CROCO Sediment dynamics: From regional to nearshore problems

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From shelf-ocean exchanges ...

CROCO sediment transport off West Africa (Karakas et al., 2006)
... to surf-shelf exchanges
Imperial Beach, 29 September 2009: « rip current ejection events are the dominant cross-shore surf-shelf exchange mechanism » Hally-Rosendahl et al., JGR 2014

- How important?
- Processes: flow instability or flash rip?
- 2D, 3D, NH dynamics?
- Stratification? Rotation?
- Sediment processes?
WAVES (WKB, WW3)

Hs, T, Dir

DATA

WAVES
Boundary forcing and breaking parameters

SEDIMENTS
Sediment and bed properties

BOTTOM LAYER
Bottom stress due to waves and currents

SEDIMENT model
Deposition, erosion, suspended and bedload transport, bed evolution

ATMOSPHERE (WRF)

OCEAN CIRCULATION
Wave-averaged U,V,Tracer equations
The system is horizontal only, and 3D vectors are designated by \( \mathbf{x}, \mathbf{y}, \mathbf{z}, \mathbf{c}, \mathbf{D} \), and \( \mathbf{F} \). The barotropic momentum equation indicates \( \partial \mathbf{u} / \partial t + (\mathbf{u} \cdot \nabla) \mathbf{u} + w \frac{\partial \mathbf{u}}{\partial z} + f \hat{z} \times \mathbf{u} + \nabla \phi - \mathbf{F} = -\nabla \mathbf{K} + \mathbf{J} + \mathbf{F}^v \), where \( \phi \) is the sea-level component of the potential vorticity. The quasi-static sea-level component is defined by \( \xi = -p_{atm} / \rho_0 - A^2 k / 2 \sinh(2\mathbf{K}) \). The wave-averaged tracer diffusivity is defined by \( \mathbf{K} \).

The vertical component of the 3D Stokes velocity is \( \mathbf{V}_f = \mathbf{V}_f^c \mathbf{u} + \mathbf{V}_f^w \mathbf{w} \), where \( \mathbf{V}_f^c \) and \( \mathbf{V}_f^w \) are horizontal only, and 3D vectors are designated by \( \mathbf{x}, \mathbf{y}, \mathbf{z} \). The dots in the barotropic momentum equation indicate contributions from \( \mathbf{F} \) and \( \mathbf{J} \). This implies a superposition of the \( 2 \mathbf{V}_f \) and \( \mathbf{F} \).

The vortex force (including Stokes-Coriolis) is \( \nabla \times \mathbf{u} \). The Bernoulli Head is \( \mathbf{V}_f \cdot \mathbf{u} + w \frac{\partial \mathbf{u}}{\partial z} \). The non-conservative forces are\n
- acceleration due to breakers
- bottom friction and streaming
- vertical mixing

The Stokes advection is \( \partial \mathbf{c} / \partial t + (\mathbf{u} \cdot \nabla) \mathbf{c} + w w \frac{\partial \mathbf{c}}{\partial z} \). Quasi-static sea-level is \( \xi \).
USGS Sediment model
Blaas et al. (2007); Warner et al. (2008)

- Wave input (specified, WKB, or WW3)
- Wave-current combined bottom stress (Soulsby, 1995)
- Erosion (armoring), deposition, suspended transport
- Bedload transport and flux divergence
- Bed model (sand, mud, or mixed)
- Morphological evolution (with acceleration factor)
- Wetting and drying
- Positive-definite advection schemes (WENO, TVD)
- Sediment influence on density
Suspended transport
Blaas et al. (2007)

- Suspended sediment transported as a tracer with additional source/sink terms.
- Multiple sediment classes
- For each class: grain size, density, settling velocity, erosion rate, bed porosity, and critical shear stress for erosion

\[
\frac{\partial C}{\partial t} + \frac{\partial U_i C}{\partial x_i} = \frac{\partial}{\partial x_i} \left( K_H \frac{\partial C}{\partial x_{1,2}} + K_V \frac{\partial C}{\partial x_3} \right) + \text{Sources / Sinks}
\]

Erosion formulation
\[\text{Source} = E_0 (1 - \varphi) \frac{\tau_b - \tau_{ce}}{\tau_{ce}} \quad \text{when } \tau_b > \tau_{ce}\]

Deposition formulation
\[\text{Sink} = w_s \frac{\partial C}{\partial z}\]
Active layer thickness (Harris and Wiberg, 1997).

$$Z_a = k_1(\tau_W - \tau_c) + k_2 D_{50}$$

**Erosion.** ($\tau_b > \tau_c$)

Mix sediment from lower layers so that surface layer is at least $Z_a$ thick. Split bottom layer. Erode from surface layer.

$$\text{erosion} = \text{MIN} \left[ \frac{dt}{E_i*(1-\text{poro})*\text{frac}_i*(\tau_W/\tau_{c,i} - 1)} \right]$$

$$\rho_1*(1-\text{poro})*\text{frac}_i*Z_a + \text{dep}_i$$

**Deposition.**

Rule: create new layer if deposition $> 5$ mm (user defined). Mix surface layer to be at least $Z_a$ thick. Combine bottom layer.

$$\frac{\partial C_i}{\partial t} = -w_{ij} \frac{\partial C}{\partial z}$$
**MPM or Soulsby and Damgaard (2005):** Bedload transport due to combined asymmetrical waves and currents (with bed slope effects)

\[
q_{bl} = \Phi \sqrt{(s - 1)gD_{50}^3\rho_s}
\]

\[
\Phi_x = \max(\Phi_{x1}, \Phi_{x2})
\]

\[
\Phi_{x1} = A_2 \theta_m^{1/2} (\theta_m - \theta_{cr})
\]

\[
\Phi_{x2} = A_2 (0.9534 + 0.1907 \cos 2\phi) \theta_w^{1/2} \theta_m
\]

\[
+ A_2 (0.229 \Delta \theta_w^{3/2} \cos \phi)
\]

**Wave asymmetry parameter:**

\[
\Delta = \frac{\theta_{W,2}}{\theta_0}
\]

ratio between amplitude of second and basic harmonics of the oscillatory shear stress (from Stokes’ 2nd order theory)
MUSTANG (LeHir et al., 2011)
Mud and Sand Transport Modeling

Cohesive sediments:
- Flocculation
- Consolidation
Currents-sediment coupling

- Numerical treatment: volume and constancy preserving scheme
- Speed-up equilibration: morphological factor (Roelvink, 2006)
- Test case: Sand Bar formation (Roelvink & Stive 1989)
Morphodynamics
Warner et al. (2008)

- Currents-sediment coupling
  - Numerical treatment: volume and constancy preserving scheme
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![Diagram showing the interaction between waves, currents, sediment transport, and bed evolution with morphological feedback.]

Bed Evolution - 0h/12h/24h

No coupling
Currents-sediment coupling

- Numerical treatment: volume and constancy preserving scheme
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Morphodynamics

Warner et al. (2008)
REAL NEARSHORE CASES
Biscarrosse rip currents
Experiment 13-17 June 2007 (Bruneau et al., 2009)
Wave crest conservation with depth-induced and current-induced wave refraction (no diffraction and reflection) and conservation of wave action:

\[
\frac{\partial \mathbf{k}}{\partial t} + \mathbf{c}_g \cdot \mathbf{V}_\perp \mathbf{k} = -\mathbf{\tilde{k}} \cdot \mathbf{V}_\perp \mathbf{\tilde{u}} - \frac{k\sigma}{\sinh 2kD} \mathbf{V}_\perp D \\
\frac{\partial \mathcal{A}}{\partial t} + \mathbf{V}_\perp \cdot (\mathcal{A}_g \mathbf{c}_g) = -\frac{\epsilon^w}{\sigma}, \quad \epsilon^w = \epsilon^b + \epsilon^{wd} \\
\frac{\partial \mathcal{A}^r}{\partial t} + \nabla \cdot (\mathcal{A}^r \mathbf{c}) = \frac{\alpha_r \epsilon^b - \epsilon^r}{\sigma}
\]

Wave breaking dissipation (flow acceleration)

\[
\mathbf{c}_g = \mathbf{\tilde{u}} + \frac{\sigma}{2k^2} \left( 1 + \frac{2kD}{\sinh 2kD} \right) \mathbf{k}.
\]

The flow can be time-filtered for consistency with assumptions.
Church and Thornton 1993:

\[
\varepsilon_b = \frac{3\sqrt{\pi}}{16} \rho g f_B r^3 \frac{H_{\text{rms}}^3}{h} N \left[ 1 - \frac{1}{\left(1 + \left(\frac{H_{\text{rms}}}{\gamma h}\right)^2\right)^{5/2}} \right]
\]

where

\[
N = 1 + \tanh \left[ 8 \left(\frac{H_{\text{rms}}}{\gamma h} - 1\right)\right].
\]

Wave height-to-depth ratio \( \gamma = 0.3 \)

% of broken wave face \( Br = 1.3 \)
Biscarrosse beach: 2D vs. 3D models

Cross-shore current [cm/s]

Cross-shore current [m/s]

Local Time (day/hour)
Hoi-An AFD project (2016)
Protection against erosion
Saint-Louis, Senegal (AFD, 2018)
ECORS Truc-Vert 2008 experiment
Model intercomp., MEPELS (J. Chauchat)
Wave-resolving CROCO

Validation of wave breaking
(GLOBEX B2, Michalet et al., 2014)

SGS model: WENO + $k$-$\varepsilon$
Sediment dynamics formulations in wave-resolving model?

- Surfzone turbulence effect on sediment resuspension
- Sediment concentration effect on turbulence and bottom drag
- Formulations for resuspension, bedload transport, bottom drag ...
CONCLUSIONS

◆ CROCO provides 3D hydrostatic and non-hydrostatic solvers for problems from regional to nearshore dynamics

◆ Two sediment models are implemented and needs completion (e.g., cohesive sediments)
  ◆ USGS model & MUSTANG (community efforts)
  ◆ Need for common test case: COMODO-Sediments?