Coastal modelling of nearshore processes

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CREST Meeting (Ostend, 23-24/11/2017)
Outline

- Introduction
- Nearshore processes
- Process-based/reduced complexity models
- Applications with Telemac
- Present limitations
References

- SINBAD Project, 2013: Hydrodynamic and sand transport processes
- D.A. van der A., et al.: Large scale laboratory study of breaking wave hydrodynamics, JGR Oceans, March 2017
- Kirby, J.T. 2017: Journal of Marine Research 75, 263-300
- van der Westhuysen, 2012: Modeling near shore wave Processes, ECMWF Workshop
Introduction

Nearshore zone

→ Challenge for scientists
→ Strategic importance

✓ Major infrastructures
✓ Tourism activities
✓ Fishing industry
✓ Richness of wild life and habitat
Vulnerability of the coastal zone

Impact of climate change:
- sea level rise
- increased storminess

→ Substantial loss of shoreline over the next 20 years

2013-2014 Winter storms
- Severe damages due to flooding
- Major coastal erosion
Motivations

- **Accurate predictions** of hydrodynamic conditions (currents, sea level, waves), sediment transport rates and resulting morphodynamic evolutions are required.

- **Wide range of applications:**
  - Design of coastal structures and coastal protections
  - Estimation of the risk of coastal flooding and erosion

- Development of **coastal models** (~ 10 km/decades)

*Predict impact of natural hazards at the local engineering scale*
A wide range of processes ... interacting at different scales
Bathymetry induced wave transformation

- Refraction
- Diffraction
- Bottom friction
- Triad interactions

Breaking criteria

Wave energy dissipation
- Bore propagation
- Turbulence
- Long waves
- Longshore current
- Undertow

Wetting and drying
- Percolation
- Set up and overflow
- Surf beat
Depth-induced wave modifications

→ Modification of the group velocity
   ✓ Shoaling: increase of the wave height in the direction of wave propagation
   ✓ Refraction: modification of the wave orthogonals
   ✓ Diffraction: transfer of energy in the shallow area
   ✓ Reflection (partial or total) by a shoal, a beach or coastal structure
→ long waves generation

→ Non linear properties
   ➢ Energy transfer (triad interactions) → high energy
   ➢ Energy dissipation (bottom friction and breaking)
   ➢ Wave-current interactions

→ Wave-Induced currents
First-order linear wave theory

- Fundamental: basis of most existing coastal propagation models (TOMAWAC, SWAN, ...)
- Strictly valid for small amplitude waves and flat beds
  Irrotational flow
  \[ \delta = \frac{a}{h} \ll 1 \]
- Nonlinear properties (boundary layer, streaming, mass transport, radiation stresses) are derived from the linear wave approach

\[ \omega^2 = gk \tanh kh \]
\[ c^2 = gh \frac{\tanh kh}{kh} \]
\[ E = \rho g \frac{a^2}{2} \]
\[ c_s = \frac{1}{2} \left( 1 + \frac{2kh}{\sinh 2kh} \right) c \]

Shallow water

\[ \omega^2 = ghk^2 \]
\[ C_g = C = \sqrt{gh} \]
\[ E = \rho g \frac{a^2}{2} \]

\[ \mu = kh \ll 1 \]
Bottom friction (non breaking waves)

- Wave induced boundary layer
  - Orbital velocity at the bed
  - Amplitude of the orbital motion:
    \[ U_0 = \frac{a \omega}{\sinh(kh)} \]
    \[ A_0 = \frac{U_0}{\omega} \]

- Wave induced bottom shear stress
  - Intense friction at the bed:
  - Phase lag effects
  - Different regimes
  \[ \hat{t}_0 = \frac{1}{2} \rho f_w U_0^2 \]
  \[ \phi \approx 20^\circ - 30^\circ \]
  \[ f_c \left( \frac{A_0}{k_i}, \text{Re} \right) \]
Non linear waves theories

- Weakly non linear models: Boussinesq
- Fully non linear 3D RANS (Navier Stokes)
- LES, SPH...

- Sinusoidal 1st order: $\delta = \frac{a}{h} \ll 1$
- Asymmetrical Waves
- Cnoidal waves: $\delta \approx 0.1$
- Solitary waves: $\delta > 0.1$
- Breaking Turbulent bore

Telemac 3D

$h=10m\ a=2m\ T=60s$
Propagation of a wave over a shoal

Experiments by Dingemans (1997)

Test C: T=1.0s, Hs=4cm

LHS: Telemac 3D (red Dx=2.5 cm, Dt=0.0025s)
RHS: Boussinesq (Gobbi & Kirby, 1999)
Wave effect on the mean flow (WEC)

- Decomposition of flow variables:
  \[ x(t) = X + x_w(t) + x' \]

- Wave induced radiation stresses:
  \[ S_{xx} = \int_{-h}^{h} \rho u_w^2 \, dz + \int_{-h}^{h} (P - P_0) \, dz \]
  \[ S_{yy} = \int_{-h}^{h} \rho u_w v_w \, dz \]

- Wave induced mass flux: \( U_s = \frac{1}{\rho h c} \frac{E}{H} \)

- Return current: Undertow
- Surf zone (U=0.5-1m/s)

- Wave induced shear stress (BL streaming):
  \[ < u_w w_w > \]

Wave induced currents

Wave energy dissipation → Driving force for wave-averaged flows

→ Longshore currents
  Large current with max for waves at an angle of 45°

→ Set up/set down: large contribution to the risk of flooding/overtopping
  Maximum values for waves normal to the beach
  (see for example 3Way coupling with Telemac 2D)

→ Rip currents generated by variation of the set-up (irregularity in the bar position or edge waves (Quilfen PhD))

→ Surf beat
  - Influence of long waves increases in the surf zone
  - Reflection of long waves (standing waves)
  - Reflection not easily accounted for in phase-averaged models
Current effect on the waves (CEW)

- **Doppler effect:**
  - Wave energy flux is not conserved
  - Wave action:
    - W+C: Lengthening of the waves (W+C)
    - W-C: Wave steepening, breaking
      - Wave blocking
  - Current Shear: refraction

- **Wave + Current boundary layer**
  - Maximum bed shear stress and mean value are increased
  - Increase apparent bed roughness
Surf zone dynamics

- Breaking criteria
- Dissipation of wave energy
- Turbulence generation
Breaking criteria

- Breaker type depends
  - Spilling
  - Plunging
  - Surging

- Position of breaker line depends on:
  - bed slope $\beta$,
  - wave steepness

$$\xi = \frac{\tan \beta}{\sqrt{H_0 / L_0}}$$

$$H_b = \alpha h$$

$\alpha \approx 0.7 - 1.2$

From Svendsen, 2006
Surf zone – Energy models

*Most challenging for modellers and experimentalists*

- **Bore analogy**
  Transfer of energy from the waves to the roller
  (Svendsen, 1978, Battjes and Janssen, 1978)

- **Roller model**

\[
D_w = \frac{\alpha Q_o \sigma E_w}{\pi}
\]

\[
\frac{\partial E_w}{\partial t} + \frac{\partial E_w c_q}{\partial x} = -D_t - D_w
\]

\[
\frac{\partial E_r}{\partial t} + \frac{\partial (c_s E_r)}{\partial x} + \frac{\partial (c_s E_r)}{\partial y} = D_w - D_r - D_t
\]
Turbulence in the outer breaking

- Recent progress
  - Modelling: Boussinesq, SPH and LES models, 3D Navier Stokes) : Ting & Kirby, Ting(2006), ..
  - High quality data sets (SINBAD) → highly detailed description of turbulent processes in the surf zone

- Turbulence  in the transition zone
  - Spilling/plunging breakers
    - TkE: \[ k^2 = \langle u'^2 + w'^2 \rangle \]
  - Spilling: sharp gradient of tke
    - Development of coherent structures (horizontal eddies)
  - Plunging: strong vertical mixing
    - More intermittent k(t)
    - Turbulence hit the bed before reversal

Mocke, 2001
Data – plunging breakers

- **Detailed measurements**
  - Summer, 2014: flat bed
  - SINBAD 2017: barred beach
  - T= 4s H=0.85 (ADV, LDA data)

- **Bar effect**
  - Cross-shore variation
  - Undertow reaching 0.8 m/s
Reynolds stress $\rightarrow$ wave dominated

Turbulent Reynolds stress $\rightarrow< u'w' >$
$
\rightarrow$ generated at the surface
Shoreward of the bar
$
\rightarrow$ impact on the bed of the roller generate turbulence

Wave-related component $\rightarrow< u_w w_w >$
$
\rightarrow$ Dominant in the roller region
Wave effect on the mean flow

➢ Decomposition of flow variables:

\[ x(t) = X + x_w(t) + x' \]

➢ Wave induced stresses & radiation stresses

*Wave induced mass flux:* \( U_s = \frac{1}{\rho h c} E \)

→ Return current: Undertow
→ Surf zone (\( U = 0.5\text{--}1 \text{ m/s} \))

➢ Wave induced shear stress (Boundary layer)

\[ \langle u_w w_w \rangle \] (cf. Longuet Higgins, 1953)
Wave induced currents

- **Longshore currents**
  Large current with max for waves at an angle of 45 °

- **Set up/set down**: large contribution to the risk of flooding/overtopping
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- **Wave energy dissipation** → a driving force for wave-averaged flows
Wave interactions

- General representation of irregular

\[ \eta(x, y, t) = \sum_{i=1}^{N} \eta_i(x, y, t) = \sum_{i=1}^{N} a_i \cos \left[ k_i (x \sin \theta_i + y \cos \theta_i) - \omega_i t + \varphi_i \right] \]

- Variance density directional spectrum

\[ F(f, \theta) = \frac{1}{\rho g} E(f, \theta) \]

- Non-linear interaction between waves in the spectrum
  - No loss of overall energy
  - Transfer of energy to other frequencies

- Limits of phase-averaged models
  - Loss of phase information
  - Not suited for reflection/diffraction
  - Long waves

\[ \Rightarrow \text{Shallow water} \]
Sediment transport processes

- Influence of waves
  - Large increase of transport rates
  - Role of ripples

- Rippled/flat bed regimes
  - Quasi-steady/unsteady formulae

- Influence of wave breaking
Transport rates in W+C

- Rippled regime
- Unstationary formulae (Dibajnia and Watanabe, 2003)
  - Wave asymmetry
  - Phase lag effects

References: SEDMOC, SANTOS, Davies and Villaret 2003, Van Rijn, 2007
Comparison of ‘Research’ models (TkE) and practical sand transport predictors with SEDMOC data base

- Bijker
- Bagnold-Bailard
- TRANSPOR’93
- Dibajnia-Watanabe
- SEDFLUX
- Soulsby Van Rijn

Accuracy with prescribed bed roughness

- by factor about 3 for plane beds
- by factor 50-200 for rippled beds

With bed roughness predictor

- by factor about 2 for plane beds
- by factor 10 for rippled beds
SANTOS model

Extension of the DW unstationary model
To account for wave non-linearity

Mean flow transport
Phase lag effects dominant

\[
\bar{Q} = \frac{\alpha \bar{T}^{\gamma}}{W_{D_{50}}} 
\]
Effect of breaking waves

- **Breaker zone:** Plunging jets and turbulence
  - high increase in the suspended sediment load
- **Inner surf zone:** High level of turbulence
  - Sediment advection/diffusion
- **Transport of kinetic energy is expected to be similar to transport of sediments** (Ting and Kirby, 1996)

\[ Q_k = \langle u(t)k(t) \rangle \]

- Plunging breaker (RHS)
  - Phase lag effects dominant: $\rightarrow$ Net onshore transport $Q_k > 0$
- Spilling breaker (LHS)
  - Undertow dominant $\rightarrow$ Net offshore transport $Q_k < 0$

- **Modification of transport formulae**

  $\rightarrow$ account for the effect of breaking waves & increased diffusion (Camenen and Larsen, 2008, SINBAD project)

Coherent vortices plunging breakers (SPH, Fahrani 2012)

TKE under spilling (NHWAVE, 2015)
Scenarios
- Extreme events
- Sea level

Coastal model

Empirical rules
- Input parameters
- Accuracy?

Shoaling
- Wave generation
- Wave-wave interactions
- Surges
- Tides
- Wind

Surf zone
- Refraction
- Shoaling
- Depth induced breaking
- Water level

Swash zone
- Overtopping
- Overflowing
- Breaching

Offshore
Nearshore
Shoreline response
Flood inundation

Domestic physical processes

Receptor
Reduced complexity/conceptual models
- parameterization of small scale processes
- Large scale/long term evolution

→ useful for **global understanding**
  (even if results are incorrect)

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<th>Process-based model</th>
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<td>- Coupling of models</td>
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<tr>
<td>- Downscaling methods</td>
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</table>

→ useful for **predictive purposes**
  (even if interactions are incorrect)

Research models
- Navier_Stokes, LES, SPH ...

<table>
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<tr>
<th>Detailed processes</th>
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<td>→ CPU limitation</td>
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(Coastal Evolution Model, cf. Murray 2007)

Ex. Mike 21, Delft 3D, Roms, Telemac ...

(cf. Dalrymple, Christensen, 2005)
Wave Propagation models

- **Spectral wave models**
  - Stationary mode (COWADIS, HISWA)
  - Third generation mode
  - **TOMAWAC, SWAN, WAM**

  \[ \Delta x \gg L \text{ and } \Delta t \gg T_p \]

  Suitable for large scale models

- **Phase resolving models for detailed representation**
  - **Artemis model** – solves the Berkhov equation
  - Boussinesq model – see a review in Kirby, 2017
  - Telemac 3D – Navier Stokes equations (non hydrostatic)

  \[ \Delta X \ll L/10 \text{ and } \Delta t \ll T_p/10 \]

  Suitable local scale models
Coastal Modelling using Telemac

- Method of finite element system and internal coupling of different modules/Nesting

- 3 way coupling between Telemac-2D/Tomawac/Sisyphe through radiation stresses

- ST Processes (wave effects included) and W+Cinteractions (Davies and Villaret, CS 2003)

- Bed roughness predictor to ensure consistency between Flow and ST calculations

Examples: the Dee estuary (Bangor), the Somme estuary (CETMEF), Britany rip currents
Nesting/coupling models

Imposed Water levels and velocities
TELEMAC-2D COASTAL APPLICATIONS
Long shore transport: Newhaven harbour
Sedimentation in Newhaven harbour
Longshore currents

⇒ Littoral current: large transport rates in the direction parallel to the shore (CERC formula, Komar and Inman, 1970)

⇒ Erosion upstream and deposition downstream of dikes

⇒ 3-WAY coupling Telemac-2d/Tomawac/Sisyphe
Influence of bed roughness preditor (Sisyphe)

Set-up/Set-down

Longshore transport
Rip currents at low tide – La Palue

Lostmarch’h beach:
- length: 590 m
- $a/C_l = 0.45$
- mean slope: 1.9 %

La Palue beach:
- length: 1390 m
- $a/C_l = 0.16$
- mean slope: 1.7 %
- small island in the southern intertidal zone

PhD V. Quilfen, 2016
Long term evolution of tidal inlet

(TUC, 2015)

- Schematic representation
  - $L = 12\text{ km} \times 16\text{ km}$ – inlet width = 2 km
  - Mesh size 100 m
  - $H = 4\text{ m}$ offshore – tidal range = 1 m

- Development of channel patterns over decades
Still missing in Telemac

- No Cross-shore processes in 2D (undertow, Roller, mass transport)
- No coupling between Telemac-3D/Tomawac
- PhD of Theles not included in the final
- Wave effect in the surf zone?
- Swash zone

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<tr>
<th>Physical process</th>
<th>TELEMAC</th>
<th>XBeach</th>
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<td><strong>Waves</strong></td>
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<td>Breaking</td>
<td>☒ (Roelvink)</td>
<td>☒ (Roelvink)</td>
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<tr>
<td>Bottom friction</td>
<td>√</td>
<td>√</td>
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<tr>
<td><strong>Roller</strong></td>
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<td>Stokes drift</td>
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<td>Bound long wave</td>
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<td><strong>Currents</strong></td>
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<td>Bottom friction</td>
<td>☒ (Strickler variable in space)</td>
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<td>Turbulent mixing</td>
<td>☒ (Elder model)</td>
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<td>Uncovered beds</td>
<td>☒ (masking of exposed elements)</td>
<td>☒ (Stelling et. Duinmeijer)</td>
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</table>
Accuracy of predictions in the nearshore zone?
Uncertainty analysis

First-order second method (FOSM)
- Assume first order Taylor expansion
- Independent input variables

Algorithmic Differentiation (AD)
- Partial derivatives
  - Chain rules and local differentiation
- Machine accuracy

AD generated Tangent Linear Model (TLM) of TELEMAC-2D/SISYPHE
- AD-enabled NAG Fortran compiler (dco/fortran/adnag, 2013)
- Method developed by U. Aachen and BAW (6.2 release)
- TLM and Adjoint developed by LNHE (7.0 release)

(See also Villaret et al., Computers and Geoscience, 2015).
**TOMAWAC**
Battjes and Janssen (1978) breaker model

\[ D_{br} = -\frac{\alpha Q_b f_c H_m^2}{4} \]

\[ \frac{1 - Q_b}{\ln Q_b} = \frac{H_{ms}}{2H_m^2} \]

\[ h_m = \gamma d \]

Qb: probability of breaking

**Roelvink’s model (1993)**
The Roelvink’s breaking model [53] is based on the analogy with a hydraulic jump and on two types of wave height distribution in the breaking zone (Weibull or Rayleigh). The energy sink term is written according to the wave height distribution in the breaking zone:

\[ D_w = 2\frac{\alpha}{T_{rep}} Q_b F_w \]

\[ Q_b = 1 - \exp \left( -\left( \frac{H_{ms}}{H_{max}} \right)^\alpha \right) \]

\[ H = \sqrt{\frac{8F_w}{\rho g}} \]

\[ H_{max} = \frac{\gamma \tanh k h}{k} \]

**Bottom friction**

**Bows and Komen**

\[ Q_{bf} = -\Gamma \left( \frac{\alpha}{g \cdot \sinh (k d)} \right)^2 F \]

\[ \Gamma : \text{friction coefficient} \ G = 0.038 \ \text{m}^2/\text{s}^3 \]
THANK YOU!
Quasi-steady sand transport formulae

**BIJKER**

\[ Q_{sc} = b D_{50} \left( \frac{\tau_{ce}}{\rho} \right)^{0.5} \exp \left( -0.27 \left( \rho_s - \rho \right) g D_{50} \frac{\tau_{cwe}}{\tau_{cwe}} \right) \]

- **Advection term**

**SOULSBY-VANRIJN**

\[ Q_{tot} = A_s U \left[ \left( \frac{U^2}{C_D U_w^2} \right)^{1/2} - U_{cr} \right]^{2.4} \left( 1 - 1.6 \tan \beta \right) \]

\[ A_s = A_{sb} + A_{ss} \]

\[ u_{cr} = \begin{cases} 0.19 (D_{50})^{0.1} \log_{10} \left( \frac{4h}{D_{50}} \right) & \text{si } 0.1 \leq D_{50} \leq 0.5 \, \text{mm} \\ 8.5 (D_{50})^{0.6} \log_{10} \left( \frac{4h}{D_{50}} \right) & \text{si } 0.5 \leq D_{50} \leq 2 \, \text{mm} \end{cases} \]

- **Bed load**
- **Suspended load**
Sediment transport:

Effect of ripples:
- Ripples appear in the shoaling zone
- Washed out in the swash zone

→ Effect on the bed roughness & wave related Shields parameter

→ Modification of sediment transport processes
  - Plane Bed
  - Rippled bed

Vortex shedding & phase lag effects →

e.g. Swart, 1974
Camenen, 2000