numerical information produced through modeling or statistical analysis; results of laboratory experiments; sensor readings; photographs and written observations of field sites; documentation of construction management processes; and survey questionnaires and interviews. MATLAB, Excel, and R are all commonly-used software environments (R being both a software environment and a programming language) for data manipulation and numerical computing. In addition to these tools, researchers employ a host of specialized software programs to support tasks including statistical analysis, qualitative "coding," modeling, graphing, Bayesian belief network analysis, traffic simulation, GIS work, and machine learning. They code using R, Python, and, less commonly, C++.

In addition to the data they collect and produce themselves, many civil and environmental engineering researchers obtain research data from other scholars. They also rely heavily on data produced by governments, NGOs, and private organizations in the industry. This includes research data collected or posted online by government agencies and NGOs; data obtained through services such as Google Maps and Google Earth; and industry-specific documentation such as construction specifications and energy consumption records.

The challenges of discovering and accessing data in civil and environmental engineering mirror those experienced by scholars in agriculture, another applied and multidisciplinary field.[9] Datasets are often discovered incidentally while reading journal articles, attending conferences, or talking to colleagues or practitioners; scholars follow up on interesting leads by downloading supplemental files directly from a journal's website, looking for the dataset in a repository, or getting in contact with the researcher who created it. When a scholar needs to search proactively for data, they often rely on their familiarity with the major repositories, databases, and industry organizations that pertain to their research area. One transportation researcher explained they often "just happen to know" who has the needed data, since "it's a relatively small industry." Some scholars even build programs that automatically identify and download new data from specific websites. Challenges arise, however, when a researcher begins to look for information in more disparate or less familiar domains.

[9] Cooper et al., "Agriculture Scholars," 15-17.

Faced with the task of discovering new datasets, some scholars turn to Google or Google Scholar.[10] Others lean on their professional networks. One interviewee who frequently uses government data described a process of first identifying the type of information needed, then working to determine whether that information has been collected by any government agencies: "Sometimes it takes a couple of conversations with a couple people to get … to the right person to get you the data." Even this "blind search" is highly relational: the researcher reported being helped by contacts with whom they have an established relationship, and prefers to call, rather than email, potential sources "because you get engaged in the conversation, and through that conversation sometimes things come out that's [sic] very useful."

> Challenges arise when a researcher begins to look for information in more disparate or less familiar domains.

Accessing data can also prove challenging. Setting aside the task of convincing other researchers to share their data, which will be discussed in the next section, there are numerous potential barriers to accessing industry information. Some datasets must be purchased from local governments or private companies – an expense university libraries are often unable to shoulder. The collection and availability of government data can be subject to changing political priorities, and workarounds often involve leveraging professional networks. One interviewee reported that when climate change data was removed from the Environmental Protection Agency's website, the data remained accessible only because some researchers, whom the interviewee knew "through Twitter and through other conference interactions," had downloaded and publicized the data as a precautionary measure.[11] Another researcher who sometimes needs to access air quality data collected by foreign governments noted that "that data is not available to us formally. But sometimes we have mechanisms get that." Graduate students are sometimes responsible for the labor of collecting difficult-to-access data: an interviewee reported that one of their students has assembled data from hundreds of water utilities by submitting Freedom of Information Act requests.

[10] Interviews for this project were conducted before the launch of Google Dataset Search on September 5, 2018: https://www.blog.google/products/search/making-it-easier-discover-datasets/.

[11] This comment was likely in reference to the Data Refuge initiative, https://www.datarefuge.org/, although the interviewee did not refer to the initiative by name.

Discovering Gray Literature

Ithaka S+R's report on the research practices of public health scholars highlighted the difficulty of tracking down relevant gray literature;[12] interviewees for this project echoed similar concerns. "Gray literature" refers to texts that are sufficiently technical and rigorous to be used in academic research, but which are not published by traditional academic presses. In civil and environmental engineering, this includes reports published by government agencies and NGOs, engineering codes and standards, and patents. Unpublished academic outputs such as conference posters and dissertations may also be considered gray literature. These texts are essential for allowing scholars to gather information about what is happening in applied engineering settings, but, like research data, gray literature is dispersed across the internet and nearly impossible to search systematically. One water researcher reported that because relevant gray literature is being released by a plethora of NGOs and governments, they find it "very challenging" to know "what's out there without knowing in what organization it exists and going to their website." Aside from domain expertise and incidental discovery, researchers rely on Google Scholar, which captures some gray literature, and, again, on their professional networks. Finding gray literature "is a lot of nitty-gritty one-on-one conversation work," one interviewee explained.

Data management

Civil and environmental engineering researchers face many of the same challenges with data organization and storage that Ithaka S+R's reports have identified for other STEM-related fields.[13] Few scholars are able to articulate comprehensive, systematic data management strategies for their research groups. Instead, data management practices tend to be habitual and reactive: as one interviewee put it, "when it gets past a certain point, we learn how to do something a little bit better." Most research groups maintain a rough-and-ready system whereby students and postdocs keep data on their computers and periodically upload it to shared Box, Dropbox, or Google Drive folders. Group leaders make a particular effort to collect data from students before they graduate, but may struggle to navigate or understand that data later on. Quotidian data management responsibilities – maintaining file hygiene, updating metadata – often fall to graduate students, and many scholars would like their graduate students to receive data management training.

[12] Cooper et al., "Public Health Scholars," 13-14.

[13] Long and Schonfeld, "Chemists," 25-29; Cooper et al., "Agriculture Scholars," 17-19; Cooper et al., "Public Health Scholars," 21-23.

In some cases, data which is governed by IRB (institutional review board) approval because it involves human subjects, or which is otherwise restricted by its provider, must be stored locally or only using approved software; such data may also need to be destroyed after research is complete. Setting aside those governed by specific data privacy or copyright requirements, very few interviewees spoke of a destruction schedule for data. Rather, the preference is for keeping information as long as possible – purchasing additional hard drives as necessary, despite the risk of file formats becoming outdated and unreadable over time.

"I do have concerns that I may not be quite living up to the expectations of the funding agencies as far as data management."

It is important to note that although funders are increasingly requiring grant recipients to articulate data management plans,[14] there is a perceived gap between funders' expectations and the availability of grant money to support data management efforts, for instance by paying the salary of a full-time expert. One interviewee admitted, "I do have concerns that I may not be quite living up to the expectations of the funding agencies as far as data management." Comments like this suggest that merely writing data management plans into grant requirements may not have the desired effect. Significantly changing scholars' data management practices will require research funding organizations and other stakeholders to take a more proactive approach.

Electronic laboratory notebooks (ELNs) have not been widely adopted among civil and environmental engineering researchers. Some record notes and results in generic software programs like OneNote or Excel, while many prefer the traditional paper notebook. Researchers who regularly do fieldwork or potentially messy laboratory experiments are cautious of damaging computing equipment: "All of these nice tablets are not working that well in the rain," one quipped. Another interviewee seemed unaware of ELNs altogether, suggesting that they would like a cloud-based method of recording data in the lab but that this was "not very realistic for now." Still another explained that, as a young woman in a male-dominated field, she feels that using a traditional hard-copy notebook protects her credibility among her colleagues: "If I'm

[14] Anne R. Diekema, Andrew Wesolek, and Cheryl D. Walters, "The NSF/NIH Effect: Surveying the Effect of Data Management Requirements on Faculty, Sponsored Programs, and Institutional Repositories," *Journal of Academic Librarianship* 40, nos. 3-4 (May 2014): 322-31.

sitting with you, or I'm at a conference, and I'm taking notes on my electronic lab notebook, they might perceive that as, she's just messing around, playing games on her tablet. This [physical notebook] is a little more believable."

Academic Literature

Civil and environmental engineering scholars use published academic literature to undergird and inform their own research projects, to stay abreast of new developments in the field, and to discover potentially relevant datasets, collaboration opportunities, and other academic literature. Published scholarly communications in this field primarily take the form of peer-reviewed journal articles, although researchers will occasionally also use textbooks, dissertations, and printed conference proceedings.

Google and Google Scholar are the favored search platforms for literature discovery, with Web of Science and subject-specific bibliographic databases, such as Compendex and Engineering Village, also widely used. Like scholars in other disciplines,[15] civil and environmental engineering researchers combine direct internet searches with a variety of ad hoc techniques for finding relevant published information, including setting up automated alerts for relevant content with publishers and search platforms; following references in literature they've already identified; and taking advantage of peer reviewing, editing, and graduate supervision commitments to stay abreast of new publications. Graduate students are often tasked with writing literature reviews or finding published information on particular topics, and interviewees expressed a desire for their students to receive additional training this area. A few groups employ systematic methodologies, such as Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA), when conducting literature reviews, or keep shared spreadsheets in which group members identify and describe what they've read. Finally, researchers also identify potentially useful literature socially, by attending conferences, talking with colleagues and practitioners, and, in some cases, utilizing social networking sites, especially Twitter and ResearchGate.

Civil and environmental engineering researchers strongly prefer to access academic literature online. They use preprints when they come across them in the course of searching for literature, but in general do not proactively seek them out. This is in contrast to other STEM-related fields, such as physics, mathematics, and computer

[15] Rutner and Schonfeld, "Historians," 17-20; Long and Schonfeld, "Chemists," 24-25; Long and Schonfeld, "Art Historians," 22-23; Cooper et al., "Religious Studies Scholars," 20-25; Cooper et al., "Agriculture Scholars," 11-15; Cooper et al., "Public Health Scholars," 10-13; Cooper et al., "Asian Studies Scholars," 9-12.

science, which have strong preprint culture.[16] When an item is not available online, a researcher will request it through interlibrary loan, ask a librarian for assistance, or, occasionally, email the article's author directly to ask for a copy. Some institutions have document scanning services, through which faculty members can request materials only available in print to be scanned and emailed to them; these services may be under-utilized due to a lack of awareness among faculty members.

Once a scholar has identified a relevant article, they usually download it in PDF format and may annotate it digitally. Although some researchers organize their personal collections[17] of scholarly literature using citation management software such as Zotero, Mendeley, or EndNote, many prefer to maintain more or less systematic file systems on their own computers. Although some interviewees reported workflow inefficiencies in navigating their own literature collections, these do not appear to rise to the level of a major research challenge for most civil and environmental engineering scholars.

Sharing Data

This section discusses how researchers share data – how they use others' data and make their own data available for others to use. Data can be produced by other academic researchers or by industry partners. Interviewees reported a range of attitudes in their research communities toward sharing data, and these attitudes vary within subfields, methodologies, and institutions. The majority of interviewees reported that they are at least somewhat engaged in sharing data with others.

There are a number of reasons why civil and environmental engineering scholars use others' data. Those whose research focuses on modeling require large quantities of experimental or field data with which to work, and they often rely on data produced by others. Experimental researchers may look for data that can be used to benchmark their own results or to assemble a larger sample for analysis, especially when the experimentation is expensive to perform. Still other researchers may seek a more rounded analysis by accessing data of a type that falls outside their own methodological specialty. Some types of data – such as seismic and weather recordings, public health records, and traffic data – are traditionally or proprietarily collected by government

[16] Vincent Larivière et al., "arXiv E-Prints and the Journal of Record: An Analysis of Roles and Relationships," *Journal of the Association for Information Science and Technology* 65, no. 6 (2014): 1157-69.

[17] Danielle Cooper and Oya Y. Rieger, "Scholars ARE Collectors: A Proposal for Re-thinking Research Support," *Ithaka S+R*, last modified Nov. 28, 2018, https://doi.org/10.18665/sr.310702.

agencies, NGOs, or private companies. Finally, researchers sometimes conduct meta-analyses of the results of multiple field-based tests and observations.

Researchers share data either personally or impersonally. Personal data sharing involves direct contact between the researcher who created or collected the data and the researcher who wishes to use the data, usually via email. Impersonal data sharing involves placing data in a publication, repository, or database and allowing it to be downloaded; the author does not control, and may not even be aware of, who is using their data or for what purpose. Sometimes, a researcher will need to use both personal and impersonal methods to get the data they need. They might download supplemental information from a journal article and then contact the article's author with follow-up questions; or, they might contact a colleague to ask for data and receive a link to an online repository where the data is stored.

Three Conditions for Sharing Data

Three main considerations influence whether and how civil and environmental engineering researchers share their data with others or use others' data:

> *Trust*. The researcher must trust that others' data is reasonably accurate; when data is shared personally, the data provider must trust that their data will be used in a worthwhile manner.
>
> *Context*. The user of the data must understand its context – what it measures and how it was gathered. The data provider must ensure that sufficient contextual information accompanies the data.
>
> *Format*. The data must be made available in a format suitable for transfer and reuse.

Unsurprisingly, mutual trust between the provider and the user of the data is most important when data is shared personally. Researchers often reach out via email to others to ask for data which they learn about through publications, conferences, or word-of-mouth. Although some researchers are happy to share data "on good faith"; such requests for data sharing are more likely to receive a response when the two scholars have an existing professional relationship. As one interviewee noted, "Sometimes we'll contact the authors [of journal articles] and ask them for the raw data. It's really rare that they respond, or give us anything, unless I know them personally."

Interviewees hinted at an unspoken rule that the more effort a researcher puts into sharing their data with others, the more recognition they will expect to receive in return. If they reference a figure from someone else's published article, "then we just acknowledge in a paper, thank you for providing those data. But if we said, no, no, no, can you redo the analysis such that you get rid of this factor, so that [it's] a little bit more consistent with my model, then you basically ask them to do more work. They will … let us co-author." Convincing another researcher to share their data often involves demonstrating how it will benefit them through citations or, better yet, a more formal collaboration. "Since we're usually trying to get other people's data rather than the other way around, we have to first show them, usually with a little subset of the data, that we could do something very interesting with it, and they can be either lead authors or joint authors with us," one researcher explained.

Close Reading:
Trust Breakdown in a Request to Share Data

"Gosh, this one drives me crazy. A publication that we were building off of from a contact at another university. We read through the statement in the paper that says, 'We disaggregated these data based on population and economics.' How? 'For more detail, [see] the supporting information.' Pull up the supporting information. There's a paragraph that pretty much just says that exact same thing. … Huh? No really, how'd you do this? Because we would like to do the same thing and cite you. Get in touch with the corresponding author, who I know, and he says oh. 'We're working on a project on that right now, wait until our new paper comes out with the data.' It still hasn't come out and this was two years ago. … It's just really been frustrating. It's just the exact opposite of an open data thing. So yeah there's plenty of stories like that. I just want to shake something. Because it kind of seems like you just did some hand waving and made stuff up."

Even though the data was published, the contextual information in the article wasn't adequate to make the data useful.

The interviewee knew the author's article personally, but this alone didn't supply the trust needed to initiate data sharing.

The interviewee and the article's author had different expectations around data sharing: the interviewee assumed that a citation was sufficient incentive to share data, while the article's author assumed that data shouldn't be shared until any resulting publications had been published.

The resulting breakdown in trust made the interviewee question the validity of the data itself: "You just did some hand waving."

Trust can play a role even in more impersonal methods of sharing and obtaining data. Numerous interviewees acknowledged that using others' data – especially government data – comes with a risk of inaccuracy or irregularity. Those whose work relies heavily on data produced by others are generally willing to accept this risk. "When other people share stuff, you're subject to whatever their internal quality control is on sharing data. So it's better than nothing. It's not perfect," one interviewee explained. Those who work with large enough quantities of data have the luxury of simply throwing out segments that are clearly anomalous. Others expressed greater reservations: "You've got to be really alert," one researcher cautioned, while another reported that they often "conduct a little bit of validation stuff initially just to make sure it appears to be … good data, something that we are able to use."

Many interviewees stressed the importance of shared datasets being accompanied by adequate contextual information, since "unless it's been really well documented, how their test set up was constructed and what types of data they're using, it can be really difficult to interpret the data correctly." Some insisted that personal communication between researchers was the only way to adequately establish a dataset's context. "For what I'm doing, the notion that anybody could upload data that would be self-explanatory without the PI [principal investigator] interaction would be very surprising," one interviewee insisted. Another recounted an instance in which they almost made a significant mistake because a dataset had been incorrectly contextualized in a government repository. The error was only avoided when the researcher contacted the authors of the dataset directly. Even when a complete dataset has been appended to an article, researchers regularly find that the article does not provide enough contextual information to make the data usable. When this happens, they may email the article's author directly to ask for more information.

"Unless it's been really well documented … it can be really difficult to interpret the data correctly."

Difficulties with formatting, storage, and transmission can also impede data sharing. Some experimental researchers produce raw data in highly specialized or even proprietary formats which are difficult for other researcher to use. One interviewee expressed that they "thankfully" are not responsible within their collaboration for working with others' data, because "it would take half the time just to learn what the data is," even within the same subfield of air quality. The sometimes time-consuming task of format standardization can also discourage researchers from uploading their data to repositories. "I mean we're happy to publish them," one researcher who produces data in a specialized format explained, “but at the same time, I don't want to frustrate people .... And then obviously another question is like okay, how much time do I want to spend on bringing the data to a level that is really directly useful?” The same interviewee indicated that they would prefer to wait until someone contacts them to ask for data before investing this time, rather than reformatting data which might sit in a repository unused. The need to process sensitive data to meet privacy standards before publicizing it throws up an additional barrier to sharing some datasets. One interviewee who works with utility data explained that they must often sign confidentiality agreements to head off concerns about potential lawsuits if their data is released to the public.

Researchers also experience difficulties when sharing large data files. As one interviewee succinctly put it: “I’ll be happy to give it away, but where do I put it?” When a dataset is too large to be uploaded or downloaded easily from the internet, it is not uncommon for researchers to resort to physically mailing hard drives to each other. Another method is to grant a colleague access to the servers on which the data is stored. One interviewee described their extensive efforts to make a large dataset publicly available on servers which they maintain themselves. These “become a pain because every time the server is down I get emails.”

Finally, it should be noted that a number of civil and environmental engineering researchers share their software models and other code on their group websites or, more frequently, through GitHub. These models are not data per se, but rather tools developed by researchers to manipulate and analyze data. Although one researcher complained of the need to field requests for “software maintenance” after having made a model publicly available, on the whole interviewees seemed less concerned about the practical difficulties of sharing their models through GitHub than about the challenges of sharing data online.

Future Directions

One interviewee summarized the perspectives of many civil and environmental engineering researchers well: “In a way, it’s like it’s not like I don’t want to make [data on] that topic available, it’s the extra effort I have to put in to make them publicly available.” Many researchers remain unconvinced that the benefits of sharing data – or of sharing data more widely and efficiently – outweigh the practical difficulties.

It is clear that there are significant inefficiencies in current data sharing practices within civil and environmental engineering. As one interviewee put it, “You just have to realize there's sometimes where if somebody just got data and it's just what you need, you're just not going to get it.” Authors retire or lose track of old data files; internet links become outdated. There is a culture among some researchers that data is not shareable until any publications resulting from it have been accepted. “I see [data] as part of our intellectual property,” one interviewee stated. “I don’t necessarily want to share it with somebody outside unless I have to.” However, the same researcher’s group regularly extracts data from figures and tables in published articles. In fact, many scholars habitually extract numerical data from the processed figures and tables published in articles. Most use a software called ImageJ to do this; one interviewee reported having used a ruler to estimate values from a printed PDF of an article by hand. Unsurprisingly, these techniques yield only approximations of the underlying raw data. As one scholar put it, “you never get it exactly correct, it's kind of, ‘It's close, close-ish.’” Re-using data becomes like a game of telephone.

It is clear that there are significant inefficiencies in current data sharing practices.

Many interviewees suggested that online data repositories have the potential to improve this state of affairs. Some imagine repositories streamlining, but not replacing, personal methods of data sharing. When one scholar gets an email from another requesting data, they can reply simply by sending a DOI for the archived dataset, with subsequent communication required only to answer specific follow-up questions. It is worth emphasizing that the interviewees who described using repositories in this way assumed that data sharing would still be initiated through personal, direct contact between researchers.

The use of data repositories is uneven in civil and environmental engineering. Area-specific databases appear to be the most successful, with the Natural Hazards Engineering Research Infrastructure (NHERI)’s DesignSafe repository repeatedly cited by interviewees as a positive model.[18] Researchers appreciate that uploading data to this repository “is more of an organized effort, and you have [a] professional helping you” to standardize the dataset’s format and contextual information. Civil and environmental engineering researchers whose work intersects with biology also benefit from well-established genetics repositories. By contrast, other subfields lack an area-specific repository: noting a colleague’s use of a DNA sequencing repository, one air quality researcher commented, “I keep thinking, ‘Well, we need to be doing that in air pollution.’”

[18] See https://www.designsafe-ci.org/ for more information.

There is also some concern that area-specific databases may have limited lifespans if their funding is cut. Interviewees described a repository funded by the National Science Foundation (NSF) as "constantly functioning on a shoestring budget" and mused that "nothing NSF is forever."

Scholars see "big data" as something they hope to tackle in the future rather than as a present research concern.

Interviewees also expressed an interest in data repositories hosted by their institutions or by journals. Journals have the advantage of being a common discovery point for relevant datasets, but as one interviewee pointed out, it is important that archived data be updated to reflect ongoing work, "which is obviously going to be advanced from the time when we lock down submission and publication of a certain manuscript."

On the whole, the multiplication of data repositories – along with increasing funder requirements for making data available – has left some researchers bewildered. As one put it, "Some universities have their repositories. Some funding agents won't accept those. And so that's not really a permanent archive. There's different names. Journals are claiming that they do that. There's some other systems who are different. But I think that's just a huge mess."

Although some civil and environmental engineering researchers are trying to collect large quantities of others' data for use in modeling, meta analyses, and synthesis papers, difficulties with sharing data have meant that the field as a whole has not fully embraced data-intensive research methodologies. "I would measure the success [of data repositories] by how many people are actually using the data to do something new," one interviewee said. "I don't know if I hear about that a lot .... I certainly don't hear about it as much as I hear about the new projects, the new tests, the new big things coming out." Many scholars in the field see "big data" and associated tools, such as artificial intelligence, as something they hope to tackle in the future rather than as a present research concern. It therefore appears that there is potential for enhanced data sharing practices to transform methodologies and research directions in civil and environmental engineering.

Communicating Research

Civil and environmental engineering scholars disseminate their research findings to three main groups: other academic researchers, industry partners, and the general public. Academic communications are, unsurprisingly, prioritized, with traditional peer-reviewed journal publications universally the medium of choice. Some researchers also supplement or promote their publications using academy-facing websites, blogs, and social media accounts. However, the applied nature of the field – and the reciprocal benefits of academia-industry partnerships, as discussed in the "Working with Others" section above – mean that many scholars are substantially engaged in communicating their research findings to engineering practitioners through specialist publications, courses, workshops, webinars, and professional conferences. By contrast, civil and environmental engineering scholars are relatively disinterested in communicating their research findings to the general public. "We kind of serve two masters," one interviewee explained. "Obviously [there are] all the things one would do academically, but we also need to provide value to the [industry] partners." Although public engagement is not unknown in the field, many civil and environmental engineering researchers prefer to concentrate their dissemination efforts on the "two masters" of academia and industry.

Engineering and technology scholars broadly speaking have been relatively slow to adopt preprint sharing and open access publishing relative to scholars in other scientific disciplines;[19] interviewees' comments confirm this is true of civil and environmental engineering specifically. Although it is possible to find enthusiastic open science proponents within the field, many scholars are ill-informed and hesitant to allocate precious time and grant money to make their research outputs publicly available – especially when they feel they are already successfully reaching key industry players. When asked why they do not publicize their research on social media, one interviewee responded, "I'm able to reach the communities of people that I need to reach without it."

[19] Vincent Larivière and Cassidy R. Sugimoto, "Do Authors Comply with Mandates for Open Access?" *Nature* 562, no. 7728 (25 Oct. 2018): 483-86, at 484; Eric Archambault et al., *Proportion of Open Access Papers Published in Peer-Reviewed Journals at the European and World Levels - 1996-2013* (European Commission, 2014).

Scholarly Communications

Like academics in other STEM subjects, civil and environmental engineering researchers primarily disseminate their research to other scholars through peer-reviewed journal articles.[20] They select which journal to publish in based on relevance, prestige, and, to a lesser extent, the perceived speed and quality of the journal's review process. Other academic publications – textbooks, conference proceedings – are viewed as less selective and therefore less desirable for tenure and promotion purposes. However, some subfields on the "civil" side of the field have journals, such as the Transportation Research Record, which selectively publish conference proceedings and which carry prestige in their respective research communities. Across subfields, conference presentations themselves, though important, are thought of as mechanisms for discovering and sharing new developments in the field, rather than as valuable research outputs. In general, tenured researchers feel more freedom to publish in ways that best reach target academic audience regardless of impact factor, whereas junior faculty members decide where to publish based on impact factor and the perceived opinions of senior colleagues. "I'm reaching the audience that will read it, and I'm also sending a signal to people that decide on my career," one interviewee explained.

Civil and environmental engineering journals – like journals in many STEM fields[21] – are increasingly enabling, or requiring, a variety of methods to make the datasets underlying research articles easily accessible to readers. Many interviewees said that they regularly publish articles with supplemental data files, and that this is an increasingly common practice. Others reported being required by journals to provide statements of whether the data they used is freely available and, if so, where, often linking directly to a data repository or publicly available government database. As discussed in the previous section on "sharing data," data included in or appended to articles is more than a mechanism for ensuring research integrity; it is one of the principal ways in which scholars obtain others' data for use in their own work. Nevertheless, most scholars still

[20] Cooper et al., "Agriculture Scholars," 20-21; Cooper et al., "Public Health Scholars," 24-26; Long and Schonfeld, "Chemists," 31-32.

[21] Victoria Stodden, Peixuan Guo, and Zhaukun Ma, "Toward Reproducible Computational Research: An Empirical Analysis of Data and Code Policy Adoption by Journals," *PLOS One* 8, no. 6 (2013), https://doi.org/10.1371/journal.pone.0067111; Philip Herold, "Data Sharing among Ecology, Evolution, and Natural Resources Scientists: An Analysis of Selected Publications," *Journal of Librarianship and Scholarly Communication* 3, no. 2 (2015), https://doi.org/10.7710/2162-3309.1244; Sarah C. Williams, "Practices, Policies, and Persistence: A Study of Supplementary Materials in Crop Science Journals," *Journal of Agricultural & Food Information* 17, no. 1 (2016): 11-22; Bobby Lee Houtkoop et al., "Data Sharing in Psychology: A Survey on Barriers and Preconditions," *Advances in Methods and Practices in Psychological Science* 1, no. 1 (2018): 70-85; Dan Sholler et al., "Enforcing Public Data Archiving Policies in Academic Publishing: A Study of Ecology Journals," arXiv:1810.13040 [cs.CY], Oct. 2018; Nicole A. Vasilevsky et al., "Reproducible and Reusable Research: Are Journal Data Sharing Policies Meeting the Mark?" *PeerJ* 5 (2018), https://doi.org/10.7717/peerj.3208.

view data as auxiliary to research articles, rather than a research output in its own right. Interviewees had little to say about "data journals," which publish datasets with contextual information rather than traditional articles. Referring to the analogous "map journals" in the coastal engineering subfield, one interviewee mused, "It's a lot of time for very little recognition, and in particular for junior faculty, right?"

Many of the challenges civil and environmental engineering researchers face when publishing for academic audiences are not unique to the field. The peer review system is viewed simultaneously as indispensable and as broken; a few interviewees reflected positively on recent experiments with open review systems. Many interviewees complained that their graduate students, who are largely responsible for drafting articles, lack adequate academic writing skills, especially since many students in the field are not native English speakers. Another challenge – one shared with other cross-departmental fields[22] – is that it can be difficult to match interdisciplinary research to the right journal: "Sometimes it seems like you don't fit anywhere."

The peer review system is viewed simultaneously as indispensable and as broken.

The use of social media to promote publications to the academic community is uneven. Twitter is the most widely used social media platform; researchers use it to float new ideas, highlight and discover relevant literature, and publicize their own work. Of those who use ResearchGate, most simply maintain a basic profile, while a few actively promote their publications. Facebook and LinkedIn are used as professional tools only rarely. In general, those who avoid social media usually cite time constraints and an ability to reach key audiences through other means. They may also believe that their work will still be discoverable online even if they don't actively promote it: "The good thing is, on Google, everything is there. And even if I don't post it on ResearchGate, someone else will." However, one interviewee noted that the field is "evolving" toward greater use of social media to promote publications: "The old model of just publishing papers and expecting them to get picked up is – it still works to some degree, but you can definitely do better if you can promote it a little bit more."

[22] Cooper et al., "Public Health Scholars," 25-26; Cooper et al., "Agriculture Scholars," 20-21; Cooper et al., "Asian Studies Scholars," 24.

Communicating with Industry

As discussed in the "Working with Others" section above, communicating research findings to practitioners plays an important role in building mutually beneficial industry-academia relationships. It enables research funders to see a return on investment and signals a willingness to address practical engineering challenges. Communicating with industry "is helping us to get more projects," one interviewee explained, because practitioners help determine which projects get funded. "They say, 'Oh, [he] has a proven track record. He's not a guy who will just publish [academic articles]; he wants to help.' So we have built that relationship now."

Communicating research findings to practitioners plays an important role in building mutually beneficial industry-academia relationships.

Publications aimed at practitioners include industry magazines, reports, and standards. Magazines are published by professional organizations and often combine what one interviewee called "researchy" articles – often syntheses of academic articles or research project findings – with more practical pieces and advertisements. They are not peer reviewed in the academic sense, but are instead reviewed by editors and professionals. Said one scholar, "They actually probably get more attention" than academic articles, "when it comes to emails that I'm receiving afterwards, immediately after publication." Reports are often published by government agencies or NGOs; they distill the results of one or more research projects and suggest applications. According to an interviewee, practitioners refer to one such report on water infrastructure management as a "bible. We get more impact from there than [a] journal paper." Finally, researchers may also write standards, which are publications issued by professional societies and NGOs establishing uniform engineering practices. These standards are rigorously reviewed by committees of practitioners, providing a forum for in-depth research communication. There is probably room to develop new, digital-friendly platforms for academic-industry communication: for instance, one interviewee is currently considering how to make reports easily readable on a smartphone, ensuring that "if someone's on a construction site and has a problem, they can pull out their phone and get an answer immediately."

Scholars also communicate their research findings to practitioners in person, through short courses and workshops, professional conferences, or virtually through webinars. Professional conferences provide opportunities for researchers to not only communicate their findings to practitioners, but to network and generate new ideas. Courses and webinars can be hosted by professional bodies such as the American Society of Civil Engineers, or by local government agencies. One interviewee said they are about to embark on a ten-state tour, "trying to improve basically the state of practice" by holding training workshops for engineers at state Departments of Transportation.

It should be noted that not all civil and environmental engineering researchers are enthusiastic about industry communications. Academic reward structures dissuade some from devoting work hours to forms of dissemination other than peer-reviewed articles unless absolutely necessary. "I don't really like them," one interviewee said of trade journal articles, because "they take a lot of time." This researcher does, however, publish in trade journals when required to do so under the terms of an industry-sponsored project. Another interviewee expressed concern that publicly available technical reports "steals your thunder if you're going to write a journal article" arising from the same project.

The prioritization of industry communications in the face of significant academic disincentives underscores the field's close relationship with adjacent industries.

Most researchers, however, try to strike a balance between publishing peer-reviewed articles and engaging practitioners. One interviewee explained, "To me a good project is one where we get a refereed journal article, a refereed conference publication, and something practical, a specification or ... something a practitioner can use." Although those who make an effort to communicate their research findings with industry reap the benefits of stronger collaborative partnerships, they must contend with institutional cultures and tenure committees which place a low value on this type of dissemination. "This doesn't give you much impact factor," one interviewee admitted. "Gets me in trouble with the head of department." The prioritization of industry communications in the face of significant academic disincentives underscores the field's close relationship with adjacent industries.

Public Engagement

By contrast, most civil and environmental engineering scholars are not highly engaged with disseminating research findings among the general public. Some interviewees said they maintain blogs or public-facing websites for their academic work or for particular projects they are working on, in one case with support from their institutional library. Others admitted that they once had blogs or other online presences which have since fallen out of use. Occasionally public resources may come about as a byproduct of other scholarly activities. One interviewee said they upload videos to YouTube in order to have them readily available there for teaching purposes. Another described, with some bewilderment, working on a proposal that must include plan for “rapidly disseminating” research findings: “And so I’ve been thinking about, you know, would I want to make a YouTube video? I think that’s probably the easiest thing to do, is to make a video ... and then putting it somewhere. But where would I put it, and who would make the video?”

This is not to say that all civil and environmental engineering researchers are disinterested in publicly disseminating their work. One interviewee voiced enthusiasm about “science communication,” reporting that they regularly post videos on YouTube that “translate the science to a broader audience”; they noted, however, that this level of social media engagement is “atypical” in the field. Another reported giving well-attended public lectures in the aftermaths of major earthquakes, and even speaking at local schools. Several interviewees said their work has been featured by regional or national news sources; others typically put out press releases and videos when their work is published in Nature or Science, or write general readership pieces for those journals. One interviewee who works in the transportation subfield described an aspiration of engaging the public in order to change social norms around automobile and pedestrian safety, starting with their own campus and extending outward. This scholar did not indicate that they were actively involved in starting such a campaign, but their comments demonstrate how some researchers might envision their work having a significant impact on the general public – even if their own capacity to enact this vision may be limited.

Open Access Publishing

Although most of the ways civil and environmental engineering scholars communicate their research are targeted to a particular audience – other scholars, industry, or the general public – the growing movement around open access academic publishing has the potential to blur these lines, making peer-reviewed journal articles available for anyone to read. However, many scholars are reluctant to wade into the rapidly-evolving open access landscape. Mused one interviewee about “this open access thing”: “I think that’s going to turn some things upside down that I'm not sure that I know what they are. But I think they're going to make some big waves that are going to complicate life, or may make life better for everybody.”

The most common form of open access publishing – by paying article processing charges (APCs) to “hybrid” journals – is usually selected by researchers only if their funder requires it and allows APCs to be written into the project's budget. (As one interviewee noted and as research has shown,[23] enforcement of funder open access requirements is inconsistent at best.) A few scholars reported having taken advantage of institutional funding for APCs, often administered through their institutional libraries.

Civil and environmental engineering researchers rarely publish in purely open access journals. This is due not to resistance to the concept of open access per se, but rather to the widespread perception in the field that there are few sufficiently reputable open access journals available in which to publish. While most interviewees echoed this sentiment, a few named exceptions, including Earth's Future, Nanomaterials, and Atmospheric Chemistry and Physics. Open access, multidisciplinary "mega journals" garnered mixed reviews from interviewees. A few reported having published in PLOS ONE, while another said of Scientific Reports, "You know, it was pretty good for a while, and then they grew out of control and just accepted everything .... Now people just, kind of, laugh at you if you have a paper in Scientific Reports. 'Oh, yeah, everything gets in there.'"

In comparison with these challenges, the principal barriers to the widespread adoption of preprint dissemination in civil and environmental engineering appear tractable. Many interviewees expressed amenability to uploading preprints to their institutional repositories, but did not know that the opportunity existed, did not know how, or had not found the time to do so. This is in spite of the fact that interviewees reported reading others' preprints when available. Confusion around copyright is another significant deterrent. "Maybe a lot of it comes from disinformation," one interviewee said, "but I'm just shying away from it." Another interviewee decided not to make a preprint available because their colleague predicted that other researchers would continue to cite the preprint version even after the article was published. Still another gave up after having several engineering articles rejected by the repository arXiv, which focuses on physics, mathematics, and computer science – apparently unaware of other suitable options. It should be noted that the experience of Canadian researchers in this area differs from that of their American counterparts; Canada's three major government funding agencies recently began requiring that resulting research be made openly available at least in preprint form within twelve months of publication.[24]

[23] Larivière and Sugimoto, "Do Authors Comply?"

[24] *Tri-Agency Open Access Policy on Publications*, last modified Dec. 21, 2016, http://www.science.gc.ca/eic/site/063.nsf/eng/h_F6765465.html?OpenDocument.

The decision whether or not to make academic research openly available – whether in hybrid or pure open access journals or as preprints – is frequently made amid misinformation and uncertainty. Several interviewees were unsure what types of online publication qualified as "open access" or "preprints," or were confused about the difference between the two terms. Many appeared unaware of debates around the extent to which open access publication increases citation count.[25] There is also confusion as to which open access journals are considered "predatory." A few interviewees alluded to "some lists of predatory journals out there,"[26] but voiced uncertainty about where to locate or what to do with this information; one was considering editing a special issue for a journal until a colleague told them the journal was "predatory." "Then I thought, 'Well, gosh, it would be really nice to know what's considered predatory right now,'" the scholar explained. "Like, most of us don't know. I mean, we only know about impact factors or how journals treat you."

Moreover, other ways of sharing publications seem sufficient to many. Most researchers in the field will readily send PDFs of their own articles to "anybody in the world" who emails them to ask, and some share articles through ResearchGate or compile PDFs or links to online journal issues on their own websites, copyright restrictions notwithstanding. (The presence of Academia.edu is minimal in this field.) Researchers whose dissemination efforts focus on academia and industry often feel that these solutions are adequate. Explained one interviewee, "The research community has access through their libraries. The practitioner community can either email me or pay for it. If there's somebody that wants to read it in the private sector, their bill out rates are probably $80, $100 an hour at least for overheard. So why should I subsidize [open access] so they don't have to pay $35?"

For a few researchers – particularly on the "environmental" side of the field – ethical considerations weigh into decisions about access. Those who work on infrastructure and sanitation projects in the Global South are conscious of the need to make their research accessible to practitioners overseas who cannot afford to pay for access. Explained one interviewee, "That I would go to [another country] and do a bunch of measurements and then someone [there] would have to pay 50 bucks to see a paper that was paid for by,

[25] For a brief summary of the literature which suggests that open access does increase citation rates see Erin C. McKiernan et al., "How Open Science Helps Researchers Succeed," *eLIFE* 5 (July 7, 2016), https://doi.org/10.7554/eLife.16800, 2-3. Note especially Teja Koler-Povh, Primož Južnič, and Goran Turk, "Impact of Open Access on the Citation of Scholarly Publications in the Field of Civil Engineering," *Scientometrics* 98, no. 2 (Feb. 2014): 1033-45. For the opposing view see especially Philip M. Davis, "Open Access, Readership, Citations: A Randomized Controlled Trial of Scientific Journal Publishing," *The FASEB Journal* 25, no. 7 (July 2011): 2129-34.

[26] This was likely a reference to "Beall's List of Predatory Journals and Publishers," https://beallslist.weebly.com/.

say, an international NGO or the government – it doesn't sit well with me." A similar logic underlies the ethical concerns of some scholars whose research touches hot-button, domestic public health issues. Referring to the lead contamination crisis in Flint, Michigan, one interviewee said, "There's increased pressure – not even just pressure, but desire for us to become more engaged in society, with the public. And so communicating findings and making them accessible and available to the public is going to become increasingly important." The equation becomes more complex for climate change researchers, who must sometimes weigh a desire to influence public discourse and government policy against the fear that their research may be targeted or co-opted for anti-scientific ends.

Close Reading: Open Access Risks

"We do not publish our data [in open access articles]. … The world is filled with – in the case of climate research – with people who are more than interested in taking those data and interpreting them in ways that are highly problematical. And I'm not at all sure that our response to this is the right one because, right, there's a trope that people are hiding their data. [But] the ferocity with which some colleagues have been confronted with reanalyses of their [data] … and then what most of the scientific community would regard as inappropriate conclusions … has made us fairly defensive of just saying, hey, yeah, data is good. … We have the mechanisms in place in academia, within the cloistered Ivory Tower, to have a recognition that, oh, that's good work, and this isn't. We have less of an ability as a broader society for people to say, 'Oh, that's good work, and that isn't,' rather than, 'That's the cabal of people who are maintaining their priestly oversight of the information, and here is the brave counter researcher who is reading that they're a bunch of bunk.'"

The interviewee is required by European funding agencies to publish open access articles, but avoids including complete datasets in these articles.

Two competing priorities are at work: gaining the public's trust through transparency, and controlling the public discussion around the science of climate change.

The interviewee believes that the scientific community is able to collectively adjudicate which interpretations are scientifically sound, but they fear an opposing narrative that "the cloistered Ivory Tower" is really a "cabal" being opposed by "the brave counter researcher."

They acknowledge the irony that the research community's self-policing and reticence contribute to this narrative: "I'm not at all sure that our response [i.e. to not share research openly] is the right one."

There is deep skepticism within the field that open access publishing is essential for communicating research outside the academy. Focusing on the engineering community specifically, one scholar mused hopefully that open access articles might put research insights into the hands of more practitioners: "I'm still young enough to think that we can change the way our community of researchers publishes … . Some of the stuff you write, you really do wish that people who are actually doing engineering had access to it." Most interviewees, however, did not discuss industry communication in the context of open access publishing. Already-established channels – trade publications and continuing professional education – are seen as preferable. Referring to the rapid dissemination timelines often touted as an advantage of open access publishing, one water researcher mused that "the preoccupation with timelines is a bit of a red herring. The world doesn't change as fast as people think it does. Adoption within engineering takes a long time. You come up with a good idea, you have to market it, you have to have infrastructure for it, you [have] to build it up … . If you've produced a good system for decades, are you going to just jump to the latest fad?"

Conclusions

This report examined the research practices of civil and environmental engineering scholars in working with others, working with information, sharing data, and communicating research. When these areas of practice - and current research support infrastructures - are evaluated as a whole, two key themes arise which inform our recommendations.

Industry as a Research Partner

Industry – by which this report means all the government agencies, NGOs, and private companies who carry out relevant engineering projects – is not just a recipient of academic civil and environmental engineering research. Rather, industry is a research partner. Far from simply providing project funding, industry organizations and individuals provide crucial data, contribute expertise, and shape future research directions.

This report describes how industry-academia partnerships are often mutually beneficial and self-perpetuating. Industry partners gain research-based solutions to technical problems and innovation needs, while scholars gain funding, access to data, and the opportunity to see their work effect real improvements in the built and natural environments. Although many of these industry-academia partnerships are thriving, our findings suggest that scholars face significant challenges in communicating their research to industry. Some civil and environmental engineering scholars are publishing in trade magazines, writing standards and reports, attending professional conferences, and delivering workshops, despite the fact that institutional tenure and performance evaluations place little value on these activities. Others – especially pre-tenure researchers – feel that only academic outputs are worth investing precious time. Our recommendations urge universities and others to systematically incentivize innovative and effective industry communications in order to strengthen essential academia-industry partnerships.

Open access is unlikely to be a panacea for research impact.

Another implication of the close relationship between civil and environmental engineering researchers and industry is that open access is unlikely to be a panacea for research impact. Although scholars in the field are concerned about shaping public narratives around infrastructure, the environment, and climate change, their primary "public" is engineers and engineering organizations.

Big Data Still on the Horizon

Ever-increasing access to data is revolutionizing academic research methodologies. Civil and environmental engineering scholars are already collecting, analyzing, and developing new uses for large quantities of data, including data produced by other researchers and industry partners. Yet the field still awaits a deep methodological reorientation toward data-intensive technologies. For instance, numerous interviewees indicated that they foresee future applications of artificial intelligence in their subfields. Describing this looming transformation, one interviewee said, "The tools then change, and the thinking changes. Quite dramatically. And that's a generational evolution, right?"

Our findings indicate that one major impediment to data-driven innovation may lie in the limitations of current systems and practices for sharing research data. Well-enforced funder, journal, and institutional requirements can help, but successful data sharing also requires trust between researchers, adequate contextual information, and useable file formats. The current landscape of overlapping generalist, subject-specific, institutional, and journal data repositories is overwhelming to many scholars, and data publications and other data sharing activities are little valued in tenure portfolios. Outside of data repositories, the diffuse nature of industry data, the lack of comprehensive discovery tools, and the privatization of important datasets present further challenges. When data sharing works, it is often because scholars are leveraging their professional networks to discover and obtain what they need, and we recommend that any interventions build off of the field's existing capacity in this area.

It remains unclear who is best positioned to enact systematic improvements in data sharing.

It remains unclear who is best positioned to enact systematic improvements, but our findings suggest important considerations for the main contenders. Research into open access requirements suggests that funders' policies can shape disciplinary cultures,[27] and arguably the most successful data repository in the field is the NSF-funded DesignSafe. Journals, on the other hand, have the advantage of already being one of the most important ways in which researchers discover relevant datasets - at least until search engines like Google Datasets improve to the point of widespread adoption. Universities, which have the potential advantage of being able to integrate institutional repositories with their own data management services, have not yet grappled with the possibility that they might incentivize data sharing by tying it to faculty members' performance evaluations.

Other Considerations

Industry partnerships and data sharing are not the only areas in which research support services for civil and environmental engineers can be improved. In fact, many of the challenges interviewees identified resonate with the experiences of scholars in other applied, interdisciplinary, and STEM fields. Our findings suggest potential interventions to help scholars collaborate more effectively and more often; to increase uptake of library services and information technologies; to improve lab group workflows and data management; and to train graduate students in essential research skills. The recommendations that follow point to the dynamic work necessary to support Civil and Environmental Engineering scholars' research in the years to come.

[27] Larivière and Sugimoto, "Do Authors Comply?"

Recommendations

Academic Libraries

Approach the issue of open access with greater nuance. Academic libraries currently invest considerable funds in supporting open access publishing, but this does not meet the needs of fields – like civil and environmental engineering – where open access is not a priority for most scholars.

Support industry-focused research impact. Many interviewees feel their work will have the greatest impact if communicated to relatively narrow target audiences within adjacent industries. Librarians should help scholars identify and use methods for measure the impact of research communicated to engineering practitioners.

Facilitate inter-departmental encounters. Civil and environmental engineering researchers work extensively with scholars in other fields, but sometimes feel isolated within their own institutions. Research seminars and dedicated interdisciplinary workspaces can encourage serendipitous knowledge exchanges.

Provide tools to smooth negotiations with collaborators. Civil and environmental engineering scholars collaborate extensively, but interviewees indicated that they face challenges in navigating issues around authorship and intellectual property with collaborators. Develop protocols and templates to help them address these sensitive issues effectively.

Train graduate students to navigate the scholarly communications landscape. Much of the burden of literature discovery and review falls on graduate students. They need thorough training, not just in utilizing the services which their university library offers, but in navigating the broader ecosystem of scholarly communication, from Google Scholar to preprint repositories to Twitter, in order to identify relevant research.

University and Departmental Administrators

Simplify collaboration. The research of civil and environmental engineering scholars is increasingly conducted in collaboration with other researchers. But working with others introduces frictions around information management, communication, and expectations. Increase collaborative productivity by providing subscriptions to file sharing platforms, preferably with integration capabilities with citation management tools.

Support data management best practices. Civil and environmental engineering scholars are aware of the gap between ideal and reality when it comes to their own data management regimes. It is not enough to simply offer software subscriptions and consultations.[28] Universities must incentivize good data management – for instance, by integrating tenure

[28] Kate Dohe, Babak Hamidzadeh, and Ben Wallberg, "Doing More, With More: Academic Libraries, Digital Services, and Revenue Generation," *Ithaka S+R*, forthcoming.

review processes with institutional data repositories. They must also invest in technologies, such as Montana State's intent-based network,[29] that allow campus IT professionals to customize data storage solutions to engineers' idiosyncratic needs. This is also an area in which training and habits have not kept pace with technological affordances. Within research groups, graduate students already shoulder much of the responsibility for data management day-to-day. Graduate programs should provide early training in version control, metadata creation, and data security.

Reward impactful research communication. Civil and environmental engineering scholars already engage with practitioners in spite of institutional pressure to publish exclusively in academic journals. Dissemination to industry is an essential part of mutually beneficial, research-shaping collaborations. Revise tenure and promotion criteria to recognize effective and innovative engagement outside the academy.

Fairly evaluate data papers. So-called "data papers" have not gained significant traction within civil and environmental engineering, at least in part because scholars doubt they will be worth taking time away from writing traditional articles. In concert with faculty members, develop tenure and promotion criteria that give researchers appropriate credit for making valuable datasets more widely available.

Improve training in academic writing for graduate students. Civil and environmental engineering researchers acknowledge that there is a formula to good academic writing – but they are often unwilling or unable to teach it to their graduate students, many of whom speak English as a second language. Graduate programs should incorporate teaching and assessment of academic writing skills, preferably early on. There may be potential for fruitful collaborations between liaison librarians and writing centers to provide engineering-specific writing instruction.

Technology Developers

Help scholars find gray literature. Many civil and environmental engineering scholars struggle to locate the data and gray literature they need, or even to know what information exists. Develop and improve search engines to retrieve data and gray literature from the webpages of industry, government, and NGO websites as well as from academic repositories. These efforts will require coordination with organizations that publish data in order to optimize formatting for discoverability.

Create lab-proof and field-proof notetaking hardware. Scholars are already using cloud technologies to facilitate collaboration within their research groups, but many still rely on handwritten laboratory and field notes because they are reluctant to expose computing equipment to hazardous conditions. Before this field can weigh the merits of different electronic laboratory notebook (ELN) software packages, technology developers must first create durable hardware for use with ELNs.

[29] See https://edscoop.com/montana-states-flexible-research-network-is-improving-security-and-reducing-costs/.

Professional Societies

Make academic collaborators discoverable. Civil and environmental engineering researchers often find themselves searching for potential academic collaborators with a specific expertise or geographic presence. However, they have not widely adopted online networking tools like ResearchGate for this purpose, likely because of insufficient coverage. A simple, up-to-date directory of civil and environmental engineering research interests across universities and departments – similar to state-wide research directories in New Jersey and Ohio[30] – would facilitate new collaborations.

Develop new channels and formats to reach professional audiences. Trade publications and workshops are already successfully used for translating engineering research for practitioners, but there is room for innovation. Develop better ways to get research insights into practitioners' hands, whether through searchable online digests, videos, or smartphone apps. Similar ventures in the medical field suggest ways forward.[31]

Provide leadership in public communication. In addition to reaching practitioners, scholars are increasingly interested in engaging the general public on issues such as climate change and infrastructure. But many are ill-equipped to translate their work into strategic, compelling messages or worried about dealing singlehandedly with hostile reactions. Societies are ideally placed lead public engagement initiatives at scale, such as by providing researchers with communications advice, hosting outreach events, and publicizing relevant research.

Research Funding Organizations

Fund good data management – and enforce it. Simply forcing scholars to write data management plans into grant requirements isn't sufficient. Civil and environmental engineering researchers need user-friendly, funder-approved data repositories, and they need funders to greenlight the dedication of grant dollars for data management. Given this provision, researchers' data management practices would also be improved through periodic check-ins and enforcement to ensure best practices not just before a project begins, but during research and after completion.

Support data gathering and dissemination projects. Some scholars are already working to make difficult-to-access data – whether because it is politically volatile or simply disparate – easily accessible to their peers and the public. Funders should seek to back projects that serve the civil and environmental engineering research community in this way.

Adjust grant requirements to reflect the importance of industry. Major funding organizations are increasingly stipulating that grant recipients must make their publications freely accessible, but it is often more important – and more socially impactful – for civil and environmental engineering scholars to disseminate their findings to practicing engineers.

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[30] Research with New Jersey, https://www.researchwithnj.com/; Ohio Innovation Exchange, https://www.ohioinnovationexchange.org/.

[31] See the Icahn School of Medicine's Levy Library's list: "Medical Apps & Mobile Resources: Drug and Clinical Information Apps," Icahn School of Medicine at Mount Sinai, https://libguides.mssm.edu/apps, accessed Dec. 4, 2018.

Requirements for grant recipients should acknowledge this. For instance, engineering scholars might be allowed to fulfill a funder's requirements by publishing in a trade magazine rather than publishing in an open access journal.

Appendix 1. Research Teams and Local Reports

Carnegie Mellon University

Xiaoju Chen, Jessica G. Benner, Sarah Young, and Matthew R. Marsteller, "Understanding the Research Practices and Services Needs of Civil and Environmental Engineering Researchers – A Grounded Theory Approach," https://figshare.com/articles/Understanding_the_research_practices_and_services_needs_of_civil_and_environmental_engineering_researchers_-_a_grounded_theory_approach/7253303.

Georgia Institute of Technology

Lisha Li and Fred Rascoe, "Investigating the Practices and Needs of Civil and Environmental Engineering Scholars at Georgia Tech," https://smartech.gatech.edu/handle/1853/60485.

Iowa State University

Erin Thomas and Kris Stacy-Bates, "Library & Administrative Support for Civil & Environmental Engineering Scholars," https://lib.dr.iastate.edu/libreports/15.

North Carolina State University

Bertha Chang, Alexander Carroll, and Colin Nickels, "A Study of Research Support Service Needs for Civil, Construction, and Environmental Engineering Researchers at North Carolina State University," https://repository.lib.ncsu.edu/handle/1840.20/35687.

University of Colorado Boulder

Rebecca Kuglitsch, Emily Dommermuth, and Abbey Lewis, "Research Practices of Civil and Environmental Engineering Scholars," https://scholar.colorado.edu/libr_facpapers/132/.

University of Delaware

Tom Melvin, Sabine Lanteri, and Erin Daix, "Ithaka S&R Study: Examining the Research Support Needs of Civil and Environmental Engineering Faculty," http://udspace.udel.edu/handle/19716/23896.

University of Illinois Urbana-Champaign

William H. Mischo, Mary C. Schlembach, Alexandra C. Krogman, Christie A. Wiley, and Carly A. Hafner, "ITHAKA S+R Civil and Environmental Engineering Research Support Services Study: University of Illinois at Urbana-Champaign Report," https://www.ideals.illinois.edu/handle/2142/102077.

University of Toronto

Angela Henshilwood, Michelle Spence, and Mindy Thuna, “Research Support Services for the Field of Civil and Environmental Engineering,” https://tspace.library.utoronto.ca/handle/1807/91074.

University of Waterloo

Siu Yu, Jennifer Haas, and Rachel Figueiredo, “Research Practices of Civil and Environmental Engineering Scholars at the University of Waterloo,” https://uwspace.uwaterloo.ca/handle/10012/13812.

University of Wisconsin – Madison

Dave Bloom, Erin Carrillo, and Todd Michelson-Ambelang, “Assessing the Research Practices of Civil & Environmental Engineering Researchers at the University of Wisconsin-Madison: An Ithaka S+R Local Report,” https://minds.wisconsin.edu/handle/1793/78823.

Virginia Polytechnic Institute and State University

Whitney Hayes, Virginia Pannabecker, Yi Shen, Erin M. Smith, and Larry Thompson, “Faculty Research Practices in Civil and Environmental Engineering: Insights from a Qualitative Study Designed to Inform Research Support Services,” http://hdl.handle.net/10919/86409.

Appendix 2. Semi-Structured Interview Guide

Research focus and methods

- Describe your current research focus and projects.
  - How is your research situated within the field of civil and/or environmental engineering?
- Does your work engage with any other fields or disciplines?
  - What research methods do you typically use to conduct your research?
- How do your methods relate to work done by others in civil and/or environmental engineering (and, if relevant, in the other fields with which you engage)?

Working with others

- Do you regularly work with, consult, or collaborate with any others as part of your research process?
  - If so, whom have you worked with and how?
  - Lab or on-campus research group
  - Other scholars or researchers [e.g. faculty at the university or other universities, student assistants, independent researchers]
  - Research support professionals [e.g. librarians, technologists]
  - Other individuals or communities beyond the academy
  - Others not captured here?
- Have you encountered any challenges in the process of working with others? [Focus on information-related challenges, e.g. finding information, data management, process of writing up results.]
- Are there any resources, services or other supports that would help you more effectively develop and maintain these relationships?

Working with Data

- Does your research typically produce data? If so,
  - What kinds of data does your research typically produce? [Prompt: Describe the processes in which the data is produced over the course of the research.]
  - How do you analyze the data [e.g. using a pre-existing software package, designing own software, create models]?
  - How do you manage and store data for your current use?
  - Do you use any other tools to record your research data [e.g. electronic lab notebooks]? If so, describe.
  - What are your plans for managing the data and associated information beyond your current use [e.g. protocols for sharing, destruction schedule, plans for depositing in a closed or open repository]?

- Have you encountered any challenges in the process of working with the data your research produces? If so, describe.
- Are there any resources, services or other supports that would help you more effectively work with the data your research produces?

- Does your research involve working with data produced by others? If so,
  - What kinds of data produced by others do you typically work with?
  - How do you find that data?
  - How do you incorporate the data into your final research outputs [e.g. included in the appendices, visually expressed as a table or figure]?
  - How do you manage and store this data for your current use?
  - What are your plans for managing the data beyond your current use?
  - Have you encountered any challenges working with this kind of information?
  - Are there any resources, services or other supports that would help you more effectively work with the data produced by others?

Working with Published Information

- What kinds of published information do you rely on to do your research [e.g. pre-prints, peer-reviewed articles, textbooks]?
  - How do you locate this information? [Prompt for where and how they search for information and whether they receive any help from others in the process.]
  - How do you manage and store this information for your ongoing use?
  - What are your plans for managing this information in the long term?
  - Have you experienced any challenges working with this kind of information?
  - Are there any resources, services, or other supports that would help you more effectively work with this kind of information?

Publishing Practices

- Where do you typically publish your scholarly research?
  - What are your key considerations in determining where to publish?
  - Have you ever made your scholarly publications available through open access [e.g. pre-print archive; institutional repository, open access journal or journal option]? If yes, describe which venues.
  - Describe your considerations when determining whether or not to do so.
- Do you disseminate your research beyond scholarly publications? [If so, probe for where they publish and why they publish in these venues.]
- Do you use social networking or other digital media platforms to communicate about your work [e.g. ResearchGate, Twitter, YouTube]?
  - If yes, describe which venues and your experiences using them.

    - If no, explain your level of familiarity and reasons for not choosing to engage with these kinds of platforms.

- How do your publishing practices relate to those typical in your discipline?
- Have you encountered any challenges in the process of publishing your work?
- Are there any resources, services or other supports that would help you in the process of publishing?

State of the Field and Wrapping Up

- How do you connect with your colleagues and/or keep up with trends in your field more broadly [e.g. conferences, social networking]?
- What future challenges and opportunities do you see for the broader field?
- Is there anything else about your experiences or needs as a scholar that you think it is important for me to know that was not covered in the previous questions?