Simulation of Wave Propagation Used for the Detection of Submerged Stone Age Artifacts

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Mathematics

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Introduction to the Research & Motivation

- Interdisciplinary between UTC’s mathematics department (Dr. Chris Cox & Dr. Boris Belinskiy) and UTC’s anthropology department (Dr. Morgan Smith).

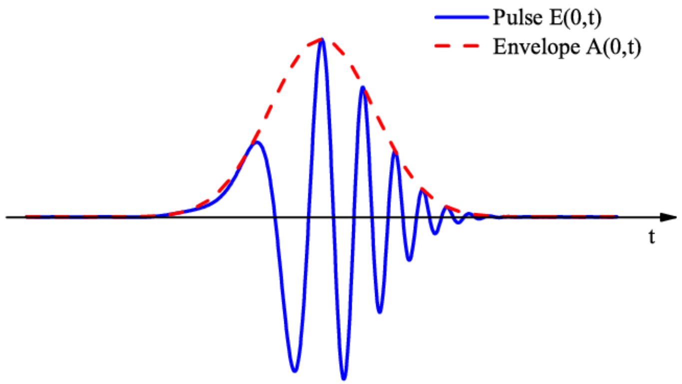
- As industrial digging in the sea increases for the construction of energy sources, there is a growing need to quickly identify submerged indigenous archeological sites.

Introduction to the Research & Motivation Cont’d

- The two main methods currently employed are insufficient:
  - 1) The use of high-frequency (600 – 2000 kHz) sound waves by way of side-scan sonar.
  - 2) Use of geophysics to identify landmarks that *could* have potentially attracted pre-contact (indigenous) people.
- This research will greatly enhance our ability to identify sites in deepwater settings and at Pleistocene and Early Holocene coastlines which are now submerged under as much as 130 m of seawater.

Equipment & Wave Form

- As opposed to using side-scanning sonar, we are interested in using a sub-bottom profiler (SBP) that uses significantly lower frequency sound waves (4 – 24 kHz).



Generic Chirp Emitted by an SBP

3100-P Portable SBP

Hypotheses

- In using this equipment, we hope to validate the following two hypotheses:
  - 1) Low-frequency sound waves create structural resonance in stone tools which can be observed within the range of SBP equipment (4 – 24 kHz).
  - 2) Low-frequency sound waves do not create structural resonance in other materials (ceramics, bone, shell, etc.) within the range of SBP equipment (4 – 24 kHz). Only stone tools resonate within this spectrum and the signatures seen in SBP data are exclusively those produced by stone tools.

Hermand's Simulations

- A team of European scientists (headed by Jean-Pierre Hermand) published simulations in 2011 using a similar low-frequency wave and gave validity to this research.

- Our current plan is to replicate these simulations (only-known numerical modeling experiment conducted in this frequency range to date) before experimentally validating them with the equipment previously mentioned.

Hermand's Simulations Cont'd

- We will do this by first using Hermand's parameters for layers under the seabed.

Density	2300 kg/m^3
Compression speed	8433 m/s
Shear speed	5843 kg/m^3
Young's module	185 GPa
Poisson's Ratio	0.27

Above: Acoustic parameters of typical flint material.

Below: Bottom layer properties. The cultural layer contains the flint pieces. Parenthetical values in column two are used in simulations.

Layer	Thickness (cm)	ρ (kg/m^3)	c_p(m/s)	c_s(m/s)	α_p(dB/λ)	α_s(dB/λ)
seawater	0 – 500 (200)	1000	1500	–	–	–
sand	10 – 25 (10)	1900	1650	110	0.8	–
mud	20 – 30 (20)	1500	1500	50	0.2	–
cultural	5 – 10 (5)	1500	1500	50	0.2	–
sand	15 – 50 (15)	1900	1650	110	0.8	–
substrate (moraine)	semi–∞	2100	1950	600	0.4	1.0

Length (cm)	Resonance frequency (kHz)
8	17.72
10	14.18
12	11.82
14	10.13

Above: Predicted resonance frequencies of flint pieces of differing lengths.

FEniCS Python Software & Numerical Methods

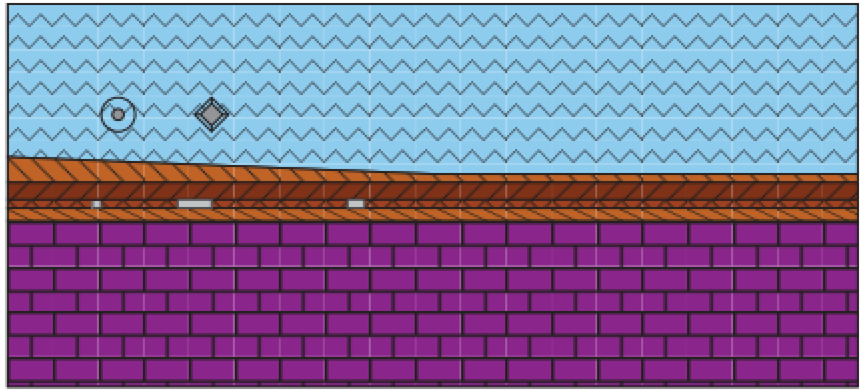
- While SPECFEM was originally used by Hermand's team, we have opted to use FEniCS.

- It is powerful open-source software that interfaces with Python to allow the implementation of mathematical models into finite element code.

- The finite element method is a popular method for numerically solving partial differential equations by discretization of the spatial dimensions using a mesh.

Current Simulation Progress

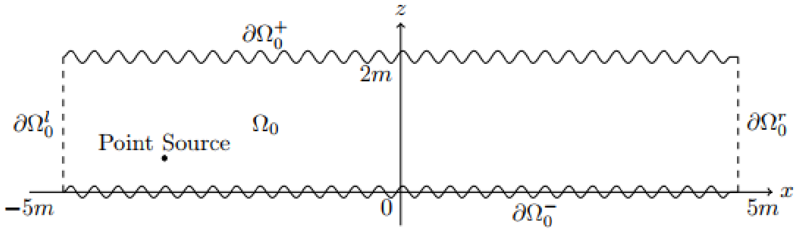
- As of this presentation, we have successfully modelled the seawater layer using FEniCS and the appropriate parameters from Hermand's paper using the 2D wave equation.



Visual representation of the bottom layer properties.

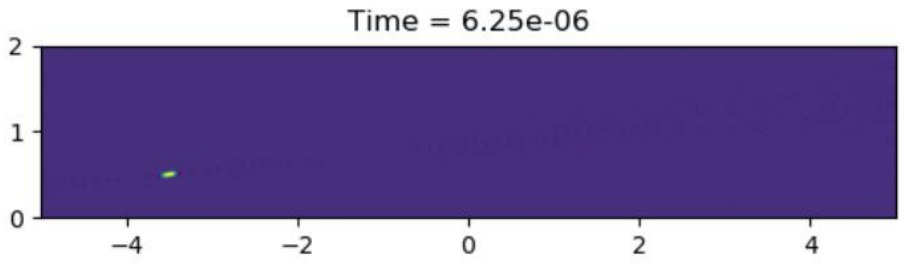
$$\frac{\partial^2 u}{\partial t^2} = c^2 \left(\frac{\partial^2 u}{\partial x_1^2} + \frac{\partial^2 u}{\partial x_2^2} + \cdots + \frac{\partial^2 u}{\partial x_n^2} \right)$$

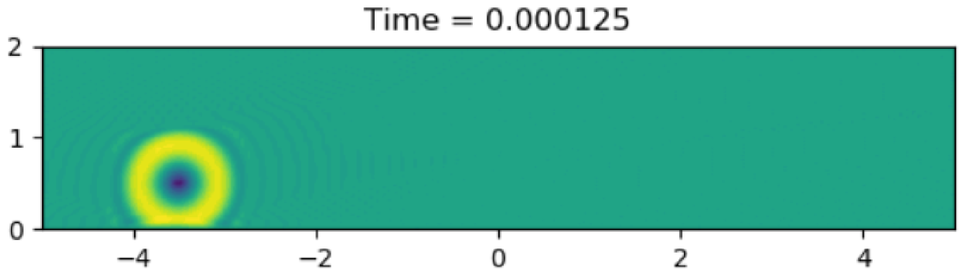
$$\mathbf{u}_{tt} = c^2 \nabla^2 \mathbf{u}$$



Top: Wave equation; Middle: Wave eq. simplified using the Laplace operator; Bottom: Diagram of seawater layer with point source and boundary conditions.

Current Simulation Progress Cont'd

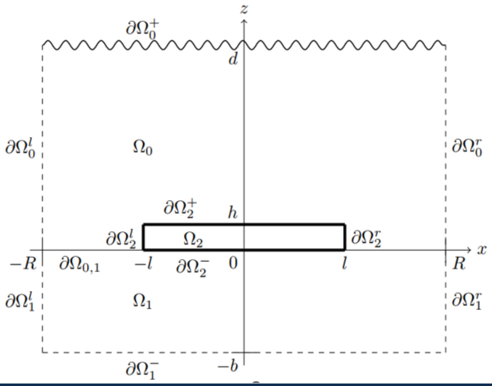




Both images are generated by FEniCS. Notice the point source in the seawater layer aligns with the diagram on the previous slide. Both axes measure distance.

Next Simulation Additions

- Very soon, the simulations will have all correct boundary conditions (e.g., PML) and layers added.
- Once the simulations are replicated successfully, we will begin novel simulations to explore the resonance frequencies of various artifact materials. Including the configuration in the figure below:



Left: Seawater layer with an artifact (or artifact cluster) resting on the seafloor as opposed to being submerged.

Future Work

- In addition to creating new simulations, there is a promising application with machine learning (ML) that could allow for the geometric description of complex objects from eigenvalues and resonances.

- In our current simulations, the archeological objects are approximated by a perfect rectangular area – which is not completely realistic!

- We will also explore physics-informed generative adversarial networks and their application to (stochastic) PDEs in the context of this research problem.

Conclusion

- Archeology is in dire need of a new method to preserve archeological dig sites.

- This research is poised to provide such a solution using an SBP in a novel way.

- The data generated could also inform mathematical modeling techniques by way of ML.

References

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- EdgeTech - User Hardware Manual. (n.d.). Retrieved from https://www.edgetech.com/wp-content/uploads/2019/07/0004802_Rev_F.pdf.
- J.-P. Hermand, O. Grøn, M. Asch and Q. Ren, Modelling flint acoustics for detection of submerged Stone Age sites, OCEANS'11 MTS/IEEE KONA, 2011, pp. 1-9, doi: 10.23919/OCEANS.2011.6107308.

Questions?