Computational Analysis of Oil Spill in Shallow Water due to Wave and Tidal Motion

Madhusuden Agrawal
ANSYS Houston
OUTLINE

• Overview of Oil Spill & its Impact
• Technical Challenges for Modeling
• Open Channel Flows and Waves Modeling in ANSYS
• CFD Modeling for Oil Spill in 2D and 3D domains
• Conclusion
Oil Spill: Overview

An “Oil Spill” usually refers to an event that led to a release of liquid petroleum hydrocarbon into the environment due to human activity and is a form of pollution.

- Release of crude oil - Tankers, offshore platforms, drilling rigs and wells
- Release of refined petroleum products - Large ships such as bunker fuel and storage tanks
Major Oil Spill Events

- Arabian Gulf oil spill ~ 446 million gallons of oil
- Deepwater Horizon oil spill ~206 million gallons of oil
- Ixtoc 1 oil spill ~ 140 million gallons of oil
- Amoco Cadiz oil spill ~ 68 million gallons of oil
- Exxon Valdez oil spill ~ 10.9 million gallons of oil
Impact of Oil Spill Event and Mitigation

- Short term: Cost of clean-up is huge
- Long term: Environmental concerns

Prevent such oil spill events or at least mitigate the effects of oil spill

- Containment or control of spread of the oil
- Predict – Trajectory of oil slick

“Traditionally empirical models are used”
Prediction Challenges

**Physics - Spread of Oil Slick**

- Ocean Hydrodynamics
  - Advection
  - Turbulent Diffusion
  - Surface Spreading

- Complex Physics
  - Evaporation
  - Dissolution
  - Emulsification
  - Hydrolysis
  - Photo-Oxidation
  - Bio degradation
  - Particulation

“Hydrodynamics of the ocean waves play a major role”
Hydrodynamics – Ocean Waves

Classification

• Deep water wave:
  • Depth > ½ Wave Length
  • Higher wavelength and travel faster

• Transitional Waves:
  • Depth < ½ of wavelength but greater than 1/20 of wavelength

• Shallow Waves:
  • Depth < 1/20 wavelength
Hydrodynamics – Ocean Waves

• Shallow water wave:
  - Waves are higher and steeper
  - Elongated ellipse orbital paths with minor axis in vertical direction
  - As water depth decreases, waves slowdown
  - There is no orbital motion of water particles, very close to beach
  - When breaking criteria is exceeded (H/L > 1/7), waves become too steep and break, enhancing dispersion of oil from slick to seawater
CFD Modeling Challenges

• Relatively Large Computational Domain and Strict Mesh Requirement
  • Resolve boundary layers, air-water-oil interface and oil release pipe

• Large computational time
  • Need to run for long flow time (few hours to days)

• Three Phases VOF with surface tension
  • Time step size for proper convergence

• Open Channel Condition with higher order wave and current specifications
  • Need to ensure wave stability and propagation
Multiphase Models in ANSYS CFD

Mixture Model
- Free Surface Flows
  - Cavitation Model
  - Wet Stream Model
  - Prescribed slip velocity
- Multi-fluid Model
  - Multi-fluid free surface
    - Eulerian Model
    - Granular Model
    - Boiling Models

Population Balance Model
- Interfacial Area
- Moment Method
  - QMOM
  - DQMOM
- Sectional Method
  - Homogenous
  - Inhomogenous

Lagrangian Description
- Dispersed Phase
  - Dense DPM
  - Fully Coupled DEM
- Macro Particle Model
Volume of Fluid Model

- VOF model is used to model immiscible fluids with clearly defined interface.
  - Shape of interface is of interest
    - Two gases cannot be modeled since they mix at the molecular level.
  - VOF is an Eulerian fixed-grid technique.
  - VOF is numerically robust and accurate

- Typical problems:
  - Jet breakup
  - Motion of large bubbles in a liquid
  - Motion of liquid after a dam break
  - Steady or transient tracking of any liquid-gas interface
Numerical Modeling of Open Channel Flows with Waves

- Open Channel Flows with Wave BC
- There are number for wave model formulations
  - First order (L WT) - for shallow to deep liquid depth ranges
  - Higher order (NLWT) - for intermediate to deep liquid depth range.

Numerical beach treatment
Open Channel Flows: Example Floating body in wave Tank

Wave Conditions (5th Order Stokes)

Numerical beach fluid zone near the outlet

Remeshing and Smoothing in MDM and 6DOF Model to predict the motion of body
Open Channel Flows: Example Wave impingement on Submarine

Top (pressure-outlet)

Bottom (wall)

inlet

submarine

Mesh: Hexagonal cells

SST k-omega model

Fifth order Wave

Cell count: ~1.1 million
2D CFD Modeling for Oil Spill

- **Computational Domain**
  - 2km long with water depth of 100m at deep end and 50m at shallow end.

- A Good Quality Mesh was created

- **Volume of Fluid multiphase model – 3 phases**

- Oil release was modeled as separate phase with a prescribed mass flow rate

- Surface Tension Effect included

- Effect of wave amplitude, wave length and current investigated
Dynamic Mesh Adaptation

Automatic Mesh Refinement and Coarsening based on Oil volume fraction

No need to have fine mesh for the entire region

Improve accuracy of interface prediction
2D Model: Effect of Wave Length

Amplitude 10m, Wavelength 500m, No current

Amplitude 10m, Wavelength 1000m, No current

Impact of Wavelength on Oil Film Thickness

Short wave has lower celerity hence kinetic energy. So less dispersion of oil and thicker slick.
2D Model: Effect of Wave Amplitude

Amplitude 5m, Wavelength 500m, No current

Amplitude 10m, Wavelength 500m, No current

Impact of Wave Amplitude on Oil Film Thickness

Waves with Smaller Amplitude cause More Spread of the Oil Slick
2D Model: Effect of Wave Current

Amplitude 10m, Wavelength 500m, No current

Amplitude 10m, Wavelength 500m, 1m/s current

Impact of Wave Current on Oil Film Thickness

Wave Current enhances Oil Film to Travel Further in the Wave Direction
2D CFD Study - Observations

• Effect of Ocean Dynamics in the wave direction captured well
  • Waves with Smaller Amplitude cause More Spread of the Oil Slick
  • Wave Current enhances Oil Film to Travel Further in the Wave Direction
  • At high wavelength, oil dispersion underwater increases and hence extent of oil film on sea surface

• Limitation:
  • Circular leak area can not be modeled
  • Dispersion in transverse direction can not predicted
3D CFD Modeling for Oil Spill

- Full 3D Domain
  - 2km long, max water depth 110m
  - Domain tapered at one end – mimic shallow coastal area
- Volume of Fluid (VOF) – Three Phases
- Open channel wave boundary condition with fifth order stokes wave theory – non-linear waves
- Dynamic adaptation of mesh to capture oil interface
- Four simulations with different wave amplitude, wave length and current conditions

OTC 21949: Computational Analysis of Oil Spill in Shallow Water due to Wave and Tidal Motion by M. Agrawal and D. Dakshinamoorthy, ANSYS Inc
3D CFD Model

Grid refined near sea surface to capture waves
Observations - Velocity Profiles

• The oil droplets float upward slowly after spilling due to buoyancy
• High velocity near surface due to wave interaction
• Oil droplets diffuse to water in horizontal direction due to circulation pattern in water flow
• As wave steepness increase – Non linear waves results
• Coastal region or Shallow water region impacts the wave profile

5m Amplitude and 500m Wavelength Wave
Oil Slick at Sea Surface

5m Amplitude and 500m Wavelength Wave

10m Amplitude and 500m Wavelength Wave

5m Amplitude and 750m Wavelength Wave
Animation of Oil Spread

5m amplitude and 500m Wavelength wave

10m amplitude and 500m Wavelength wave

5m amplitude and 750m Wavelength

5m amplitude and 500m Wavelength With Current
3D CFD Study: Observations

• 3D effect on oil jet pattern as well as oil film spread
  • Spread of oil slick in transverse direction captured well
• Spread pattern is different for different wave conditions
  • Spread of oil film increases with higher interaction of wave and current
  • Polluted area is more towards coastal area or in shallow water
  • High wave amplitude cause less spread in transverse direction
    • oil traveled faster to the coastal area
  • High wavelength cause more spread in transverse direction
Other Physics for CFD Simulations

• Evaporation
  • Multiphase evaporation models
  • Heterogeneous heat and mass transfer

• Emulsification
  • Calibrate Viscosity models or PB

• Particulation
  • Agglomeration kernels in PB
  • Level set + VOF

• Dissolution
  • Mixing or Reactions
Conclusion

- Overview of the oil spill and its impact on oil and gas industry
- Presented detailed 2D and 3D CFD models for oil spill
  - Open channel wave boundary condition
  - Focused on shallow water waves – Dispersion of oil slick is more
- Wavelength, Amplitude and Current has decisive effects on oil dispersion and overall spill dynamics
  - Location, extent and thickness of oil film on sea surface
  - Wave and current break oil slick on surface and enhance oil mixing, hence slick thickness and spatial spread
- Next step to add other Complex Physics
Questions

Thank you very much