“Mechanism of Fluid-Mud Interactions under Waves”

Theory and Modeling

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Mechanisms of Wave Dissipation over Muddy Seabed

I. Direct Wave Interactions

II. Indirect Wave Interactions

III. Resonant Wave-Wave Interactions

IV. Shear Unstable and Turbulent Mud-Flow Interactions

V. Generalized Large-Scale Broad-Band Wave Mud-Bottom Interactions
I. Direct wave Interactions

Indirect Wave Interactions

Resonant wave-wave Interactions

Shear Unstable and Turbulent mud-flow Interactions

**Proposed Mechanisms:**
- Surface wave interaction with Newtonian (viscous) or non-Newtonian (visco-elastic/visco-plastic) mud flow
- Modeling the mud as a rough bottom of rigid; elastic; thin boundary layer; porous; or poro-elastic material

**Assumptions:**
- Linear or weakly nonlinear long waves
- Laminar mud flow
- Finite mud depth / thin mud depth / zero mud depth

**Proposed Approaches:**
- Asymptotic theoretical analysis
- Direct wavefield simulations with physics-based wave dissipation models
I. Direct wave Interactions

II. Indirect Wave Interactions

Resonant wave-wave Interactions

Shear Unstable and Turbulent mud-flow Interactions

**Proposed Mechanisms:**
- Resonant or near-resonant interactions of long and short waves
- Long wave generation associated with radiation stress
- Dissipative interaction of long wave with mud bottom (mechanism I)
- Short wave attenuation via long-short wave interactions

**Assumptions:**
- Nonlinear water waves
- Laminar mud flow
- Finite mud depth / thin mud depth / zero mud depth

**Proposed Approaches:**
- Asymptotic theoretical analysis
- Direct wavefield simulations with physics-based wave dissipation models
I. Direct wave Interactions

II. Indirect Wave Interactions

III. Resonant wave-wave Interactions

Proposed Mechanisms:
- Resonant interaction of surface waves, mud waves, and/or wavy mud bottom

Assumptions:
- Nonlinear water waves, mud waves and wavy mud bottom
- Low mud concentration
- Laminar mud flow

Proposed Approaches:
- Asymptotic theoretical analysis
- Direct multi-layer wavefield simulations
Proposed Mechanisms:
- Shear flow instability of water-mud interface
- Water wave interaction with turbulent mud flow

Assumptions:
- Low mud concentration
- Turbulent mud flow

Proposed Approaches:
- Stability analysis of shear mud flow
- CFD using direct numerical simulations (DNS) and large eddy simulations (LES)
- Coupled direct wavefield simulations with CFD mud flow
MURI Theory & Modeling

Perturbation Theory $O(\lambda/\varepsilon^n)$
- Cross validation
- Shear instability characteristics
- Parameter for simulations

Direct Wavefield Simulation $O(100\lambda)$
- Cross validation
- Interfacial boundary conditions
- Parameters for simulations
- Dissipation model development

DNS/LES $O(\lambda) \sim O(10)\lambda$
- Kinematic and dynamic boundary conditions on interface
- Mud energy dissipation for wavefield simulation

Laboratory Experiments $O(10\lambda)$ / Field Measurements $O(100\lambda)$
- Mud properties
- Range of validity of assumptions
- Guidance for lab/field setup and measurements
- Cross validation

- Mud properties
- Initial/boundary conditions for wavefield simulations
- Guidance for lab/field setup and measurements
- Validation and cross validation
- Parameterization of wave dissipation models

- Mud properties
- Shear/turbulence mud flow characteristics
- Validation and cross calibration
Assumptions:
- Weak nonlinearity
- Laminar mud motion
- Shallow → thick mud layer depth
- Long → intermediate mud wavelengths
- Narrowband → broadband mud waves
- Horizontal → sloping bed
- Visco-plastic mud flow

Long wave attenuation over muddy seabeds
— Rate of energy decrease:

\[
\frac{h}{H} \ll 1, \quad \frac{\delta_m}{h} \ll 1; \quad kA \ll 1, \quad kH = O(1)
\]

\[
\frac{\tau_{fl}}{H} \frac{\partial U}{\partial t} = O\left(\frac{f A}{2 H} \left(1 - \frac{u_m}{U}\right)^2\right) \ll 1
\]

\[
\frac{d}{dx} \left(\rho g A^2 C_g\right) = -(D_I + D_Y + D_b)
\]

\[
D_Y = \tau_o \frac{\partial u_b}{\partial y}
\]

\[
D_b = \mu \int_{-h}^{-h+\gamma} \left(\frac{\partial u_b}{\partial y}\right)^2 \, dy
\]

Liu & Mei 1987
CFD (DNS & LES) Simulations of Fluid-Mud Interactions under Waves

Objectives:
• physical understanding of vortical and turbulent mud flow structure and statistics under waves
• identify and quantify turbulent dissipation processes in mud flows; develop dissipation models for direct wave simulation
• direct comparison and cross calibration and validation of CFD with measurements and other theories

Approach:
• DNS and LES of vortical & turbulent mud flow
• non-Newtonian inhomogeneous mud properties
• coupling of mud flow with surface wave motion across lutocline
• inclusion of mud concentration transport

Expected outcomes:
• detailed flow and mud concentration descriptions
• CFD-based research tool for vortical and turbulent mud flow mechanisms
• parameterization of mud dissipation models
Simulation and Modeling of Nonlinear Water, Mud Layer and Mud Bottom Wave-Wave Interactions over Large Scales

- Direct phase-resolved simulations
- Physics-based modeling of wave dissipation by mud bottom guided by asymptotic theories and CFD for the mud layer
- Evolution of large-scale broadband wavefield propagating over muddy seabed utilizing parallelized HPC computations
- Validation, cross-calibration and parameterization of dissipation modeling by direct quantitative comparisons to laboratory experiments and field measurements
- Development of efficacious dissipation models for phase-averaged wavefield prediction tools (such as SWAN)

Close-up of rogue wave evolution in a large wavefield of 30km × 30km
ONR Mud/MURI Kick-off Meeting, Baltimore, January 15, 2007

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Theory and Modeling

- Development of Perturbation Theories for Wave Dissipation Over Fluid Mud (Chiang Mei)
- CFD (DNS & LES) Simulations of Fluid-Mud Interactions under Waves (Lian Shen)
- Simulation and Modeling of Nonlinear Water, Mud Layer and Mud Bottom Wave-Wave Interactions over Large Scales (Yuming Liu)