List of Suggested Reviewers or Reviewers Not To Include (optional)

SUGGESTED REVIEWERS:

Saverio E. Spagnolie; spagnolie@math.wisc.edu; University of Wisconsin, Madison.
Michael S. Siegel; michael.s.siegel@njit.edu; New Jersey Institute of Technology.
Daniel H. Rothman; dhr@mit.edu; Massachusetts Institute of Technology.

REVIEWERS NOT TO INCLUDE:

N/A

The following information regarding collaborators and other affiliations (COA) must be separately provided for each individual identified as senior project personnel. The COA information must be provided through use of this COA template.

Please complete this template (e.g., Excel, Google Sheets, LibreOffice), save as .xlsx or .xls, and upload directly as a Fastlane Collaborators and Other Affiliations single copy doc. Do not upload .pdf.

Please note that some information requested in prior versions of the PAPPG is no longer requested. THIS IS PURPOSEFUL AND WE NO LONGER REQUIRE THIS INFORMATION TO BE REPORTED. Certain relationships will be reported in other sections (i.e., the names of postdoctoral scholar sponsors should not be reported, however if the individual collaborated on research with their postdoctoral scholar sponsor, then they would be reported as a collaborator). The information in the tables is not required to be sorted, alphabetically or otherwise.

There are five separate categories of information which correspond to the five tables in the COA template:

COA template Table 1:
List the individual's last name, first name, middle initial, and organizational affiliation in the last 12 months.

COA template Table 2:
List names as last name, first name, middle initial, for whom a personal, family, or business relationship would otherwise preclude their service as a reviewer.

COA template Table 3:
List names as last name, first name, middle initial, and provide organizational affiliations, if known, for the following:
- **The individual's Ph.D. advisors; and**
- **All of the individual's Ph.D. thesis advisees.**

COA template Table 4:
List names as last name, first name, middle initial, and provide organizational affiliations, if known, for the following:
- **Co-authors on any book, article, report, abstract or paper with collaboration in the last 48 months (publication date may be later); and**
- **Collaborators on projects, such as funded grants, graduate research or others in the last 48 months.**

COA template Table 5:
List editorial board, editor-in chief and co-editors with whom the individual interacts. An editor-in-chief must list the entire editorial board.
- **Editorial Board: List name(s) of editor-in-chief and journal in the past 24 months; and**
- **Other co-Editors of journal or collections with whom the individual has directly interacted in the last 24 months.**

The template has been developed to be fillable, however, the content and format requirements must not be altered by the user. This template must be saved in .xlsx or .xls format, and directly uploaded into FastLane as a Collaborators and Other Affiliations Single Copy Document. Using the .xlsx or .xls format will enable preservation of searchable text that otherwise would be lost. It is therefore imperative that this document be uploaded in .xlsx or .xls only. Uploading a document in any format other than .xlsx or .xls may delay the timely processing and review of the proposal.

This information is used to manage reviewer selection. See Exhibit II-2 for additional information on potential reviewer conflicts.

1 Note that graduate advisors are no longer required to be reported.
2 Editorial Board does not include Editorial Advisory Board, International Advisory Board, Scientific Editorial Board, or any other subcategory of Editorial Board. It is limited to those individuals who perform editing duties or manage the editing process (i.e., editor in chief).

List names as Last Name, First Name, Middle Initial. Additionally, provide email, organization, and department
Fixed column widths keep this sheet one page wide; if you cut and paste text, set font size at 10pt or smaller, and
To insert *n* blank rows, select *n* row numbers to move down, right click, and choose Insert from the menu.
You may fill-down (crtl-D) to mark a sequence of collaborators, or copy affiliations. Excel has arrows that enable sorting.
For "Last Active Date" and "Last Active" columns dates are optional, but will help NSF staff easily determine which information remains relevant for reviewer selection.
“Last Active Date” and “Last Active” columns may be left blank for ongoing or current affiliations.

Table 1: List the individual’s last name, first name, middle initial, and organizational affiliation in the last 12 months.

1	Your Name:	Your Organizational Affiliation(s), last 12 m	Last Active Date
	Moore, Matthew N J	Florida State University	

Table 2: List names as last name, first name, middle initial, for whom a personal, family, or business relationship would otherwise preclude their service as a reviewer.

R: Additional names for whom some relationship would otherwise preclude their service as a reviewer.

2	Name:	Type of Relationship	Optional (email, Department) *to disambiguate common names*	Last Active
	N/A			

Table 3: List names as last name, first name, middle initial, and provide organizational affiliations, if known, for the following.

G: The individual’s Ph.D. advisors; and
T: All of the individual’s Ph.D. thesis advisees.

3	Advisor/Advisee Name:	Organizational Affiliation	Optional (email, Department) *to disambiguate common names*

G:	McLaughlin, Richard M	University of North Carolina, Chapel Hill	Mathematics Department
G:	Camassa, Roberto	University of North Carolina, Chapel Hill	Mathematics Department
T:	Karina Khazmutdinova	Florida State University	Geophysical Fluid Dynamics Institute

Table 4: List names as last name, first name, middle initial, and provide organizational affiliations, if known, for the following:

A: Co-authors on any book, article, report, abstract or paper with collaboration in the last 48 months (publication date may be later); and

C: Collaborators on projects, such as funded grants, graduate research or others in the last 48 months.

to disambiguate common names

4	Name:	Organizational Affiliation	Optional (email, Department)	Last Active
A:	Bolles, C. Tyler	Florida State University		
A:	Byrne, Helen M.	Oxford University		
A:	Cogan, Nicholas G.	Florida State University		
A:	Gray, Leonard	Unaffiliated		
A:	Jain, Harsh V.	Florida State University		
A:	Jakowski, Jas	Oak Ridge High School		
A:	Majda, Andrew J.	New York University		
A:	Nof, Doron	Florida State University		
A:	Quaife, Bryan	Florida State University		
A:	Sorribes, Inmaculada C.	Florida State University		
A:	Speer, Kevin	Florida State University		
A:	Steinbock, Oliver	Florida State University		
A:	Tremaine, Darrel	Oberlin College		
A:	Qi, Di	New York University		
A:	Wang, Xiaoming	Southern University of Science and Technology		
A:	Ye, Ming	Florida State University		
A:	Ye, Wenjing	Hong Kong of Science and Technology		
C:	Mohammadigoushki, Hadi	Florida State University		

Table 5: List editorial board, editor-in chief and co-editors with whom the individual interacts. An editor-in-chief must list the entire editorial board.

B: Editorial Board: List name(s) of editor-in-chief and journal in the past 24 months; and

E: Other co-Editors of journal or collections with whom the individual has directly interacted in the last 24 months.

to disambiguate common names

5	Name:	Organizational Affiliation	Journal/Collection	Last Active
	N/A			

<u>Table 1:</u> List the individual's last name, first name, middle initial, and organizational affiliation in the last 12 months.

1	Your Name:	Your Organizational Affiliation(s), last 12 r	Last Active Date
	Quaife, Bryan, D	Florida State University	Currently employed

<u>Table 2:</u> List names as last name, first name, middle initial, for whom a personal, family, or business relationship would otherwise preclude their service as a reviewer.

R: Additional names for whom some relationship would otherwise preclude their service as a reviewer.

to disambiguate common names

2	Name:	Type of Relationship	Optional (email, Department)	Last Active
R:				

<u>Table 3:</u> List names as last name, first name, middle initial, and provide organizational affiliations, if known, for the following.

G: The individual's Ph.D. advisors; and

T: All of the individual's Ph.D. thesis advisees.

to disambiguate common names

3	Advisor/Advisee Name:	Organizational Affiliation	Optional (email, Department)
G:	Kropinski, Mary-Catherine	Simon Fraser University	mkropins@math.sfu.ca
T:	Bystricky, Lukas	KTH	lukasby@kth.se
T:	Gannon, Ashley	Florida State University	ag12s@my.fsu.edu
T:	Robinson, David	Florida State University	djr16@my.fsu.edu
T:	Bishnu, Siddhartha	Florida State University	siddhartha.bishnu@gmail.com

Table 4: List names as last name, first name, middle initial, and provide organizational affiliations, if known, for the following:

A: Co-authors on any book, article, report, abstract or paper with collaboration in the last 48 months (publication date may be later); and

C: Collaborators on projects, such as funded grants, graduate research or others in the last 48 months.

to disambiguate common names

4	Name:	Organizational Affiliation	Optional (email, Department)	Last Active
A:	Biros, George	University of Texas	biros@ices.utexas.edu	11/1/17
A:	Bystricky, Lukas	KTH	lb13f@my.fsu.edu	12/1/18
A:	Chiu, Shang-Huan	New Jersey Institute of Technology	shang.h.chiu@njit.edu	12/1/19
A:	Christlieb, Andrew	Michigan State University	andrewch@math.msu.edu	7/1/17
A:	Coulier, Pieter	Industry	pieter.coulier@gmail.com	5/1/17
A:	Currie, Miles	University of Washington	mcurr@uw.edu	12/1/18
A:	Darve, Eric	Stanford	darve@stanford.edu	5/1/17
A:	de Anna, Pietro	University of Lausanne	pietrodeanna@gmail.com	11/1/17
A:	Gannon, Ashley	Florida State University	ag12s@my.fsu.edu	12/1/19
A:	Goodrick, Scott	US Department of Agriculture	sgoodrick@fs.fed.us	12/1/18
A:	Hiers, Kevin	Tall Timbers Research Station	jkhiers@talltimebrs.org	12/1/19
A:	Jiang, Shidong	New Jersey Institute of Technology	jiang@njit.edu	9/1/13
A:	Juanes, Ruben	MIT	juanes@mit.edu	11/1/17
A:	Kabacaoglu, Gokberk	University of Texas	kabacaoglu.gokberk@gmail.com	11/1/17
A:	Kropinski, Mary-Catherine	Simon Fraser University	mkropins@math.sfu.ca	11/1/17
A:	Lindsay, Alan	Notre Dame	a.lindsay@nd.edu	11/1/17
A:	Mendoza-Cortes, Jose	Florida State University	mendoza@eng.fsu.edu	8/1/17
A:	Moore, Nick	Florida State University	mnmoore2@fsu.edu	12/1/19
A:	Mueller, Kevin	Florida State University	km17h@my.fsu.edu	9/1/18

A:	Nigam, Nilima	Simon Fraser University	nigam@math.sfu.ca	4/1/16
A:	O'Brien, Joe	US Department of Agriculture	joseph.j.obrien@usda.gov	12/1/18
A:	Ong, Bejamin	Michigan Techological University	ongbw@mtu.edu	4/1/17
C:	Seal, David	United States Naval Academy	seal@usna.edu	7/1/17
A:	Shanbhag, Sachin	Florida State University	sshanbhag@fsu.edu	12/1/19
A:	Speer, Kevin	Florida State University	kspeer@fsu.edu	12/1/19
A:	Veerapaneni, Shravan	University of Michigan	shravan@umich.edu	10/1/19
A:	Young, Yuan-Nan	New Jersey Institute of Technology	yyoung@njit.edu	12/1/19

Table 5: List editorial board, editor-in chief and co-editors with whom the individual interacts. An editor-in-chief must list the entire editorial board.

B: Editorial Board: List name(s) of editor-in-chief and journal in the past 24 months; and

E: Other co-Editors of journal or collections with whom the individual has directly interacted in the last 24 months.

to disambiguate common names

5	Name:	Organizational Affiliation	Journal/Collection	Last Active
B:				

COVER SHEET FOR PROPOSAL TO THE NATIONAL SCIENCE FOUNDATION

PROGRAM ANNOUNCEMENT/SOLICITATION NO./DUE DATE PD 16-1271 12/02/19	☐ Special Exception to Deadline Date Policy	FOR NSF USE ONLY NSF PROPOSAL NUMBER **2012560**
FOR CONSIDERATION BY NSF ORGANIZATION UNIT(S) (Indicate the most specific unit known, i.e. program, division, etc.) DMS - COMPUTATIONAL MATHEMATICS		

DATE RECEIVED	NUMBER OF COPIES	DIVISION ASSIGNED	FUND CODE	DUNS# (Data Universal Numbering System)	FILE LOCATION
12/02/2019	2	03040000 DMS	1271	790877419	12/09/2019 4:14pm S

EMPLOYER IDENTIFICATION NUMBER (EIN) OR TAXPAYER IDENTIFICATION NUMBER (TIN) 591961248	SHOW PREVIOUS AWARD NO. IF THIS IS ☐ A RENEWAL ☐ AN ACCOMPLISHMENT-BASED RENEWAL	IS THIS PROPOSAL BEING SUBMITTED TO ANOTHER FEDERAL AGENCY? YES ☐ NO ☒ IF YES, LIST ACRONYM(S)

NAME OF ORGANIZATION TO WHICH AWARD SHOULD BE MADE Florida State University	ADDRESS OF AWARDEE ORGANIZATION, INCLUDING 9 DIGIT ZIP CODE Florida State University 874 Traditions Way, 3rd Floor TALLAHASSEE, FL 32306-4166
AWARDEE ORGANIZATION CODE (IF KNOWN) 0014894000	
NAME OF PRIMARY PLACE OF PERF Florida State University	ADDRESS OF PRIMARY PLACE OF PERF, INCLUDING 9 DIGIT ZIP CODE Florida State University 1017 Academic Way Tallahassee ,FL ,323062180 ,US.

IS AWARDEE ORGANIZATION (Check All That Apply) ☐ SMALL BUSINESS ☐ FOR-PROFIT ORGANIZATION ☐ MINORITY BUSINESS ☐ WOMAN-OWNED BUSINESS ☐ IF THIS IS A PRELIMINARY PROPOSAL THEN CHECK HERE

TITLE OF PROPOSED PROJECT **Erosion, Transport, and Dispersion in Granular and Porous Media**

REQUESTED AMOUNT	PROPOSED DURATION (1-60 MONTHS)	REQUESTED STARTING DATE	SHOW RELATED PRELIMINARY PROPOSAL NO. IF APPLICABLE
$ 439,824	36 months	07/01/20	

THIS PROPOSAL INCLUDES ANY OF THE ITEMS LISTED BELOW

☐ BEGINNING INVESTIGATOR
☐ DISCLOSURE OF LOBBYING ACTIVITIES
☐ PROPRIETARY & PRIVILEGED INFORMATION
☐ HISTORIC PLACES
☐ VERTEBRATE ANIMALS IACUC App. Date ______
PHS Animal Welfare Assurance Number ______
☒ TYPE OF PROPOSAL Research

☐ HUMAN SUBJECTS Human Subjects Assurance Number ______
Exemption Subsection ______ or IRB App. Date ______
☐ FUNDING OF INT'L BRANCH CAMPUS OF U.S IHE ☐ FUNDING OF FOREIGN ORG
☒ INTERNATIONAL ACTIVITIES: COUNTRY/COUNTRIES INVOLVED
XX
☒ COLLABORATIVE STATUS
Not a collaborative proposal

PI/PD DEPARTMENT Department of Mathematics and GFDI	PI/PD POSTAL ADDRESS 208 Love Building 1017 Academic Way TALLAHASSEE,FL 323064510 United States
PI/PD FAX NUMBER 850-644-8972	

NAMES (TYPED)	High Degree	Yr of Degree	Telephone Number	Email Address
PI/PD NAME Matthew N Moore	PhD	2010	850-645-0974	mnmoore2@fsu.edu
CO-PI/PD Bryan D Quaife	DPhil	2011	850-644-5260	bquaife@fsu.edu
CO-PI/PD				
CO-PI/PD				
CO-PI/PD				

CERTIFICATION PAGE

Certification for Authorized Organizational Representative (or Equivalent) or Individual Applicant

By electronically signing and submitting this proposal, the Authorized Organizational Representative (AOR) or Individual Applicant is: (1) certifying that statements made herein are true and complete to the best of his/her knowledge; and (2) agreeing to accept the obligation to comply with NSF award terms and conditions if an award is made as a result of this application. Further, the applicant is hereby providing certifications regarding conflict of interest (when applicable), drug-free workplace, debarment and suspension, lobbying activities (see below), nondiscrimination, flood hazard insurance (when applicable), responsible conduct of research, organizational support, Federal tax obligations, unpaid Federal tax liability, and criminal convictions as set forth in the NSF Proposal & Award Policies & Procedures Guide (PAPPG). Willful provision of false information in this application and its supporting documents or in reports required under an ensuing award is a criminal offense (U.S. Code, Title 18, Section 1001).

Certification Regarding Conflict of Interest

The AOR is required to complete certifications stating that the organization has implemented and is enforcing a written policy on conflicts of interest (COI), consistent with the provisions of PAPPG Chapter IX.A.; that, to the best of his/her knowledge, all financial disclosures required by the conflict of interest policy were made; and that conflicts of interest, if any, were, or prior to the organization's expenditure of any funds under the award, will be, satisfactorily managed, reduced or eliminated in accordance with the organization's conflict of interest policy. Conflicts that cannot be satisfactorily managed, reduced or eliminated and research that proceeds without the imposition of conditions or restrictions when a conflict of interest exists, must be disclosed to NSF via use of the Notifications and Requests Module in FastLane.

Drug Free Work Place Certification

By electronically signing the Certification Pages, the Authorized Organizational Representative (or equivalent), is providing the Drug Free Work Place Certification contained in Exhibit II-3 of the Proposal & Award Policies & Procedures Guide.

Debarment and Suspension Certification

(If answer "yes", please provide explanation.)

Is the organization or its principals presently debarred, suspended, proposed for debarment, declared ineligible, or voluntarily excluded from covered transactions by any Federal department or agency? Yes ☐ No ☒

By electronically signing the Certification Pages, the Authorized Organizational Representative (or equivalent) or Individual Applicant is providing the Debarment and Suspension Certification contained in Exhibit II-4 of the Proposal & Award Policies & Procedures Guide.

Certification Regarding Lobbying

This certification is required for an award of a Federal contract, grant, or cooperative agreement exceeding $100,000 and for an award of a Federal loan or a commitment providing for the United States to insure or guarantee a loan exceeding $150,000.

Certification for Contracts, Grants, Loans and Cooperative Agreements

The undersigned certifies, to the best of his or her knowledge and belief, that:

(1) No Federal appropriated funds have been paid or will be paid, by or on behalf of the undersigned, to any person for influencing or attempting to influence an officer or employee of any agency, a Member of Congress, an officer or employee of Congress, or an employee of a Member of Congress in connection with the awarding of any Federal contract, the making of any Federal grant, the making of any Federal loan, the entering into of any cooperative agreement, and the extension, continuation, renewal, amendment, or modification of any Federal contract, grant, loan, or cooperative agreement.

(2) If any funds other than Federal appropriated funds have been paid or will be paid to any person for influencing or attempting to influence an officer or employee of any agency, a Member of Congress, an officer or employee of Congress, or an employee of a Member of Congress in connection with this Federal contract, grant, loan, or cooperative agreement, the undersigned shall complete and submit Standard Form-LLL, ''Disclosure of Lobbying Activities,'' in accordance with its instructions.

(3) The undersigned shall require that the language of this certification be included in the award documents for all subawards at all tiers including subcontracts, subgrants, and contracts under grants, loans, and cooperative agreements and that all subrecipients shall certify and disclose accordingly.

This certification is a material representation of fact upon which reliance was placed when this transaction was made or entered into. Submission of this certification is a prerequisite for making or entering into this transaction imposed by section 1352, Title 31, U.S. Code. Any person who fails to file the required certification shall be subject to a civil penalty of not less than $10,000 and not more than $100,000 for each such failure.

Certification Regarding Nondiscrimination

By electronically signing the Certification Pages, the Authorized Organizational Representative (or equivalent) is providing the Certification Regarding Nondiscrimination contained in Exhibit II-6 of the Proposal & Award Policies & Procedures Guide.

Certification Regarding Flood Hazard Insurance

Two sections of the National Flood Insurance Act of 1968 (42 USC §4012a and §4106) bar Federal agencies from giving financial assistance for acquisition or construction purposes in any area identified by the Federal Emergency Management Agency (FEMA) as having special flood hazards unless the:

(1) community in which that area is located participates in the national flood insurance program; and
(2) building (and any related equipment) is covered by adequate flood insurance.

By electronically signing the Certification Pages, the Authorized Organizational Representative (or equivalent) or Individual Applicant located in FEMA-designated special flood hazard areas is certifying that adequate flood insurance has been or will be obtained in the following situations:

(1) for NSF grants for the construction of a building or facility, regardless of the dollar amount of the grant; and
(2) for other NSF grants when more than $25,000 has been budgeted in the proposal for repair, alteration or improvement (construction) of a building or facility.

Certification Regarding Responsible Conduct of Research (RCR)
(This certification is not applicable to proposals for conferences, symposia, and workshops.)

By electronically signing the Certification Pages, the Authorized Organizational Representative is certifying that, in accordance with the NSF Proposal & Award Policies & Procedures Guide, Chapter IX.B. , the institution has a plan in place to provide appropriate training and oversight in the responsible and ethical conduct of research to undergraduates, graduate students and postdoctoral researchers who will be supported by NSF to conduct research. The AOR shall require that the language of this certification be included in any award documents for all subawards at all tiers.

CERTIFICATION PAGE - CONTINUED

Certification Regarding Organizational Support

By electronically signing the Certification Pages, the Authorized Organizational Representative (or equivalent) is certifying that there is organizational support for the proposal as required by Section 526 of the America COMPETES Reauthorization Act of 2010. This support extends to the portion of the proposal developed to satisfy the Broader Impacts Review Criterion as well as the Intellectual Merit Review Criterion, and any additional review criteria specified in the solicitation. Organizational support will be made available, as described in the proposal, in order to address the broader impacts and intellectual merit activities to be undertaken.

Certification Regarding Federal Tax Obligations

When the proposal exceeds $5,000,000, the Authorized Organizational Representative (or equivalent) is required to complete the following certification regarding Federal tax obligations. By electronically signing the Certification pages, the Authorized Organizational Representative is certifying that, to the best of their knowledge and belief, the proposing organization:
(1) has filed all Federal tax returns required during the three years preceding this certification;
(2) has not been convicted of a criminal offense under the Internal Revenue Code of 1986; and
(3) has not, more than 90 days prior to this certification, been notified of any unpaid Federal tax assessment for which the liability remains unsatisfied, unless the assessment is the subject of an installment agreement or offer in compromise that has been approved by the Internal Revenue Service and is not in default, or the assessment is the subject of a non-frivolous administrative or judicial proceeding.

Certification Regarding Unpaid Federal Tax Liability

When the proposing organization is a corporation, the Authorized Organizational Representative (or equivalent) is required to complete the following certification regarding Federal Tax Liability:

By electronically signing the Certification Pages, the Authorized Organizational Representative (or equivalent) is certifying that the corporation has no unpaid Federal tax liability that has been assessed, for which all judicial and administrative remedies have been exhausted or lapsed, and that is not being paid in a timely manner pursuant to an agreement with the authority responsible for collecting the tax liability.

Certification Regarding Criminal Convictions

When the proposing organization is a corporation, the Authorized Organizational Representative (or equivalent) is required to complete the following certification regarding Criminal Convictions:

By electronically signing the Certification Pages, the Authorized Organizational Representative (or equivalent) is certifying that the corporation has not been convicted of a felony criminal violation under any Federal law within the 24 months preceding the date on which the certification is signed.

Certification Dual Use Research of Concern

By electronically signing the certification pages, the Authorized Organizational Representative is certifying that the organization will be or is in compliance with all aspects of the United States Government Policy for Institutional Oversight of Life Sciences Dual Use Research of Concern.

AUTHORIZED ORGANIZATIONAL REPRESENTATIVE	SIGNATURE	DATE
NAME Dale Meeks	Electronic Signature	Dec 2 2019 3:08PM

TELEPHONE NUMBER	EMAIL ADDRESS	FAX NUMBER
850-644-8662	dmeeks2@fsu.edu	

PROJECT SUMMARY

Overview:

The objective of this proposal is to analyze a set of complex, dynamical problems that arise in geophysical porous-media applications by using a host of newly developed computational tools. The problems of interest include: (1) The erosion of microscopic constituents of porous media leading to anisotropic macroscopic properties; (2) The modified transport of tracers through the medium, including anomalous dispersion; (3) The occurrence of catastrophic events, such as sink hole collapse, resulting from interaction between groundwater seepage, erosion, and buoyancy forces. These problems will be analyzed using a synergetic combination of cutting-edge computational techniques and reduced mathematical models, with a complementary set of laboratory experiments for comparison.

Intellectual Merit:

The proposed research introduces a host of new computational challenges and opportunities. First the range of scales is vast: spatial scales range from microscopic granular constituents to large geological aquifers; timescales range from that of a sudden sinkhole collapse to years required for certain mechanical and chemical erosion processes. The systems are inherently multicomponent, with coupling between the fluid and solid phases. Although the governing PDEs are linear, the presence of moving boundaries introduces nonlinear feedback between geometry and flow. To tackle these challenges, the PIs will combine cutting-edge computational tools with reduced-order modeling. Mixed-scale, deep neural networks will be used to learn from the data generated by high-fidelity numerical simulations and to parameterize coarse-grained models based on the multiphase framework. Additionally, controlled laboratory experiments will be used to guide and verify theory developed herein.

Broader Impacts:

The proposed research could lead to a range of societal benefits, including better management of water resources, accurate prediction of contaminant transport, and an understanding of the long-term effects of human activities, such as hydraulic fracturing or groundwater pumping, on porous media and water resources. In such scenarios, the slow timescales of mechanical and chemical erosion are coupled to the faster timescales of human-induced changes and gravitational collapse. Currently, the relationship between these scales is poorly understood. The proposed high-fidelity and efficient computational methods will enable a deeper understanding of these processes, which is the first step towards developing effective strategies for managing water resources and mitigating catastrophic events such as contamination or structural collapse. For example, the insights gained here will potentially help identify locations in natural aquifers vulnerable to contamination, collapse,, or both.

In addition to these societal impacts, the proposed work will spur the training of mathematicians and computational scientists in fundamentally cross-disciplinary research of great societal importance. Further, the PIs will engage in educational and outreach activities to impact future generations of mathematical scientists, with particular focus on women and underrepresented minorities. Both PIs are already actively involved in graduate and undergraduate research, as well as outreach to K-12 students. Further, we have successfully recruited women and under- represented minorities in high school, undergraduate, graduate, and postdoctoral research.

TABLE OF CONTENTS

For font size and page formatting specifications, see PAPPG section II.B.2.

*Proposers may select any numbering mechanism for the proposal. The entire proposal however, must be paginated. Complete both columns only if the proposal is numbered consecutively.

Project Description:
Erosion, Transport, and Dispersion in Granular and Porous Media

M.J.N. Moore and Bryan D. Quaife

1 Introduction and Background

Naturally occurring porous and granular materials, such as soil, sand, and clay, play a pivotal role in regulating earth's water resources by filtering contaminants and, over long timescales, supplying fresh water. Not only is this process essential for human water resources, but also for the ecology of rivers, estuaries, and other natural habitats. Natural water resources, however, have been placed under enormous pressure by human population growth and associated activities that can compromise the natural filtration cycle, for example expansion of industry, urbanization, pollution, and climate change. See the UN report on water resources for further detail on these looming threats [64].

An understanding of these filtration and contamination processes relies on the complex phenomenon of transport and dispersion in porous media [22, 62, 75, 87]. Further, the action of continually flowing groundwater can alter medium properties through erosive, transportive, and other processes. Thus, it becomes necessary to understand transport through complex media whose properties change *dynamically* in response to the intervening fluid flow. These effects are most noticeable during rapid events, like the gravitational collapse of a sinkhole [74], during which medium properties can change dramatically over short timescales. Though less obvious, the accumulation of slower processes, such as mechanical or chemical erosion, can also substantially alter medium properties [25, 78].

This proposal aims to develop a suite of computational tools geared towards developing a deeper understanding of the physical processes by which groundwater flow alters porous-media properties and to characterize the associated changes in dispersive transport within the evolving medium. A recognized complexity of naturally occurring media is the heterogeneity and anisotropy of macroscopic properties such as permeability and mechanical strength [51, 61, 62]. These properties can change over short timescales, for example sinkhole collapse or hydraulic fracturing, or over long timescales, for example the slow erosion or dissolution of solid material. Potential exists for feedback between these timescales: for example the slow wearing process reaching a critical threshold beyond which catastrophic events become more likely. Physical mechanisms that can alter porous-medium properties include:

- Erosion of solid material due to fluid-mechanical stresses or chemical dissolution.
- Transport of fragments and grains due to intervening fluid flow and sedimentation.
- Compaction of the medium due to overlying loads.
- Gravitational collapse of a medium due to loads exceeding a threshold.

The above are roughly ordered according to timescale, from the slowest acting to the fastest. While many of these mechanisms have been studied individually in various contexts and to varying levels of rigor, very little is known about their combined effect on the dynamic evolution of a porous medium. Since we aim to build a quantitative model from the ground up, we will first focus on the slowest acting mechanisms, as these ultimately set the stage for the more rapid events like sinkhole collapse.

In particular, we view the slow, accumulated effects of erosion and dissolution as instrumental in altering porous-medium properties. First, by deteriorating solid material, erosion alters the size distribution of porous-medium constituents, enabling smaller fragments to be sieved through networks of larger ones. A second and more subtle way that erosion can alter medium properties is by changing the *shape* distribution of individual fragments or particles. For instance, erosion can

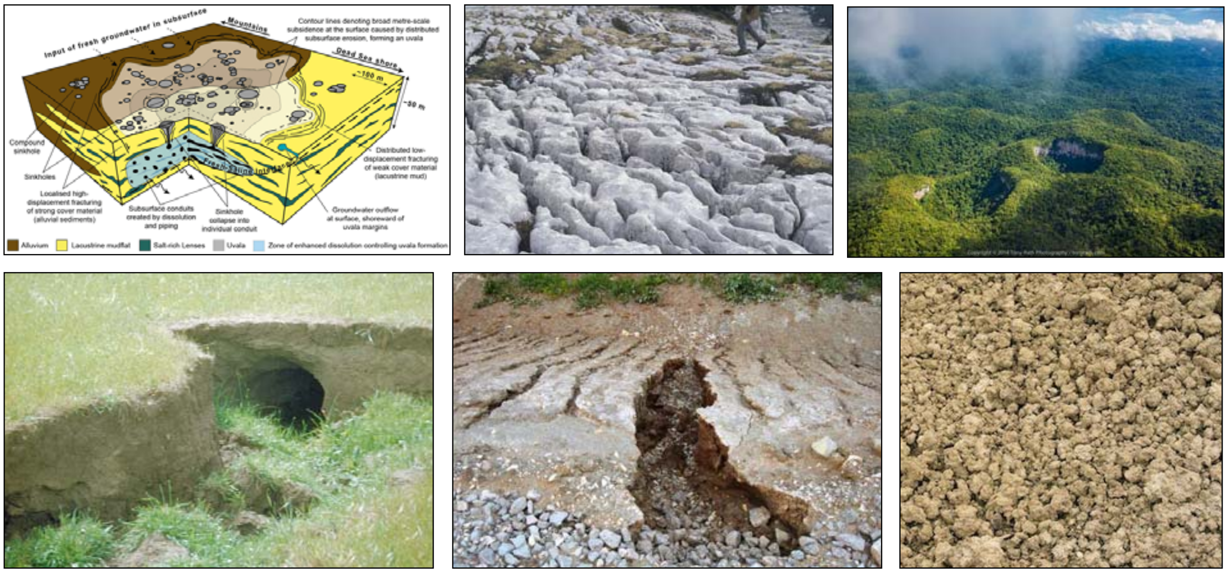


Figure 1: *Geophysical examples of chemical and mechanical erosion. Top from left: Diagram of a coupled karst-soil system with conduit formation [83]; Limestone pavement in Dent de Crolles, France; Nohoch Che'en Sinkhole in Belize. Bottom: Examples of soil erosion. The bottom right shows the microscopic soil texture, exhibiting polydispersity and anisotropy.*

carve particles into slender shapes aligned primarily in the direction of the dominant flow, thereby creating *anisotropic* characteristics. Likewise, chemical dissolution can carve well-defined conduit paths in karst networks which strongly alter transport properties [78]. Some visible effects of flow-induced erosion are shown in Fig. 1. The top row shows products of primarily *chemically-driven* erosion, i.e. dissolution, while the bottom shows effects of primarily *mechanically-driven* erosion. Some examples in the figure include the rough surface of limestone pavement, a sinkhole relic in Belize, and an erosion-curved conduit. The final image shows the small-scale structure of soil which exhibits polydispersity and anisotropy resulting from a combination of erosive, compaction, and transport actions.

More generally, the coupling between shape and flow during erosion, dissolution, and related phase-change processes is a vibrant research area in the mathematical sciences community [18,49,54, 58,59,65,70,71,73,84]. Erosion-induced shape change has been studied in the high Reynolds number regime, both experimentally [60, 70] and theoretically [32, 59, 60] and in single [49, 59, 60, 70] and multiple-body arrangements [32]. Studies on related processes of dissolution [16, 18, 37, 38, 44, 84], melting [5, 19, 26, 33, 35, 59, 73, 80], solidification [3, 19, 39, 57], and deposition [34] exhibit intriguing similarities and differences [59]. These studies reveal a rich set of possible dynamics, from the emergence of universal morphologies that erase details of the initial state and evolve self-similarly in time [33, 59, 60], to fine-scale pattern formation [16, 18, 38], to unstable morphologies that can retain or even amplify features present in the initial state [16, 84].

Only recently have these ideas been extended to the low-Reynolds-number regime that is applicable to porous media [58, 65]. While the governing fluid-flow equations become linear in this regime, porous-media applications present a host of new challenges, for example:

- Porous media typically involves dense packings so that close-range effects and even nearly contacting bodies must be considered.

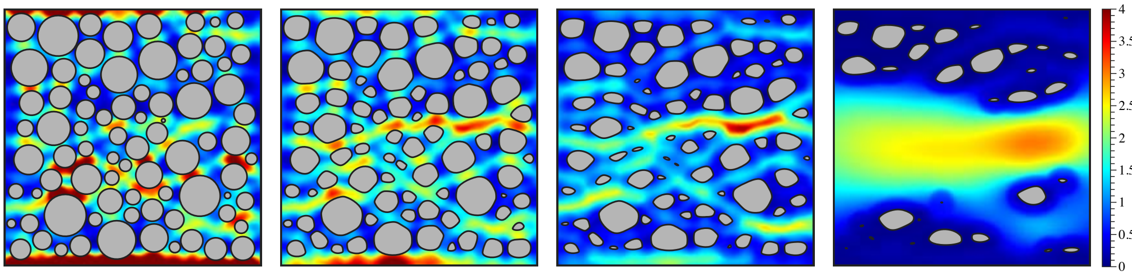


Figure 2: *High-fidelity numerical simulations of a configuration of densely-packed solid bodies undergoing mechanical erosion due to an intervening Stokes flow. The color indicates velocity magnitude which highlights the channel formation process. The solid bodies develop flat faces and sharp corners during evolution.*

- The Stokes limit introduces *longer* range effects than the inertial limit does, thus coupling the shape evolution of *all* fragments, grains, and conduits to a higher degree.
- Somewhat counterintuitively, erosion does not always act to smooth shapes but rather can create sharp features and corners [70]. These features can be difficult to resolve and, further, can trigger numerical instabilities [65]. Dissolution, meanwhile, can initiate a roughening transition [16], leading to similar numerical difficulties.
- Additionally effects, such as sedimentation, transport, and compaction constantly work to reconfigure the medium as its constituents and boundaries degrade.

These challenges require innovative computational techniques, some of which have been developed recently [65] and others that await resolution.

An ultimate goal of this proposal is to simulate $\mathcal{O}(10^2 - 10^3)$ mobile bodies undergoing simultaneous erosion, transport, sedimentation, and compaction, with high-order accuracy and the computational efficiency required to run large ensembles for statistical analysis. This topic of the dynamic erosion of a porous medium is one that has been receiving significant recent interest. Laboratory experiments on erosion of colloidal systems are currently being explored in the Datta Lab at Princeton [10]. These experiments are closely related to our proposed computational study, thus offering a great opportunity for comparison.

A major step towards the goal of developing high-fidelity simulations of dynamic porous-medium erosion is illustrated in Fig. 2. This figure shows simulated erosion of 80 bodies with an initial high volume fraction of 50%. The color indicates the velocity magnitude, which highlights the spontaneous formation of channels during the erosion process. These channels arise from small variations in the initial condition. Once formed, the larger channels transmit more flow which reinforces their growth. The process of channel formation can dramatically alter medium properties and create high levels of anisotropy, which directly impacts dispersion of transported quantities such as contaminants.

While erosion and dissolution lead to gradual changes in a medium, other events like sinkhole collapse or hydraulic fracturing represent rapid changes. Most likely, all of the mechanisms listed above—erosion, dissolution, transport, compaction, and gravitational collapse—contribute to sinkhole formation, with the slowest acting mechanisms creating conditions favorable for the final act of gravity. Sinkhole formation has been explored in preliminary experiments conducted at the Geophysical Fluid Dynamics Institute at Florida State University [79]. These scaled-down experiments offer the ability to probe various mechanisms behind sinkhole formation, for example a difference in hydraulic head between the confined and unconfined aquifers. An ultimate goal of the proposed project is to merge these two lines of inquiry to gain a deeper understanding of the influence of mechanically or chemically induced erosion on gravitational collapse. Ultimately, we envision the high-fidelity erosion simulations to inform coarse-grained models for: (i) transport and dispersion; and (ii) dynamic evolution of macroscopic medium properties. These parameterized models could then be combined with well-developed multi-phase models [12,17,24,76] to quantitatively describe and predict sinkhole collapse. Furthermore, we propose performing a set of experiments conducted at GFDI that would help to guide, calibrate, and validate the computations; See Section 2.5 and the letter of collaboration for further details.

1.1 Theoretical Foundation and Governing Equations

We first outline the theoretical foundation that will be used in later sections of the proposal. At the finest scale, the fluid flow intervening between individual constituents of a porous medium is governed by the incompressible Stokes equations

$$\mu \Delta \mathbf{u} = \nabla p, \quad \nabla \cdot \mathbf{u} = 0, \quad \mathbf{x} \in \Omega, \tag{1}$$

where $\mathbf{u}$ is the velocity field, p is the pressure field, μ is the fluid viscosity, and Ω is the fluid domain. Linear homogeneous elliptic PDEs, such as the Stokes equations, can be reformulated as a boundary integral equation (BIE). BIEs have several numerical advantages including a dimension reduction, automatic mass conservation, and high-order accuracy. An equivalent BIE formulation of the Stokes equations (1) is

$$\mathbf{f}(\mathbf{x}) = -\frac{1}{2}\boldsymbol{\eta}(\mathbf{x}) + \frac{1}{\pi}\int_{\partial\Omega} \frac{\mathbf{r}\cdot\mathbf{n}}{\rho^2}\frac{\mathbf{r}\otimes\mathbf{r}}{\rho^2}\boldsymbol{\eta}(\mathbf{y})ds_{\mathbf{y}}, \quad \mathbf{x} \in \partial\Omega, \tag{2}$$

where $\mathbf{f}$ is the Dirichlet boundary condition, $\mathbf{r} = \mathbf{x} - \mathbf{y}$, $\rho = \|\mathbf{r}\|$, and $\mathbf{n}$ is the outward unit normal of $\partial\Omega$. Once (2) is solved for the density function $\boldsymbol{\eta}$, quantities such as the velocity, pressure, vorticity, and deformation tensor can be computed in the fluid bulk. For example, the velocity at $\mathbf{x} \in \Omega$ is

$$\mathbf{u}(\mathbf{x}) = \frac{1}{\pi}\int_{\partial\Omega} \frac{\mathbf{r}\cdot\mathbf{n}}{\rho^2}\frac{\mathbf{r}\otimes\mathbf{r}}{\rho^2}\boldsymbol{\eta}(\mathbf{y})ds_{\mathbf{y}}. \tag{3}$$

Equation (1), and its equivalent BIE formulation, are microscopic descriptions required to model the shape evolution of individual fragments and grains due to fine-scale erosive effects, either mechanical or chemical. This microscopic description, however, becomes impractical when attempting to model seepage in very large porous systems where the microscopic geometry can be exceedingly complex. Instead, one must homogenize over microscopic details to arrive at an approximate description. Leading-order homogenization produces the well-known Darcy system

$$\mathbf{q} = -\mathbf{K}\nabla\phi \tag{4}$$

where $\mathbf{q}$ is the *specific discharge* or *Darcy velocity*, and $\phi = z + p/(\rho g)$ is the hydraulic head, with ρ and g representing the fluid density and gravitational constant respectively. Above, $\mathbf{K}$ is the *conductivity*, which is related to the *permeability* $\mathbf{k}$ through $\mathbf{K} = \mathbf{k}\rho g/\mu$. Both the conductivity and permeability are in general tensors, and they reduce to scalars in the case of an isotropic medium. Note that the Darcy velocity is related to the tracer velocity through $\mathbf{q} = \theta_f \mathbf{u}$, where θ_f is the porosity (i.e. fluid volume fraction). In the case of an isotropic medium, the Kozeny-Carman equation is often used to relate permeability to volume fraction [9]

$$k = C\frac{\theta_f^3}{(1-\theta_f)^2}. \tag{5}$$

The macroscopic description offered by Eq. (4), although approximate, simplifies analysis tremendously in that individual grains are no longer resolved and thus the domain geometry is generally much simpler.

Whilst the most immediate proposed work on computational methods to simulate erosion will utilize (1), the later stages of this project will incorporate (4), or closely related variants known as multiphase models [12,17,24,76], in order to develop coarse-grained descriptions for porous medium evolution and the associated dispersion within. These models will rely on statistical analysis of the data produced by the high-fidelity erosion simulations in order to parameterize the effects of erosion, leading to deterministic or stochastic reduced-order models for porous-medium evolution.

1.2 Project Overview

Broader Impacts: The proposed research could lead to a range of societal benefits, including better management of water resources, accurate prediction of contaminant transport, and an understanding of the long-term effects of human activities, such as hydraulic fracturing or groundwater pumping, on porous media and water resources. In such scenarios, the slow timescales of mechanical and chemical erosion are coupled to the faster timescales of human-induced changes and gravitational collapse. Currently, the relationship between these scales is poorly understood. The proposed high-fidelity and efficient computational methods will enable a deeper understanding of these processes, which is the first step towards developing effective strategies for managing water resources and mitigating catastrophic events such as contamination or structural collapse. For example, the insights gained here will potentially help identify locations in natural aquifers vulnerable to contamination, collapse, or both.

In addition to these societal impacts, the proposed work will spur the training of mathematicians and computational scientists in fundamentally cross-disciplinary research of great societal importance. Further, the PIs will engage in educational and outreach activities to impact future generations of mathematical scientists, with particular focus on women and underrepresented minorities. Both PIs are already actively involved in graduate and undergraduate research, as well as outreach to K-12 students. Further, we have successfully recruited women and underrepresented minorities in high school, undergraduate, graduate, and postdoctoral research.

Intellectual Merit: The proposed research introduces a host of new computational challenges and opportunities. First the range of scales is vast: spatial scales range from microscopic granular constituents to large geological aquifers; timescales range from that of a sudden sinkhole collapse to years required for certain mechanical and chemical erosion processes. The systems are inherently multicomponent, with coupling between the fluid and solid phases. Although the governing PDEs are linear, the presence of moving boundaries introduces nonlinear feedback between geometry and flow. To tackle these challenges, the PIs will combine cutting-edge computational tools with reduced-order modeling. Mixed-scale, deep neural networks will be used to learn from the data generated by high-fidelity numerical simulations and to parameterize coarse-grained models based on the multiphase framework. Additionally, controlled laboratory experiments will be used to guide and verify theory developed herein.

Relevance to the Computational Mathematics Synopsis:

- Efficient, high-fidelity computational methods form the core of the proposed research on porous-media erosion and dispersive transport. Large ensembles of the high-fidelity simulations will inform the coarse-grained models to be developed in the later stages of the proposed work.

- The coarse-grained models will harness recent advances in deep neural networks [48,52,53,63] to parameterize the effects of mechanical and chemical erosion within a multiphase [12, 17, 24, 76], or similar macroscopic, framework.
- The proposed research is interdisciplinary by nature, with immediate applications in the fields of geophysics and environmental sciences. The PIs have experience collaborating with scientists from other disciplines [11,20,24,43] through FSU's Geophysical Fluid Dynamics Institute, an interdisciplinary unit comprised of a diverse set of faculty from home departments in example Earth, Atmospheric, and Ocean Sciences, Geology, Physics, Civil Engineering, Environmental Engineering, Mechanical Engineering, Scientific Computing, Mathematics, and others.
- The proposed research is a collaborative effort with a focus on training future generations of scientists and mathematicians. The proposal will include graduate, undergraduate, and K–12 students, with close interaction and cooperation between them.

Results from Prior NSF Support: Neither PI has previous funding from NSF.

PIs' Qualifications: PI Moore joined the Department of Mathematics at Florida State University (FSU) in 2014. He is also a Research Associate in FSU's Geophysical Fluid Dynamics Institute (GFDI). His expertise includes modeling dynamic interactions between fluids and structures, especially in geophysical and biologically motivated settings. PI Quaife joined the Department of Scientific Computing at FSU in 2015 and is also a Research Associate in GFDI. His expertise includes high-fidelity and efficient numerical methods for fluid dynamics in complex geometries.

The PIs co-authored a paper in the *Journal of Computational Physics* describing numerical methods for simulating erosion in the Stokes flow regime [65], the regime relevant for the currently proposed groundwater applications. Very recently the PIs, along with postdoctoral scholar Shang-Huan Chiu, submitted a second paper on newly developed methods for precise characterization of transport and dispersion within the special class of densely packed porous-media configurations formed by erosion [15].

2 Proposed Research

The goal of the proposed research is to develop computational methods to better understand erosion processes. Specific research tasks will include:

(1) Simulating mechanical and chemical erosion, as well as transport, including sedimentation and compaction, of eroding bodies.
(2) Characterizing anisotropy, permeability, and pore size dynamics to inform homogenized models such as Darcy's relation (4).
(3) Simulating the transport of finite Peclet number concentrations in eroded porous medium.
(4) Improving numerical methods including fast summation methods, preconditioners, and quadrature.
(5) Developing and validating new parameterizations using machine learning techniques, numerical simulations, and in-house experiments.

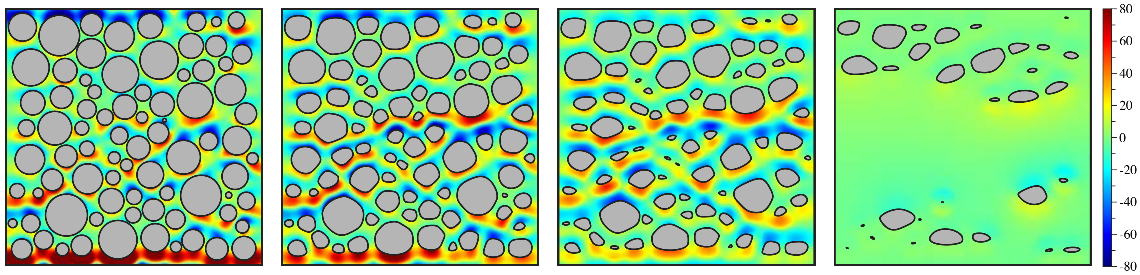


Figure 3: *Simulation of 80 bodies mechanically eroding in Stokes flow. Flow is left to right. Color represents vorticity, which provides a convenient way to visualize local shear rates.*

2.1 Mechanical and Chemical Erosion of a Porous Medium

The development of accurate and efficient numerical methods to solve the Stokes equations enables high-fidelity simulations of erosion processes. We will consider erosion induced by either fluid-mechanical forces and by chemical reaction, i.e. dissolution. In the former case, which we have already begun to investigate [65], erosion result from the shear stress $\tau = -\left(\nabla \mathbf{u} + \nabla \mathbf{u}^T\right) \mathbf{n} \cdot \mathbf{s}$, where $\mathbf{n}$ and $\mathbf{s}$ are the unit normal and tangent vectors on the surface respectively and $\mathbf{u}$ is the velocity field as computed from the incompressible Stokes equations (1). The motion of the interface is proportional to the absolute value of shear

$$V_{\mathbf{n}} = C_E \, |\tau| \, . \tag{6}$$

In the case of chemically-induced erosion, a solute concentration field c undergoes advection and diffusion:

$$\frac{\partial c}{\partial t} + \mathbf{u} \cdot \nabla c = D \nabla^2 c. \tag{7}$$

Material removal is then governed by Fick's law with interface velocity

$$V_{\mathbf{n}} = D \frac{\partial c}{\partial \mathbf{n}}. \tag{8}$$

Both erosion processes have been investigated by the PIs and collaborators in the context of single bodies in high Reynolds-number flows [37, 59, 60, 70]. In the context of a porous media at low Reynolds-number flows, numerical methods have been developed by the PIs to simulate shear-induced erosion [15, 65]. These simulations combine highly accurate BIE methods with stable interface evolution techniques. The BIE solver is accelerated by the Fast Multipole Method (FMM) [30, 31] to achieve optimal $\mathcal{O}(N)$ complexity. Meanwhile, the so-called θ–L method is used for interface evolution to prevent distortion and tangling of the interface meshes [36, 60, 65].

Figs. 2 and 3 show preliminary results of 80 bodies, initially of random position and size, undergoing mechanical erosion in Stokes flow. This simulation extends previously reported 50-body simulations to 80 bodies [65] due to a recently developed Barycentric quadrature scheme [6, 7, 15], which enables more densely packed configurations. The color in Fig. 3 represents the vorticity field surrounding the bodies. Vorticity, since it reduces to shear on solid interfaces, provides a convenient way to visualize local erosion rates, as well as the local flow intensity. Observe that erosion not only reduces the size of solid bodies, but also alters their shapes substantially. The bodies tend to become somewhat polygonal—corners develop connected by relatively flat faces.

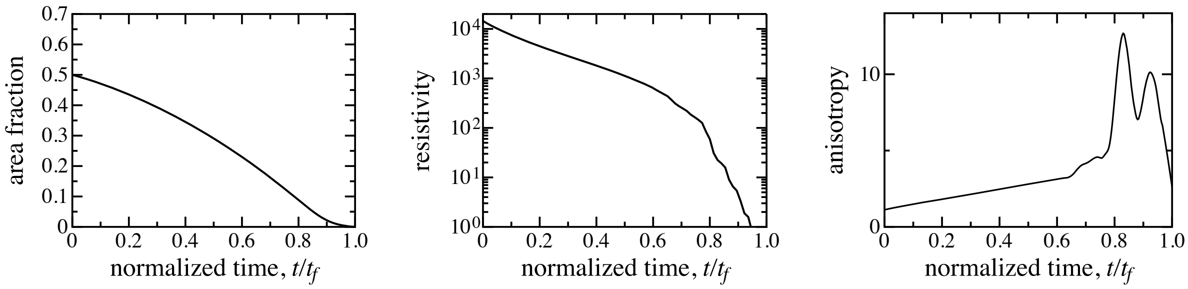


Figure 4: *Left: The area fraction of solid bodies versus time. Time is normalized by the vanishing time t_f. Middle: The resistivity of the porous matrix decrease much more rapidly than the area fraction, indicating the reshaping process to be essential. Right: The anisotropy (ratio of vertical to horizontal resistivity) as it varies in time. Erosion can create a highly anisotropic medium.*

The number of faces does not appear to be easily predicted, but rather depends on the interaction with neighboring bodies as mediated by the Stokes flow. As erosion proceeds, relatively straight channels tend to develop between the bodies. Certain channels that are initially larger transmit more flow, promoting local erosion rates and further widening these select channels. In this way, erosion creates a runaway process in which small differences in initial channel size become amplified. This channelization process is most evident by viewing the velocity magnitude in Fig. 2.

The creation and reinforcement of channels significantly impacts the macroscopic properties of the porous medium. Fig. 4 shows how certain medium properties change in time. First, the left-most plot shows the rate at which the area fraction decreases as the bodies disintegrate. Notice that the rate of area reduction does not change significantly during the simulation. The middle plot shows the resistivity, or inverse permeability of the medium. In the simulations, resistivity is calculated by measuring the total flux and the pressure upstream and downstream, then using Darcy's relation (4) to infer the horizontal permeability k_x. Naturally, as bodies erode, the resistivity they provide decreases. Note that, unlike the area plot, the vertical axis is logarithmic, so the straight line observed at early times indicates that the resistivity decreases exponentially. The much more modest decrease of area fraction is not sufficient to account for this exponential rate. Hence the reshaping process, in particular the formation of channels, plays a pivotal role in the medium's macroscopic resistivity to flow. Lastly, the right-most plot of Fig. 4 shows new, preliminary results on how medium anisotropy evolves during the reshaping process of erosion. Anisotropy is calculated as the ratio of vertical to horizontal resistivity, with the vertical resistivity computed by rotating the configuration of bodies by 90 degrees. This plot shows that the anisotropy initially increase with time. Thus, the initial isotropy is erased as bodies streamline and form primarily horizontal channels. Remarkably, the medium reaches an anisotropy of over 10, meaning that erosion can lead to a configuration that resists flow 10 times more in the vertical direction than the horizontal direction.

An immediate goal of the proposed work is to extend the range of physical effects captured in these simulations. A particular challenge of a BIE formulation is developing quadrature for nearly-singular integrands that arise when bodies are close. To address this problem, we have very recently extended a Barycentric quadrature method [6, 7] and have successfully simulated erosion with grains that are initially separated by 1% of an arclength spacing [15]. The quadrature method is a non-intrusive modification of the trapezoid rule and results in an error bound that is independent of the grain configuration. However, the current implementation does not yet fully exploit FMM acceleration. The computational challenge is to develop FMM expansions for the velocity, vorticity, pressure, and deformation-tensor layer potentials. Since these layer potentials each have distinct kernels, we will utilize kernel-independent FMMs [27, 86], and their HPC implementations [1]. Other challenges to be investigated include preconditioning strategies to reduce the number of required GMRES iterations, and time adaptivity to enable stable simulations to user-specified tolerances. PI Quaife is an expert in developing such algorithms [66, 67, 68, 69].

Next, we will extend the simulation framework to handle chemical dissolution of solid bodies via physical laws (7)–(8)**.** For this goal, much of the computational infrastructure, such as a BIE solver for the Stokes equations and the θ–L method for interface evolution, is already in place. The BIE Stokes solver, however, has not yet been coupled to the advection-diffusion equations (7) and interface law (8) required for dissolution. We propose to solve the advection-diffusion equation (7) by first using Strang splitting [77] to decompose the equation into two PDEs—one involving only linear advection, and the other only diffusion. The advection equation will be solved with a semi-Lagrangian method [72] so that it can be solved on an Eulerian grid without a restrictive CFL condition. PI Quaife has experience using semi-Lagrangian methods in the closely related context of complex viscous flow [41]. The diffusion equation is more challenging to accurately solve in the complex porous geometries. Two approaches include a memory-intensive space-time heat kernel [8,40,50], and Rothe's method coupled with a Yukawa equation solver [14,46]. A particular challenge of the latter method is extending functions from the complex geometry into a regular geometry, such as a square, so that a high-order volume integral or Fourier method can be applied [28, 29]. Alternatively, we propose to use the Laplace Transform, $C(\mathbf{x}, s) = \mathcal{L}[c](\mathbf{x}, t)$, which satisfies

$$sC(\mathbf{x}, s) - D\Delta C(\mathbf{x}, s) = c_0(\mathbf{x}), \quad \mathbf{x} \in \Omega,\ s \in \mathbb{C}, \tag{9}$$

where $c_0(\mathbf{x})$ is the initial concentration. Equation (9) will be solved with high-order accuracy and efficiently by using FMM-accelerated integral equation methods for the Yukawa equation [47]. The concentration field will then be recovered with an inverse Laplace transform [2].

By combining our BIE Stokes solver with the proposed high-order, advection-diffusion solver, simulations of simultaneous erosion and dissolution, while also including transport and sedimentation (see Section 2.3), will finally be possible. Such a framework could accurately simulate the geophysically relevant scenario of karst conduits with embedded granular media. The gradual changes in the medium and karst boundaries due to erosion and dissolution could create conditions favorable for mechanical failure or collapse of the structure, for example sinkholes.

2.2 Dispersive transport through eroded media

The transport of quantities through eroded media is a direct consequence of the pore structure. To gain understanding of transport and dispersion through the complex geometries formed by erosion, we will simulate and statistically analyze concentrations that are diffusing and being advected by the intervening flow. In an eroded geometry Ω, the dimensionless concentration c is governed by

$$\frac{\partial c}{\partial t} + \mathbf{u} \cdot \nabla c = \frac{1}{\mathrm{Pe}} \Delta c, \tag{10}$$

where Pe is the dimensionless Peclet number. In this context, the concentration c is a passive tracer and not responsible for dissolution as in the previous section.

In the infinite Peclet number limit, the concentration is governed by pure advection and the characteristics of the concentration field satisfy $\dot{\mathbf{s}}(t) = \mathbf{u}(\mathbf{s}(t))$ and are identical to the streamlines (Fig. 5). Once N_p trajectories are computed with a high-order Runge-Kutta method, transport can be quantified. Two of the most important measurements to quantify transport are the tortuosity and the anomalous dispersion, both which are defined in terms of the length of the trajectories. The tortuosity is the average length a trajectory travels across a channel relative to the length of the channel. Mathematically, it is the dimensionless number

$$T = \frac{1}{d}\left(\int_S u_1(x_0, y_0)\lambda(y_0) dy_0\right) \Bigg/ \left(\int_S u_1(x_0, y_0)\, dy_0\right), \qquad (11)$$

which is approximated using the N_p trajectories. Here, S is the vertical cross-section at $x = x_0$, d is its length, u_1 is the horizontal velocity, and $\lambda(y_0)$ is the length of the trajectory starting at (x_0, y_0) and ending at a vertical cross-section at the other end of the channel. Relationships between the tortuosity and porosity of a geometry have been developed by other groups [23,45,56], and preliminary results indicate that such models might be appropriate for geometries whose porosity increases under the action of erosion (Fig. 6(a)). Some preliminary results, however, indicate that erosion can also transiently increase the tortuosity, as seen towards the end of the erosion process in Fig. 6(a). We have observed an even more significant increase in the tortuosity at small porosities and early times, as in Fig. 6(b). These counterintuitive results are indicative of the complex interaction between material loss and shape change that occurs during erosion, so that macroscopic quantities like tortuosity do not always behave in a strict monotone fashion.

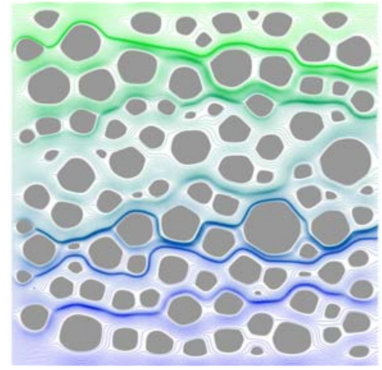
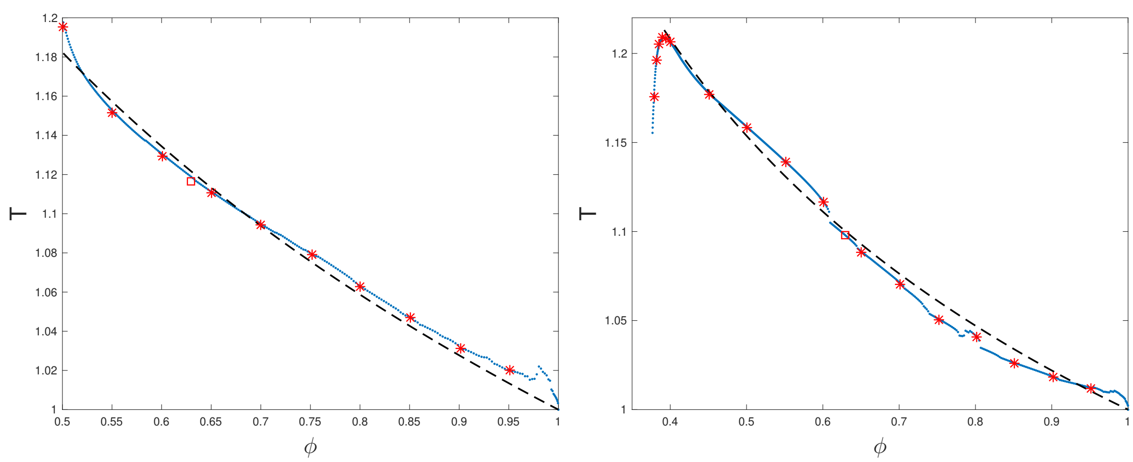


Figure 5: *Streamlines visualized with 200 tracers passing through an eroded geometry. The tracers are initialized at the left end of the channel and the flow is from left to right.*



(a) *100 eroding bodies* (b) *20 eroding bodies*

Figure 6: *The tortuosity of two different eroding geometries. The tortuosity can be computed using two different formulas (red vs. blue marks). In the left plot, the red square is the tortuosity of the geometry in Fig. 5. In both cases, there is qualitative agreement between our numerical simulations and a power-law model (black dashed line) [56].*

While the tortuosity characterizes the amount of winding of trajectories, the dispersion characterizes their spreading. Dispersion can be described using the first- and second-ensemble moments of the trajectories

$$\langle\lambda\rangle(t) = \frac{1}{N_p}\sum_{j=1}^{N_p}\lambda_j(t), \quad \sigma_\lambda^2(t) = \frac{1}{N_p}\sum_{j=1}^{N_p}(\lambda_j(t) - \langle\lambda\rangle(t))^2. \tag{12}$$

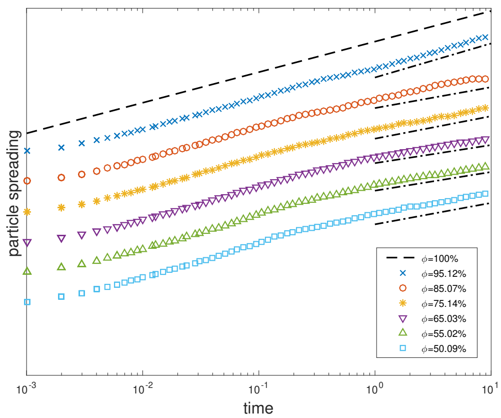
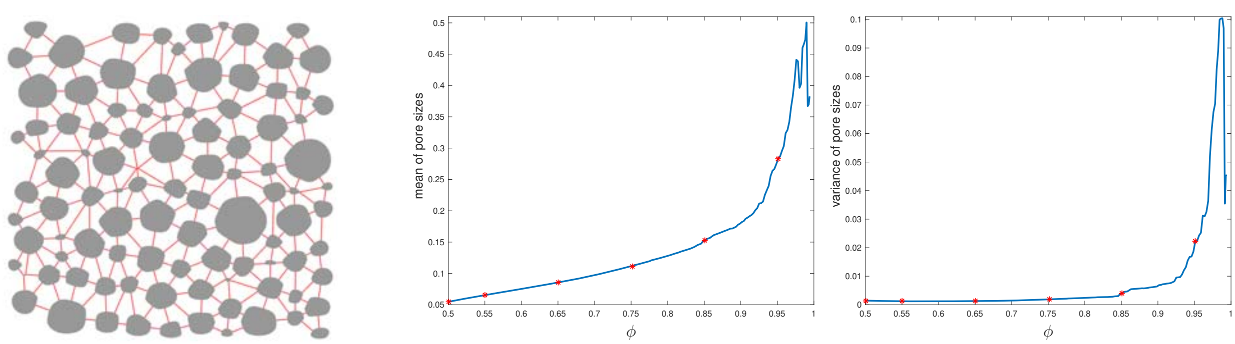


Figure 7: *The particle spreading, characterized with the standard deviation $\sigma_\lambda(t)$ at six different porosities. At early times, the line of slope 1 (black dashed curve) indicates a ballistic motion. At later times, the dispersion becomes super-dispersive at a rate indicated by the slope of the black dashed-dotted lines.*

Then, the standard deviation σ_λ characterizes the dispersion, and long-time behavior typically results in a power-law scaling $\sigma_\lambda \sim t^\alpha$, where α quantifies the long-time spreading. At early times, transport is ballistic with $\alpha = 1$, as the trajectories have not explored much of the porous geometry. Once the trajectories have traversed a few grains, however, spreading typically becomes super-dispersive with $\alpha \in (0.5, 1)$ [4]. In Fig. 7, we investigate spreading at several different porosities of a porous geometry that is initialized with 100 grains.

The rate of dispersion is directly related to the pore size distribution [21]. As such, **we propose to investigate how erosion affects pore size distributions**. In preliminary work [15], we define pore sizes between grains that share an edge of a Delanuay triangulation with vertices at the grain centers (Fig. 8(a)). We then compute and plot the mean and variance of the pore sizes as a function of porosity in Figs. 8(b) and 8(c). Continuing in this direction, we will use the notion of a *porelet*, an individual Hagen-Poiseuille flow in each of the individual pores [21], to continue to investigate the effect of erosion on pores sizes. By computing the strength of the individual Hagen-Poiseuille flows, the shear rate, and thus the local rate of erosion, can be estimated.



(a) (b) (c)

Figure 8: *(a) Two grains are neighbors if they share an edge of a Delanuay triangulation. Then, pore sizes are defined to be the distance between neighboring grains. Erosion affects the (b) mean and (c) variance of the pore sizes. The geometry initially contains 100 eroding bodies.*

We have performed a carefully chosen simulation to better understand the effect of erosion on the pore size distribution. We start with a single grain inside the channel that is sufficiently large that the spacing between the initial grain and the channel walls, which is 2 units wide, is 10^{-3}. Using a Barycentric quadrature rule, we stably simulate erosion with only 512 points on the eroding body which corresponds to an arclength spacing 12 times larger than the initial separation distance; to achieve a comparable accuracy with the spectral trapezoid rule, 60 times as many discretization points would be required. In Fig. 9, different shades of grey correspond to the configuration of the eroding grain at five equally spaced time steps. At three of the time steps, we plot the velocity between the grain and the solid wall (black line). At all three configurations, the flow is nearly parabolic, supporting the validity of the porelet model [21]. After performing a thorough analysis of the pore size growth in this simple configuration, we will develop a more complete model for pore networks that are characteristic of porous media.

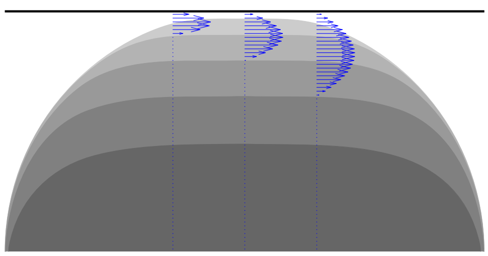


Figure 9: *An eroding body at five equally spaced time steps. At three of the time steps, the Stokesian velocity field in the bulk, which is nearly parabolic, is included.*

Finally, **we propose to extend our preliminary results by considering concentrations with finite Peclet numbers**. We will deploy the same numerical methods to simulate chemical erosion to study a concentration that is being transported through a eroded porous geometry. Again, this will encompass Strang splitting [77], a semi-Lagrangian advection solver [72], and a diffusion solver that solves an s-dependent Yukawa equation, where s is the Laplace transform variable (9).

2.3 Mobile Grain Simulations and Sinkhole Formation

Upon developing and improving numerical methods to simulate mechanical and chemical erosion, **we will develop methods to simulate seepage transport, gravitational sedimentation, and buoyancy forces acting on the porous media constituents.** In addition to the new techniques for quadrature, preconditioning, adaptivity, and fast summation described in earlier sections, this extension also requires the inclusion of contact forces between bodies to eliminate unphysical overlap that is inevitable due to discretization errors. Though conceptually straightforward, implementing contact forces in multibody fluid-structure simulations is far from simple in practice, with several competing possible strategies that are a topic of current research [13, 42, 55, 82, 85].

One approach is to introduce a potential with short-range repulsion, but such methods often introduce numerical stiffness. Alternatively, a space-time interference volume can guarantee a minimum separation between grains. In a fluid context, this method was first introduced by Lu et al. [55], and extended to allow for much smaller separation distances of rigid bodies by PI Quaife ad his previous PhD student [13]. One PhD student, who will be jointly supervised by both PIs, will simulate transport of eroding bodies by developing algorithms that resolve quadrature error and contact.

The central goal of simulating transport of eroding grains is to simulate a complex porous-medium of arbitrarily sized and shaped grains undergoing the simultaneous action of mechanical or chemical erosion and transport due to the combined effects of seepage, contact, and gravitational sedimentation. These computations will thus simulate, with high-fidelity, the multi-physics of realistic porous-medium dynamics, albeit in a scaled down context. Ultimately, such simulations could be used to build an understanding of medium reconfiguration events, such as sinkhole collapse or conduit formation in karst networks. In very preliminary work, PI Moore has run simplified simulations with a current graduate student. These preliminary simulations are based on a hybrid continuum-discrete model for the permeability field and grain particle field respectively.

They utilize the homogenized description of the flow field in (4) and incorporate the seepage and gravitational forces on the grains, feedback between the grain-distribution and the permeability field, and contact and cohesive forces between the grains. Preliminary results suggest that cohesion is essential to model sinkhole collapse.

2.4 Parameterizations of Eroding Porous Media

These sinkhole simulations have not yet begun to incorporate the slow-acting effects of mechanical and chemical erosion, and the associated gradual changes in medium properties. **A grand goal of this proposal is to merge the two lines of inquiry to develop a sound theoretical framework for porous-medium dynamics that is robust enough to capture both short-term events, such as sinkhole collapse, and long-term changes in the medium.** The greatest challenge faced is the disparate temporal and spatial scales that must be considered. Our proposed strategy is to use the high-fidelity erosion simulations to parametrize the effect of erosion on medium properties.

More specifically, we plan to run large batches of the high-fidelity BIE numerical simulations of erosion and then leverage rapid advances in the field of machine learning and deep-neural networks [48, 52, 53, 63] to develop reduced models that parametrize the effects of erosion on the evolution of macroscopic medium properties and the flow. The output of the high-fidelity simulations of the grain configuration can be transformed into essentially an image format, permitting use of cutting-edge advances in deep neural-networks for image analysis [63]. Some important advantages of referenced work are the use of dilated convolutions in a deeply connected network, which first mixes scales and second reduces the number of super-parameters present, thus largely mitigating the risk of overfitting data. Additionally, high-fidelity flow conditions can be used to train a neural network—a strategy that has been successfully used by others to predict, for example, an anisotropy tensor [53]. Both PIs will supervise a graduate student who will design and implement deep-neural networks for learning the essence of the high-fidelity simulations. Once the essential features are learned, they will be incorporated into reduced-order models that harness the multiphase framework. These reduced models will enable more efficient and larger scale simulations of dynamic erosion than are feasible with the high-fidelity BIE simulations.

2.5 Experimental Validation

Researchers at FSU's Geophysical Fluid Dynamics Institute (GFDI) have investigated the mechanisms behind sinkhole formation with a series of scaled-down laboratory experiments [79]. We will make use of the knowledge gained from these past experiments, and the facilities and equipment already in place, to inform and validate our computational program. In particular, existing data from these experiments offers a first-rate testbed for comparison against the newly developed simulation, and also provides information about the physical conditions and broad parameter regimes required for sinkhole collapse. Furthermore, and more importantly, **we propose to conduct a new campaign of laboratory experiments at the GFDI facilities that will be spearheaded by PI Moore and an undergraduate student funded by the project.** The experiments will use much of the same infrastructure, as well as GFDI technical staff who have working knowledge of the specific equipment. The experiments will be conducted in close cooperation with the graduate students to ensure constant feedback between advances in the computational program and experiments.

The proposed experiments involve two parallel lines of inquiry that will be merged in later stages of the project. The first line will investigate dynamic erosion of a porous material by mechanical or chemical processes. The porous medium will be represented by fragments of either erodible material, such as bentonite clay, or dissolve material, such as sucrose solids. We will perform controlled experiments to examine how important macroscopic properties, such as permeability, mechanical strength, and anisotropy, evolve dynamically as the constituents disintegrate. These experiments will make use of Darcy-column containers that allow precise control of flux through the medium and precise hydraulic head measurements to infer permeability. These Darcy columns have already been fabricated and are available for use at GFDI.

The second line of inquiry will extend the previously conducted sinkhole experiments of our collaborator Prof. Ming Ye (see letter of collaboration), with the specific aim of informing and validating our numerical simulations. This infrastructure permits precise control of the hydraulic head in confined and unconfined aquifers—it is the difference in the heads that creates conditions favorable for sinkhole formation. The new experiments will use both natural (sand) and artificial (glass beads) granular materials. The advantage of the latter is to achieve a mono-disperse medium for direct comparison against numerical simulations. Time permitting, we will merge the two lines of inquiry to examine the influence of material erodibility on gravitational reconfiguration and specifically sinkhole formation. The materials available for laboratory experiments, in particular the relatively rapid rates of degradation that can be achieved, will enable us to study phenomenon that occur on much longer timescales in the natural world.

3 Outreach

The PIs are committed to the development and training of students at various levels of their education throughout the time frame of the proposed research. Different aspects of the proposed research are appropriate for PhD research, undergraduate research, and high school student research. Moreover, opportunities within FSU will be seized to publicize the work to K–12 students and to the greater public.

3.1 Graduate Research

An important benefit of the proposed research is the immersion of graduate students in fundamentally *cross-disciplinary* research. This proposal involves a confluence of disciplines, most centrally computational mathematics, but also geophysics, environmental science, hydrology, and physical modeling. Exposure to a range of disciplines is, in the view of the PIs, an invaluable opportunity for young scientists.

Naturally, the proposed research will form the foundation for the PhD dissertations of the supported graduate students. Beyond this, the students will engage in publishing articles in high-quality peer-reviewed journals and attending national and international conferences where they will present their work and network with experts in the field. The PIs will closely mentor the graduate students to ensure their continued development, not only intellectually, but also in the 'soft' skills of communication, promotion, and networking. Having both PIs involved in the training of each graduate student is especially valuable for offering multiple perspectives on these issues. The PIs will make special efforts to recruit women and underrepresented minorities as the graduate students funded by this project. Both PIs have already had success recruiting women in these roles, as the first graduate student to receive her PhD under Moore's advising was female (Karina Khazmutdinova, 2016), and Quaife's current PhD student (Ashley Gannon, 2022) and Master's student (Daryn Sagel, 2020) are female.

3.2 Undergraduate Research

The proposed research represents a rich and fascinating topic for undergraduate students, while also being approachable by the skills acquired at that stage. We aim to recruit at least one undergraduate student to perform laboratory experiments at GFDI. As mentioned above, GFDI offers state-of-the-art laboratory facilities, with an already-functioning sinkhole experiment. The student will perform controlled experiments using natural and artificial porous media to precisely characterize the parameter regime leading to gravitational collapse. Parallel experiments will be conducted with erodible (bentonite clay) or dissolvable (sucrose solids) fragmented materials to represent a *dynamically* changing porous medium. These experiments will guide, calibrate, and validate the computational advances. The undergraduate students will work closely with the PIs and the graduate students to ensure that theory and experiments advance in close cooperation, with constant feedback between the two.

PI Moore has experience successfully training undergraduate students in combined laboratory and theoretical work. A recent example is Tyler Bolles who completed an undergraduate honors thesis with PI Moore at FSU on laboratory and theory of water waves. This work resulted in one *peer-reviewed* publication [11], and a second to be submitted soon. PI Quaife successfully trained an undergraduate student, Miles Currie, in a statistical analysis of flows related to prescribed fire dynamics. This work resulted in a *peer-reviewed* publication [20].

At FSU, there are at least two excellent avenues to attract interested undergraduate students: the **Undergraduate Research Opportunity Program (UROP)** and the **IDEA grant**. The UROP engages undergraduates in academic research, while the IDEA grant is a competitive program, requiring more advanced students to identify a research advisor and write an internal proposal. Both programs make special efforts to recruit from underrepresented groups. PIs Moore and Quaife already have experience using these programs to recruit interested students.

3.3 Outreach for K–12 and the General Public

The PIs have already seized the opportunity to engage K–12 students in outreach activities. In particular, PI Moore's research was the focus of an educational video created by **CPALMS**, which is the State of Florida's official source for standards information and course descriptions for K–12 education. The video features an interview and animations of research, and is used to reinforce mathematics concepts (grade levels 7–12), encourage students to consider a career in the STEM fields [81], and provides K–12 *teachers* with a broader perspective of mathematics that can be integrated into their teaching. Plans for future outreach include continued collaboration with CPALMS to create a series of educational videos. In addition, activities at **Math Fun Day**, an annual event held by the FSU Department of Mathematics to engage regional K-12 students, will be planned. PI Moore has previously led activities at Math Fun Day and, related to the current proposal, will deliver lectures and demos on porous-media flows, erosion, and sinkhole collapse. Laboratory materials for the demo are available at GFDI.

Another opportunity to expose high school students to university-level research is FSU's **Young Scholars Program (YSP)**. The YSP is a six week experience for Florida's brightest grade 11 students where they are exposed to university-level lectures and work with FSU faculty on a research project. PI Quaife participated in the YSP in 2016. The PIs will propose accessible projects throughout the duration of the proposed research. In addition to high school students receiving a university experience, the PhD students will be tasked with much of the day-to-day interaction, and this offers an excellent opportunity for the PhD students to develop leadership and mentorship skills.

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M. Nicholas J. Moore

Education and Professional Preparation

University of Tennessee, Knoxville	Mathematics	B.S. 2005
University of North Carolina, Chapel Hill	Mathematics	Ph.D. 2010
Courant Institute of Mathematical Sciences, NY	Mathematics	Postdoc 2010-2014

Employment and Appointments

2014-present	Assistant Professor of Mathematics and Associate of the Geophysical Fluid Dynamics Institute, FSU	Tallahassee, FL

Products

5 most relevant products, beginning from the most relevant

M. McCurdy, M.N.J. Moore, X. Wang. Convection in a coupled fluid-porous media system. In press at *SIAM Journal on Applied Mathematics*. Preprint available at arXiv:1901.02925 (2019).

B. Quaife and M.N.J. Moore. A boundary-integral framework to simulate viscous erosion of a porous medium. *Journal of Computational Physics*, **375**, 1-21 (2018).

M.N.J. Moore. Riemann-Hilbert problems for the shapes formed by bodies dissolving, melting, and eroding in fluid flows. *CPAM*, **70**(9), 1810-1831 (2017).

J.M. Huang, M.N.J. Moore, L. Ristroph. Shape dynamics and scaling laws for a body dissolving in fluid flow. *Journal of Fluid Mechanics*, **765**, R3 (2015).

M.N.J. Moore, L. Ristroph, S. Childress, J. Zhang, M.J. Shelley. Self-similar evolution of a body eroding in a fluid flow. *Phys. Fluid*, **25**, 116602 (2013).

Other Products

Majda, A. J., Moore, M. N. J., Qi, D. (2019). Statistical dynamical model to predict extreme events and anomalous features in shallow water waves with abrupt depth change. *PNAS*, **116**(10), 3982-3987.

Bolles, C. T., Speer, K., Moore, M. N. J. (2019). Anomalous wave statistics induced by abrupt depth change. *Physical Review Fluids*, **4**(1), 011801.

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Synergistic Activities

1. Contributed interview and research material for educational video entitled "Using Mathematics to Optimize Wing Design" published by CPALMS. CPALMS is the State of Florida's official source for standards information and course descriptions for K-12 education.

2. Co-organized SIAM Southeast Atlantic Sectional (SEAS) meeting, with B. Quaife, X. Wang and X. Wang. The meeting was held at Florida State University in Spring 2017. The organizers encouraged undergraduate and graduate student presentations, and organized awards for the best student talks.

3. Honors thesis supervisor for C. Tyler Bolles (B.S. in Mathematics, FSU 2017) whose research was selected for special recognition at the FSU President's showcase and also featured in presentations at two different *SIAM* conferences.

4. Serving on the Graduate Program Committee at the Geophysical Fluid Dynamics Institute (GFDI) at Florida State University.

5. Served on the review panel for the "IDEA grant" at Florida State University, which is a grant for undergraduate research.

(a) Professional Preparation

University of Calgary	Pure and Applied Mathematics	B.Sc. 2004
University of Calgary	Applied Mathematics	M.Sc. 2006
Simon Fraser University	Applied and Computational Mathematics	Ph.D. 2011
University of Texas	Computational Science and Engineering	August 2011–July 2015

(b) Appointments

Associate
Geophysical Fluid Dynamics Institute
Florida State University
November 2015–

Assistant Professor
Department of Scientific Computing
Florida State University
August 2015–

Research Associate
Institute for Computational Engineering and Sciences
University of Texas
September 2014–July 2015

Postdoctoral Fellow
Institute for Computational Engineering and Sciences
University of Texas
September 2011–August 2014

(c) Publications

(i) Publications Most Closely Related to the Proposed Project

- Lukas Bystricy, Sachin Shanbhag, and **Bryan D. Quaife**. Stable and contact-free time stepping for dense rigid particle suspensions. International Journal for Numerical Methods in Fluids, arxiv.org/abs/1804.11012, 2018. In press
- **Bryan D. Quaife** and M. Nicholas J. Moore. A boundary-integral framework to simulate viscous erosion of a porous medium. Journal of Computational Physics, 375:1–12, 2018.
- Pietro de Anna, **Bryan Quaife**, George Biros, and Ruben Juanes. Prediction of velocity distribution from pore structure in simple porous media. Physical Review of Fluids, 2 (12) 124103, 2017.
- Gokberk Kabacaoğlu, **Bryan Quaife**, and George Biros. Quantification of mixing in vesicle suspensions using numerical simulations in two dimensions. Physics of Fluids, 29(2):021901, 2017.
- MCA Kropinski and **BD Quaife**. Fast integral equation methods for the modified Helmholtz equation. Journal of Computational Physics, 230(2):425–434, 2011.

(ii) Other Significant Publications

- Gokberk Kabacaoğlu, **Bryan Quaife**, Bryan Quaife, and George Biros. Low-resolution simulations of vesicle suspensions in 2D. Journal of Computational Physics, 357:43–77, 2018.
- **Bryan Quaife**, Pieter Coulier, and Eric Darve. An efficient preconditioner for the fast simulation of a 2D Stokes flow in porous media. International Journal for Numerical Methods in Engineering, 113(4):561–580, 2017.
- **Bryan Quaife** and George Biros. Adaptive time stepping for vesicle simulations. Journal of Computational Physics, 306:478–499, 2016.
- **Bryan Quaife** and George Biros. High-order adaptive time stepping for vesicle suspensions with viscosity contrast. Procedia IUTAM, 16:8998, 2015.
- **Bryan Quaife** and George Biros. High-volume simulations of two-dimensional vesicle suspensions. Journal of Computational Physics, 274:245–267, 2014.

(d) Synergistic Activities

- Organized a 2017 5-day workshop at the Banff International Research Station (BIRS) on complex creeping flows.
- Supervised two high school students for six weeks in the summer of 2016 through the Young Scholars Program. They studied the effect that regularized kernels have on particle dynamics.
- Supervising undergraduate projects on simulating the dynamics of particles on closed surfaces, simulating wildfires with cellular automata, and using Bayesian analysis to study ocean circulation.
- Organizer and co-organizer of multiple minisymposiums at SIAM meetings and one SIAM regional meeting.
- Developed the courses *ISC5238: Integral Equation Methods* and *ISC5935: Iterative and Direct Methods for Linear Systems*.

SUMMARY PROPOSAL BUDGET

YEAR 1

ORGANIZATION **Florida State University**				FOR NSF USE ONLY PROPOSAL NO.	DURATION (months) Proposed	Granted
PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR **Matthew Moore**				AWARD NO.		
A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-months CAL	ACAD	SUMR	Funds Requested By proposer	Funds granted by NSF (if different)	
1. **Matthew N Moore - PI**	0.00	0.00	1.00	9,720		
2. **Bryan D Quaife - Co-PI**	0.00	0.00	1.00	10,553		
3.						
4.						
5.						
6. (0) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE)	0.00	0.00	0.00	0		
7. (2) TOTAL SENIOR PERSONNEL (1 - 6)	0.00	0.00	2.00	20,273		
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)						
1. (0) POST DOCTORAL SCHOLARS	0.00	0.00	0.00	0		
2. (1) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	0.00	0.00	0.25	2,188		
3. (2) GRADUATE STUDENTS				49,086		
4. (1) UNDERGRADUATE STUDENTS				600		
5. (0) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)				0		
6. (0) OTHER				0		
TOTAL SALARIES AND WAGES (A + B)				72,147		
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				7,546		
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				79,693		
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.)						
TOTAL EQUIPMENT				0		
E. TRAVEL 1. DOMESTIC (INCL. U.S. POSSESSIONS)				8,000		
2. INTERNATIONAL				2,000		
F. PARTICIPANT SUPPORT COSTS 1. STIPENDS $ 0 2. TRAVEL 0 3. SUBSISTENCE 0 4. OTHER 0						
TOTAL NUMBER OF PARTICIPANTS (0) TOTAL PARTICIPANT COSTS				0		
G. OTHER DIRECT COSTS						
1. MATERIALS AND SUPPLIES				2,000		
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				0		
3. CONSULTANT SERVICES				0		
4. COMPUTER SERVICES				0		
5. SUBAWARDS				0		
6. OTHER				22,008		
TOTAL OTHER DIRECT COSTS				24,008		
H. TOTAL DIRECT COSTS (A THROUGH G)				113,701		
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE) **F&A (Rate: 54.0000, Base: 91692)**						
TOTAL INDIRECT COSTS (F&A)				49,514		
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				163,215		
K. FEE				0		
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				163,215		
M. COST SHARING PROPOSED LEVEL $ 0	AGREED LEVEL IF DIFFERENT $					
PI/PD NAME **Matthew Moore**				FOR NSF USE ONLY INDIRECT COST RATE VERIFICATION		
ORG. REP. NAME* **Dale Meeks**				Date Checked	Date Of Rate Sheet	Initials - ORG

 ***ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET**

SUMMARY PROPOSAL BUDGET

YEAR 2

ORGANIZATION **Florida State University**				FOR NSF USE ONLY PROPOSAL NO.	DURATION (months) Proposed	Granted
PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR **Matthew Moore**				AWARD NO.		
A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-months CAL	ACAD	SUMR	Funds Requested By proposer	Funds granted by NSF (if different)	
1. **Matthew N Moore - PI**	0.00	0.00	1.00	**10,012**		
2. **Bryan D Quaife - Co-PI**	0.00	0.00	1.00	**10,869**		
3.						
4.						
5.						
6. (**0**) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE)	0.00	0.00	0.00	**0**		
7. (**2**) TOTAL SENIOR PERSONNEL (1 - 6)	0.00	0.00	2.00	**20,881**		
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)						
1. (**0**) POST DOCTORAL SCHOLARS	0.00	0.00	0.00	**0**		
2. (**1**) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	0.00	0.00	0.25	**2,254**		
3. (**2**) GRADUATE STUDENTS				**50,559**		
4. (**1**) UNDERGRADUATE STUDENTS				**600**		
5. (**0**) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)				**0**		
6. (**0**) OTHER				**0**		
TOTAL SALARIES AND WAGES (A + B)				**74,294**		
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				**7,606**		
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				**81,900**		
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.)						
TOTAL EQUIPMENT				**0**		
E. TRAVEL 1. DOMESTIC (INCL. U.S. POSSESSIONS)				**8,000**		
2. INTERNATIONAL				**2,000**		
F. PARTICIPANT SUPPORT COSTS 1. STIPENDS $ **0** 2. TRAVEL **0** 3. SUBSISTENCE **0** 4. OTHER **0**						
TOTAL NUMBER OF PARTICIPANTS (**0**) TOTAL PARTICIPANT COSTS				**0**		
G. OTHER DIRECT COSTS						
1. MATERIALS AND SUPPLIES				**2,000**		
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				**0**		
3. CONSULTANT SERVICES				**0**		
4. COMPUTER SERVICES				**0**		
5. SUBAWARDS				**0**		
6. OTHER				**22,228**		
TOTAL OTHER DIRECT COSTS				**24,228**		
H. TOTAL DIRECT COSTS (A THROUGH G)				**116,128**		
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE) **F&A (Rate: 54.0000, Base: 93899)**						
TOTAL INDIRECT COSTS (F&A)				**50,705**		
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				**166,833**		
K. FEE				**0**		
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				**166,833**		
M. COST SHARING PROPOSED LEVEL $ **0**	AGREED LEVEL IF DIFFERENT $					
PI/PD NAME **Matthew Moore**	FOR NSF USE ONLY INDIRECT COST RATE VERIFICATION					
ORG. REP. NAME* **Dale Meeks**	Date Checked	Date Of Rate Sheet	Initials - ORG			

 ***ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET**

SUMMARY PROPOSAL BUDGET

YEAR 3

FOR NSF USE ONLY		
PROPOSAL NO.	DURATION (months)	
	Proposed	Granted
AWARD NO.		

ORGANIZATION
Florida State University

PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR
Matthew Moore

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-months CAL	ACAD	SUMR	Funds Requested By proposer	Funds granted by NSF (if different)
1. **Matthew N Moore - PI**	0.00	0.00	1.00	**10,312**	
2. **Bryan D Quaife - Co-PI**	0.00	0.00	1.00	**11,195**	
3.					
4.					
5.					
6. (**0**) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE)	0.00	0.00	0.00	**0**	
7. (**2**) TOTAL SENIOR PERSONNEL (1 - 6)	0.00	0.00	2.00	**21,507**	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (**0**) POST DOCTORAL SCHOLARS	0.00	0.00	0.00	**0**	
2. (**0**) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	0.00	0.00	0.00	**0**	
3. (**1**) GRADUATE STUDENTS				**26,037**	
4. (**0**) UNDERGRADUATE STUDENTS				**0**	
5. (**0**) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)				**0**	
6. (**0**) OTHER				**0**	
TOTAL SALARIES AND WAGES (A + B)				**47,544**	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				**5,650**	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				**53,194**	
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.)					
TOTAL EQUIPMENT				**0**	
E. TRAVEL 1. DOMESTIC (INCL. U.S. POSSESSIONS)				**8,000**	
2. INTERNATIONAL				**2,000**	
F. PARTICIPANT SUPPORT COSTS 1. STIPENDS $ **0** 2. TRAVEL **0** 3. SUBSISTENCE **0** 4. OTHER **0**					
TOTAL NUMBER OF PARTICIPANTS (**0**) TOTAL PARTICIPANT COSTS				**0**	
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				**800**	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				**0**	
3. CONSULTANT SERVICES				**0**	
4. COMPUTER SERVICES				**0**	
5. SUBAWARDS				**0**	
6. OTHER				**11,225**	
TOTAL OTHER DIRECT COSTS				**12,025**	
H. TOTAL DIRECT COSTS (A THROUGH G)				**75,219**	
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE) **F&A (Rate: 54.0000, Base: 63995)**					
TOTAL INDIRECT COSTS (F&A)				**34,557**	
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				**109,776**	
K. FEE				**0**	
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				**109,776**	

M. COST SHARING PROPOSED LEVEL $ **0** AGREED LEVEL IF DIFFERENT $

PI/PD NAME
Matthew Moore

ORG. REP. NAME*
Dale Meeks

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INDIRECT COST RATE VERIFICATION		
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 ***ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET**

SUMMARY PROPOSAL BUDGET

Cumulative

FOR NSF USE ONLY		
PROPOSAL NO.	DURATION (months)	
	Proposed	Granted
AWARD NO.		

ORGANIZATION
Florida State University

PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR
Matthew Moore

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-months CAL	ACAD	SUMR	Funds Requested By proposer	Funds granted by NSF (if different)
1. **Matthew N Moore - PI**	0.00	0.00	3.00	**30,044**	
2. **Bryan D Quaife - Co-PI**	0.00	0.00	3.00	**32,617**	
3.					
4.					
5.					
6. ( ) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE)	0.00	0.00	0.00	**0**	
7. (**2**) TOTAL SENIOR PERSONNEL (1 - 6)	0.00	0.00	6.00	**62,661**	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (**0**) POST DOCTORAL SCHOLARS	0.00	0.00	0.00	**0**	
2. (**2**) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	0.00	0.00	0.50	**4,442**	
3. (**5**) GRADUATE STUDENTS				**125,682**	
4. (**2**) UNDERGRADUATE STUDENTS				**1,200**	
5. (**0**) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)				**0**	
6. (**0**) OTHER				**0**	
TOTAL SALARIES AND WAGES (A + B)				**193,985**	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				**20,802**	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				**214,787**	
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.)					
TOTAL EQUIPMENT				**0**	
E. TRAVEL 1. DOMESTIC (INCL. U.S. POSSESSIONS)				**24,000**	
2. INTERNATIONAL				**6,000**	
F. PARTICIPANT SUPPORT COSTS 1. STIPENDS $ **0** 2. TRAVEL **0** 3. SUBSISTENCE **0** 4. OTHER **0**					
TOTAL NUMBER OF PARTICIPANTS (**0**) TOTAL PARTICIPANT COSTS				**0**	
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				**4,800**	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				**0**	
3. CONSULTANT SERVICES				**0**	
4. COMPUTER SERVICES				**0**	
5. SUBAWARDS				**0**	
6. OTHER				**55,461**	
TOTAL OTHER DIRECT COSTS				**60,261**	
H. TOTAL DIRECT COSTS (A THROUGH G)				**305,048**	
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE)					
TOTAL INDIRECT COSTS (F&A)				**134,776**	
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				**439,824**	
K. FEE				**0**	
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				**439,824**	

M. COST SHARING PROPOSED LEVEL $ **0** AGREED LEVEL IF DIFFERENT $

PI/PD NAME
Matthew Moore

ORG. REP. NAME*
Dale Meeks

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Date Checked	Date Of Rate Sheet	Initials - ORG

C ***ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET**

Proposal Budget Justification

Senior Personnel

Funds requested include summer support for 1 summer month for years 1, 2, and 3, for the Principal investigator based on a salary of $86,156.11. Funds requested also include summer support for 1 summer month for the Co-PI based on a salary of 93,535.14. A 3.0% salary increase has been included in Year 2 for the PI and in Year 3 for both the PI and Co-PI.

Other Personnel

Funds have been requested for 2 Graduate Student in the Fall, Spring and Summer semesters in years 1 and 2 of the project to assist with the research effort. 1 Graduate student will be utilized in the Fall, Spring and Summer semesters in Year 3. The amount of funding requested is based on a current semester salary of $9,294 and Florida State University's Cost of Attendance as determined by the Financial Aid Office. A salary increase of 3.0% has been included in year 2 and 3.

Funds have been requested for 1 Technical Personnel for two weeks at a rate of $27.35/hour for 40hrs/week for Years 1 and 2 in the budget to assist with the research effort. A 3.0% salary increase has been included in Year 2 for the Techinical Personnel.

Funds have been requested for 1 Undergraduate Student for in the summer semesters in years 1 and 2 of the project to assist with the research effort. The undergraduate student will be paid for 4 weeks at $15.00 per hour for 10 hours per week.

Timesheets will not be kept on this project.

Fringe Benefits

Fringe Benefits have been calculated at 17.06% (Retirement 8.71%, Social Security 6.20% Medicare 1.45%, Workers/Unemployment Compensation .10%, and Terminal Leave .60%) for the PI for each year of the project.

Fringe Benefits have been calculated at 17.06% (Retirement 8.71%, Social Security 6.20% Medicare 1.45%, Workers/Unemployment Compensation .10%, and Terminal Leave .60%) for the Co-PI for each year of the project.

Fring Benefits for the Graduate Students have been calculated at 0.10% for Workers/Unemployment Compensation for each year of the project. A Student Health Insurance supplement for $2002 for the Graduate Student has been included in the fringe request for the funded semester and is based upon Florida State University's Policy "Salary Supplement for Health Insurance Subsidy."

Fringe Benefits for the Technical Personnel have been calculated at 1.55% (Medicare 1.45%, Workers Comp .10%).

Travel

Anticipated travel cost of $10,000 per year include:

Domestic

Domestic travel funds have been requested for two trips per year for the PI and Co-PI; and one trip per year for each graduate student to attend conferences (exact conferences TBA) and meet with other researchers each year. This is a vital part of the research effort to promote the project's research and present research with/to other experts in the field. Approximate costs for this are:
Air travel $2750, Lodging $3000, Meals $1250, and Conference Registration $1000 for a total of $8000 each year.

Foreign

Foreign travel funds have been requested for one international trip for the PI or Co-PI to attend an international conference each year of the project (exact conferences TBA). This travel is essential for the PI/Co-PI to meet the collaborators and present the research efforts while keeping up with the current state of research.
Approximate costs for this are:
Air travel $800, Lodging $600, Meals $300, and Conference Registration $300 for a total of $2000 each year.

Materials and Supplies

Funds have been requested for materials and supplies in the amount of $2,000 each year in Years 1 and 2 of the project. The funds will be used to purchase laboratory supplies- camera, plexiglass materials for building experimental tanks, sensors, etc. ($1200); and computers/software ($800) which is not otherwise available for use on this project. Funds have been requested in year 3 for computers and software in the amount of $800.

Other—Tuition

Funds have been requested to cover tuition for the graduate students at a rate of $407.55 per credit hour for 9 credit hours per funded semester of each grant year. A 1% increase in tuition costs was included in Years 2 and 3.

Indirect Cost Rate

$134,776
Indirect charges. FSU has a Federal negotiated Facilities and Administrative Cost Rate Agreement (F&A Rate). The FSU on-campus rate for federally sponsored research is 54%. The MTDC base of expenses includes all direct costs except equipment (each item over 5k), tuition remission, and rental of off-site facilities, capital expend-tures, scholarships and fellowships. To calculate the indirect cost on this proposal, the FSU on-campus rate of 54% has been applied to the MTDC of the project. MTDC (Modified Total Direct Costs) consists of all salaries and wages, fringe benefits, materials, supplies, services, and travel. FSU defines ‘year’ as its fiscal year, July 1 – June 30.

Current Support:

Title: Dynamic interactions between fluid flows and moving boundaries
Source: Simons Foundation, Mathematics and Physical Sciences-Collaboration Grants for Mathematicians
Total Award Amount: $42,000 (Travel funds only)
Duration: September 1, 2017–August 31, 2022
Person-Months Per Year Committed to Project: Calendar: 0, Academic: 0, Summer: 0

Title: A Comprehensive Experimental And Computational Fluid Dynamics Analysis Of Coning In Non-Newtonian Tailings During Extraction From Tailings Ponds
Source: Institute for Oil Sands Innovation
Total Award Amount: $171,842
Duration: January 1, 2020–January 1, 2022
Person-Months Per Year Committed to Project: Calendar: 0, Academic: 0, Summer: 0.5

Pending Support:

Title: Erosion, Transport, and Dispersion in Granular and Porous Media (this proposal)
Source: National Science Foundation, Division of Mathematical Sciences, Computational Mathematics
Total Award Amount: $439,824
Duration: July 1, 2020–June 30, 2023
Person-Months Per Year Committed to Project: Calendar: 0, Academic: 0, Summer: 1

Current Support:

Title: Computational Methods for Complex Stokesian Fluids
Source: Simons Foundation, Mathematics and Physical Sciences-Collaboration Grants for Mathematicians
Total Award Amount: $25,200 (Travel funds only)
Duration: September 1, 2017–August 31, 2020
Person-Months Per Year Committed to Project: Calendar: 0, Academic: 0, Summer: 0

Title: The Role of Vorticity and Fuel Moisture on the Near-Field Plume Structure and Ember Dynamics
Source: Department of Defense, Strategic Environmental Research and Development Program
Total Award Amount: $2,235,917
Duration: May 2020–January 2024 (This is a collaborative grant that supports 7 PIs from 4 institutions)
Person-Months Per Year Committed to Project: Calendar: 0, Academic: 0, Summer: 1

Pending Support:

Title: Erosion, Transport, and Dispersion in Granular and Porous Media (this proposal)
Source: National Science Foundation, Division of Mathematical Sciences, Computational Mathematics
Total Award Amount: $439,824
Duration: July 1, 2020–June 30, 2023
Person-Months Per Year Committed to Project: Calendar: 0, Academic: 0, Summer: 1

Computing Resources

Florida State University's (FSU) high performance computing (HPC) and high throughput computing (HTC) clusters are managed by the Research Computing Center (RCC).

The FSU HPC system is comprised of 12,492 x86 64-bit compute cores linked together by low-latency infiniband networks for MPI communication. The aggregate peak performance of the system is 264.6 TFLOPS. Compute nodes support between 2 and 16GB of memory per core. A redundant cluster of specialized nodes serve as the user entry points for the system. The Slurm job scheduler handles job submission and scheduling on the HPC system. A broad set of compilers, math and communication libraries, and software applications are made available on the HPC to maximize the utility of the system by users across diverse academic disciplines. The cluster also includes nodes with 16 NVIDIA Tesla gpGPU cards (m2050) for a total 7,168 GPU cores for a peak system performance of 19.8 TFLOPS.

The FSU HTC system, Condor, is comprised of 1,200 x86 64-bit compute cores. The system is specifically tailored to support large batches of serial jobs where overall throughput is preferred over performance. The aggregate peak performance of the system is 16.5 TFLOPS. Compute nodes support between 2 and 8 GBs of memory per core.

In addition to the HPC and HTC systems, the PI's group has access to RCC's Spear cluster. The Spear Cluster is comprised of 288 x86 64-bit process cores linked together by a QDR Infiniband network. Eight of the Spear nodes also connect to a PCI chassis equipped with 16 Nvidia Tesla gpGPU cards (M2050) for a total of 7,168 GPU cores for a peak system performance of 19.8 TFLOPS.

Personnel

The RCC has dedicated personnel who offer help with hardware specification and acquisition, software acquisition and licensing, compilation, installation, integration with the queuing system, running benchmarks, developing computational workflows, and necessary end-user training. In addition, the Department of Mathematics and the Department of Scientific Computing have systems administrators that assist with the PIs's group's computing needs.

Both the PIs are associates in the Geophysical Fluid Dynamics Institute (GFDI). GFDI is a fluids lab where experimental work will be performed. The lab includes the necessary support staff, including a machinist and system administrator, to assist with experimental setups and computational needs.

Office Space

The project will utilize office and workspace in the Department of Mathematics, Department of Scientific Computing, and Geophysical Fluid Dynamics Institute at Florida State University. Offices are equipped with a standard desktop computer and internet access.

Products of the Research

The following types of data will be produced as part of this project:

- numerical methods for simulating erosion;
- scientific software for implementing these methods;
- website for disseminating results;
- peer-reviewed journal publications.

Data Formats

The software product will consist of (i) exploratory MATLAB or Python scripts for testing analyzing the algorithms, and (ii) Julia and Fortran implementations to measure runtime efficiencies on computer architectures available at Florida State University. All scripts and codes will include explanatory comments. The website will be in ASCII plaintext using html, php, and javascript.

Access to Data and Data Sharing Practices and Policies

Source scripts and codes will be made available, often before the acceptance of the peer-reviewed papers, using the relevant scripts and libraries. This software will then be available, without restriction, to any user who wishes to download, use, or modify it. The website will be available on the Internet. All materials, including movies, images, and text, will be licensed for re-use with appropriate credit given (using a license such as the GNU Copyleft license). Data from the research will be open source, and there are no significant privacy, confidentiality, or intellectual property requirements that pertain to this research. Educational videos will be prodced by the CPALMS organization and made freely available to the public

Policies for Re-Use, Re-Distribution and Production of Derivatives

All data created as a result of this project will be freely available and usable by the public, and by other researchers. The only condition will be a citation to the appropriate publications. The PIs will further request, but not require, that users of our software contribute any changes, improvements, or additions that they make back to the appropriate open-source software project. Data or images that are copyrighted (by a journal, for example) will be marked as such by watermark or text header in the file.

Archiving of Data

Source code will be uploaded to Google Code, BitBucket, GitHub, and other Cloud-based data providers. Websites relating to this project, and all of the data on the aforementioned websites, will be hosted by Florida State University's (FSU) Information Technology group on servers that are backed up regularly. This data will be available to the public for as long as the PIs remain actively employed at FSU. If the PIs leave FSU for any reason, steps will be taken to ensure that this data remains available, either by moving it to another university or making it a part of a larger, more persistent project at FSU.

THE FLORIDA STATE UNIVERSITY

College of Arts & Sciences

Department of Earth, Ocean & Atmospheric Science

11/14/2019

If the proposal submitted by Drs. Moore and Quaife entitled "Erosion, Transport, and Dispersion in Granular and Porous Media" is selected for funding by NSF, it is my intent to collaborate and/or commit resources as detailed in the Project Description or the Facilities, Equipment and Other Resources section of the proposal.

Ming Ye, Professor
Department of Earth, Ocean, and Atmospheric Science
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