GeoClaw–ArcGIS Integration for Advanced Modeling of Overland Hydrocarbon Plumes

Pi-Yueh Chuang ¹, Tracy Thorleifson ², Lorena Barba ¹

¹ Mechanical and Aerospace Engineering, the George Washington University
² G2 Integrated Solutions
Overview

● Background, motivation, and the aims of this work
● Modeling hydrocarbon overland flow with full shallow-water equations
  ○ GeoClaw
  ○ Added features and code modifications
● Integration with Microsoft Azure
● Integration with ArcGIS
HCA analysis

- Hazardous liquids HCA (high consequence area) analysis
  - To identify “could affect” pipeline segments
  - Required by Title 49 CFR §195.452
  - Time consuming

Credit & copyright: the COMET Program
## Flow model: low-fidelity vs. high-fidelity approaches

<table>
<thead>
<tr>
<th>Low-fidelity models</th>
<th>High-fidelity models</th>
</tr>
</thead>
<tbody>
<tr>
<td>● 1D open-channel modeling</td>
<td>● 3D free-surface full Navier-Stokes equations</td>
</tr>
<tr>
<td>● 1D gravity flow modeling</td>
<td>● 2D shallow-water equations (SWEs)</td>
</tr>
<tr>
<td>Need less computing power &amp; Currently popular for HCA analysis</td>
<td>○ Full SWEs</td>
</tr>
<tr>
<td></td>
<td>○ Kinematic approximation</td>
</tr>
<tr>
<td></td>
<td>○ Diffusive approximation</td>
</tr>
<tr>
<td>Need higher computing power &amp; No open-source option specifically for HCA analysis</td>
<td></td>
</tr>
</tbody>
</table>
This work

Full shallow-water equations solver

- For HCA analysis
- Open source license

Integration with cloud computing for large projects

- Microsoft Azure
- Scalable computing power
- Auto-scaling
- Usage-based charges

Integration with ArcGIS Pro

- Launching cloud simulations from a local machine/laptop
Solver for full shallow-water equations: GeoClaw

- Websites
  - Official: http://www.clawpack.org/geoclaw
  - Source code: https://github.com/clawpack/geoclaw

- Applications
  - Tsunami simulations
  - Storm surge simulations

- Feature
  - BSD-3 open-source license
  - Adaptive mesh refinement
  - Shared-memory parallelization

Adaptive mesh refinement:
- dynamic & non-uniform spatial resolution (raster grid)
- save calculations on areas that do not require high resolution
Missing from GeoClaw

**Done in this work**
- Point source inflow (pipeline rupture point)
- Interaction with inland water bodies
- Darcy-Weisbach friction
- Temperature-dependent viscosity
- Evaporation model

**Work in progress**
- Adhesion
- Infiltration
Rupture point & viscosity model

- Point source inflow as rupture point
  - Multi-stage constant rate

- Temperature-dependent viscosity (Lewis-Squires, 1934)
  - Hydrocarbon viscosities highly depend on temperature
    \[
    \mu_a^{-0.2661} = \mu_k^{-0.2661} + \frac{(T_a - T_k)}{233}
    \]
    
    \( T_a \): desired temperature (°C)
    \( T_k \): reference temperature (°C)
    \( \mu_a \): dynamic viscosity at the desired temperature (cP)
    \( \mu_k \): dynamic viscosity at the reference temperature (cP)

Example of a multi-stage leak profile
Darcy–Weisbach friction model

- Only require fluid viscosity and surface roughness
  - No extra experiments needed
  - Vegetation on the ground

Add to the right-hand-sides of the momentum equation

\[
\begin{bmatrix}
S_{fx} \\
S_{fy}
\end{bmatrix} = \frac{f_{DW}}{8gh^3} \left[ \frac{(hu)^2}{(hu)^2 + (hv)^2} \left[ \frac{hu}{hv} \right] \right]
\]

Different coefficient calculation methods:
- affect laminar and transient regimes
- similar in turbulent regime
Intersection with In-land hydrological features

- Capture information required by hydrographic transport simulator

Example of the output data regarding hydrocarbon-waterbody intersection
Evaporation models

- Account for the primary product loss in hydrocarbon plume

**Fingas’ model for non-volatile fluids (1996)**

1. *Natural logarithm*: \[ \%_{Evap} = \left( C_1 + C_2 T \right) \ln(t) \]

2. *Square root model*: \[ \%_{Evap} = \left( C_1 + C_2 \right) \sqrt{t} \]

\%_{Evap}: percentage of evaporated against initial spill volume

\( C_1 \) & \( C_2 \): coefficient obtained from experiments

\( T \): ambient temperature (°C)

\( t \): elapsed time (minutes)
Workflow features

● Automatically download topography and hydrologic features
  ○ 3DEP server & NHD servers (US data only)
  ○ ESRI World Elevation server (require ESRI credential)

● NetCDF raster output
  ○ CF-1.7 convention
  ○ Multidimensional dataset

● Docker image available
  ○ Useful for Windows machines
Validation: silicone oil, inclined glass plate

- Angle: 2.5°; Rate: 1.48e⁻⁶ m³/sec; Surface roughness: 0; No evaporation

![Graphs showing experimental data compared to theoretical predictions at different times: T = 59s, T = 122s, T = 271s, T = 486s.](image-url)
Viscosity effect: horizontal plate spill

Gasoline:
- $\mu_a$: 0.6512 cP @ 15°C
- API gravity: 45°
- Rate: $1.48 \times 10^{-6}$ m³/sec
- Roughness: 0
- No evaporation

Maya crude:
- $\mu_a$: 332 cP @ 15°C
- API gravity: 21.5°

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Common settings of the demos

- **Inflow rate:**
  - 0 min ~ 30 min: 0.5 m$^3$/sec
  - 30 min ~ 210 min: 0.1 m$^3$/sec
  - 0 m$^3$/sec afterward

- **Total volume released:** 1980 m$^3$

- **Surface roughness:** 0.1 m

- **Ambient temperature:** 25 ºC

- **Simulation time:** 0 ~ 8 hr

**Gasoline:**
- $\mu_a$: 0.6512 cP @ 15ºC
- API gravity: 45º
- $\%_{Evap} = (13.2 + 0.21T)\ln(t)$

**Maya crude:**
- $\mu_a$: 332 cP @ 15ºC
- API gravity: 21.5º
- $\%_{Evap} = (1.38 + 0.045T)\ln(t)$
Demo: flat area

- Maya crude
- Gasoline

30 min

1 hr

2 hr
Demo: with inland water bodies

- Maya crude
- Gasoline

30 min

90 min
Demo: hill area (Maya crude)
Microsoft Azure

- geoclaw-azure-launcher
  - Source code: [https://github.com/barbagroup/geoclaw-azure-launcher](https://github.com/barbagroup/geoclaw-azure-launcher)
  - Python module [helpers.azuretools](https://github.com/barbagroup/geoclaw-azure-launcher)

- Required Azure services
  - Azure Batch account
  - Azure Storage account
Interface through ArcGIS Toolbox

- geoclaw-azure-launcher
  - Source code: [https://github.com/barbagroup/geoclaw-azure-launcher](https://github.com/barbagroup/geoclaw-azure-launcher)
  - ArcGIS Toolbox `Land-spill Azure.pyt`
  - 6 tools
    - 1 tool to create GeoClaw inputs
    - 4 tools to communicate with Azure
    - 1 utility to create credential file

[Check the demo video!](https://example.com)
ArcGIS Python toolbox workflow

Main workflow

CreateGeoClawCases → RunCasesOnAzure

MonitorAzureResources → DownloadCasesFromAzure

Import NetCDF files

Other tools

DeleteAzureResources, NewEncryptedAzureCredential

Check the demo video!
Tool: CreateGeoClawCases

- Create GeoClaw cases for selected rupture points
  - Rupture points
  - Leak profile
  - Physical properties
  - Model parameters
  - Computational parameters
  - Topography and inland water bodies
Tool: RunCasesOnAzure & MonitorAzureResources

GUI for creating Azure resources and submitting simulations

Status monitor
Conclusion

● High-fidelity simulator that provides more accurate predictions of pipeline segments affecting an HCA
  ○ **Model components**: 2D full shallow-water equations, rupture point inflow, Darcy-Weisbach friction, temperature-dependent viscosity, evaporation, hydrocarbon plume/water bodies contact
  ○ **Simulator features**: automatic downloading from 3DEP and NHD; adaptive mesh refinement; shared-memory parallelization

● Scalable computing performance through Microsoft Azure cloud

● ArcGIS Pro toolbox
Q & A

● Acknowledgement
  ○ Tom Bell, G2 Integrated Solution
  ○ Kyle Mandli, Columbia University

● Source code URLs:
  ○ https://github.com/barbagroup/geoclaw
  ○ https://github.com/barbagroup/geoclaw-landspill-cases
  ○ https://github.com/barbagroup/geoclaw-azure-launcher

● Docker image on DockerHub
  ○ barbagroup/landspill
Extra slides
Darcy–Weisbach friction model

- Add to the right-hand-sides of the momentum equation

\[
\begin{bmatrix}
S_{fx} \\
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\end{bmatrix} = \frac{f_{DW}}{8gh^3} \sqrt{(hu)^2 + (hv)^2} \begin{bmatrix}
hu \\
hv
\end{bmatrix}
\]

Three regime model

- Laminar (Re < 500): \( \frac{24}{Re} \) (or \( \frac{16}{Re} \) for wide – open channel)
- Transient (500 < Re < 1250): \( \frac{0.224}{Re^{0.25}} \)
- Full turbulent (Re > 1250): \( \frac{0.25}{\log_{10}^{2}(\sigma/14.8h + 1.64hRe^{0.9})} \)

Churchill's model

\[
A = \left[ 2.457 \ln \left( \frac{1}{(1.75/Re)^{0.9} + 0.0675\sigma} \right) \right]^{16}
\]
\[
B = \left( \frac{9382.5}{Re} \right)^{16}
\]
\[
f_{DW} = 8 \times \left[ \left( \frac{2}{Re} \right)^{12} + \frac{1}{(A + B)^{3/2}} \right]^{1/12}
\]
Evaporation models

- Evaporation
  - Fingas’ observation: contact area does not affect the evaporation rates of most hydrocarbon fluids when “the depths are shallow”.
  - Solution: treat volume on the ground and in the pipeline as a continuum
    - Initial volume: total volume that will be released to the domain
    - For each time step, both the volumes in the pipeline and on the ground undergo evaporation with percentage $\%_{\text{Evap}}$
    - Release rate is fixed => shorten the release period
Evaporation models

- Evaporation issues:
  - Oil has flown into water bodies also undergoes the same evaporation mechanism
  - High evaporation-rate fluids evaporate inside pipelines

- About 50% of the volume evaporates directly from inside the pipeline.
- i.e., 50% of the volume never participates in overland flow.
Tool: MonitorAzureResources

- Pop up a graphical monitor for the cluster and tasks
Tool: DownloadData & DeleteAzureResources

- DownloadData
  - Synchronization mode

- Delete cloud resources
Tool: NewEncryptedAzureCredential

- Create an encrypted Azure credential file
  - Batch account name, key, and url
  - Storage account name and key
- Users don’t have to copy & paste credential info every time