Cross-Shore Sediment Transport for Modeling Long-Term Shoreline Changes in Response to Waves and Sea Level Change

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US Army Corps of Engineers
Long-Term Shoreline Changes

- Prediction of long-term shoreline changes is a key task in coastal management practice.

- Multiple physical processes drive shoreline changes: wave, wind, tide, storm, current, sea level change/subsidence, sediment properties, longshore/cross-shore sediment transport, human activities (structure installation, beach refill, beach recreation), etc.

- Shoreline changes induced by natural physical processes in general are highly irregular.

- **Probabilistic shoreline change prediction** is needed for best shoreline management practice for long-term protection purpose.

- **Uncertainty estimation** of shoreline changes is required for best shoreline erosion control management.
Shoreline Change due to Coastal Management Practices

- Construction or modification of inlets for navigational purpose
- Construction of harbors with breakwaters built in nearshore regions
- Beachfills (sand nourishment)
- Sand Bypass
- Sand Mining
- Dredging Material Disposals

Fig. Headland for Erosion Protection
Fig. Sand Bypass in Indian River Inlet, DE
Outline

- Importance of Long-Term Shoreline Modeling for Coastal Management Practices
- GenCade: USACE Shoreline Evolution Simulation Model
- Cross-Shore Sediment Transport in Shoreline Change Simulation
- Shoreline Retreat due to Sea Level Rise
- Validation of GenCade’s Cross-Shore Transport Modeling Capability:
  - CHL Field Research Facility (FRF) in Duck, NC
  - Fenwick Island, DE with inclusion of Beachfills
- Conclusions
GenCade: USACE Shoreline Evolution Simulation Model

- GenCade: A one-dimensional shoreline change model driven by longshore sediment transport, including modules for inlet-sand sharing, beach nourishment, structure effect, etc.

- Combines the engineering power of GENESIS with the regional processes capability of the Cascade model.

- Development began in 2009, GenCade Version 1 in SMS Ver. 11.1 was released in 2012 (Frey et al. 2012)

- Applications in US and other international coasts.

Top: Onslow Bay, NC (for SAW)
Bottom: Galveston, TX (Galv. Park Board)
Longshore Sediment Transport
- Energy Flux Method (CERC formula)

\[ Q = H_b^2 C_{gb} \left( a_1 \sin 2\alpha_b - a_2 \cos \alpha_b \frac{\partial H_b}{\partial x} \right) \]

\( H_b \): Wave Height at breaker line

\( C_{gb} \): Group speed at breaker line

\[ a_1 = \frac{K_1}{16(s-1)(1-p)1.416^{2.5}} \]

\[ a_2 = \frac{K_2}{8(s-1)(1-p)\tan \beta 1.416^{2.5}} \]

\( K_1, K_2 = \) empirical coefficients

Typically, \( 0.5K_1 < K_2 < 1.5K_1 \)

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Cross-Shore Sediment Transport vs Nearshore Wave Asymmetry and Nonlinearity

Contributors to Cross-Shore Transport:
- Sandy bar migration (on-offshore directions)
- Undertow due to storm waves (offshore)
- Orbital motion of small waves (onshore)
- Overwash and overtopping
- ...

Beach Profile Changes in Duck, NC (Birkemeier, 2001)

Figure. Near-bed orbital velocities for a wave (height $H=1.0$ m and period $T=8$ s) at four water depths. The positive sign denotes onshore direction.

Innovative solutions for a safer, better world
Cross-shore Sediment Transport due to Wave Asymmetry and Nonlinearity

Cross-Shore Transport Rate due to Velocity Skewness

\[ \phi = \frac{\alpha_D}{1-p} (Q_V + Q_C + Q_D) \]

\( \alpha_D = \) empirical parameters (=1~2), \( p = \) porosity of sediment

\( Q_V \) and \( Q_C \) are the net sediment transport due to waves and currents (Bailaid & Inman 1981, Hsu et al. 2006)

\[ Q_V = \frac{C_w}{(s-1)g} \left( \frac{\varepsilon_B}{\tan \varphi} \left< |\vec{U}_0|^2 U_{0,x} \right> + \frac{\varepsilon_S}{W_0} \left< |\vec{U}_0|^3 U_{0,x} \right> \right) \]

\[ Q_C = \frac{C_C}{(s-1)g} \left( \frac{\varepsilon_B}{\tan \varphi} \left< |\vec{U}_t|^2 U_x \right> + \frac{\varepsilon_S}{W_0} \left< |\vec{U}_t|^3 U_x \right> \right) \]

\( U_0 = \) wave orbital velocity vector,
\( U_t = \) the total velocity vector (waves plus currents), and
\( U = \) current velocity vector, related to longshore current and undertow current.

\( \varphi = \) friction angle
\( W_0 = \) sediment fall velocity
\( C_w, C_C, \varepsilon_B, \varepsilon_S = \) empirical parameters obtained by Fernández-Mora et al. (2015)

\( Q_D \) represents a diffusive transport due to downslope move of sand:

\[ Q_D = \frac{\lambda_D v \tan \beta}{\tan \varphi (\tan \varphi - \tan \beta)} \]

\( \lambda_D, v = \) empirical parameters
Calculation of Near-Bed Horizontal Orbital Velocity: An Asymmetrical Wave Shape Model

- Abreu et al. (2010) introduced a simple analytical expression for the free-stream near-bed horizontal orbital motion

\[
\tilde{U}_0(t) = U_w f \frac{\sin(\omega t) + \frac{r \sin \varphi_w}{1 + \sqrt{1-r^2}}}{1 - r \cos(\omega t + \varphi_w)}
\]

\[ r = \text{nonlinearity measure calculated by Skewness and Asymmetry parameters (Ruessink et al. 2012)} \]

\[ f = \sqrt{1-r^2} \]

Combination of mean current and orbital velocity

\[
\tilde{U}_0(t) = (U_{undertow} + \tilde{U}_0(t) \cos \theta)i + (U_{alongshore} + \tilde{U}_0(t) \cos \theta)j
\]

\( i \): cross-shore direction, \( j \)=alongshore direction

\( U_{undertow} \) = undertow current in cross-shore direction

\( U_{alongshore} \) =mean current alongshore
Shoreline Recession due to Sea Level Rise: Bruun Model (1962, 1988)

Shoreline Retreat rate

\[ R = \frac{SW_\star}{h_\star + B} \]

S: Sea level rise rate
\( h_\star \): sediment closure depth
\( B \): Berm Height

After Shand et al. (2013)
# Projected Global Mean Sea Level Change

— IPCC Representative Concentration Pathways (RCP) scenarios

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Radiative forcing in year 2100 relative to 1750 (W/m²)</th>
<th>Approximate carbon dioxide (CO₂)-equivalent concentration (ppm)</th>
<th>Median value and likely range of temperature change (°C)</th>
<th>Median value and likely range of sea-level rise (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RCP2.6</td>
<td>2.6</td>
<td>475</td>
<td>1.0 [0.3–1.7]</td>
<td>0.40 [0.26–0.55]</td>
</tr>
<tr>
<td>RCP4.5</td>
<td>4.5</td>
<td>630</td>
<td>1.8 [1.1–2.6]</td>
<td>0.47 [0.32–0.63]</td>
</tr>
<tr>
<td>RCP6.0</td>
<td>6.0</td>
<td>800</td>
<td>2.2 [1.4–3.1]</td>
<td>0.48 [0.33–0.63]</td>
</tr>
<tr>
<td>RCP8.5</td>
<td>8.5</td>
<td>1,313</td>
<td>3.7 [2.6–4.8]</td>
<td>0.63 [0.45–0.82]</td>
</tr>
</tbody>
</table>

A relative current SLR in DUCK, NC, 4.55 +/- 0.71 mm/yr, includes mean water level rise and subsidence, which is close to the case of RCP4.5, 4.7 +/- 0.31 mm/yr.

https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=8651370
GenCade: USACE Shoreline Evolution Simulation Model

- A one-dimensional shoreline change model driven by longshore sediment transport, including modules for inlet-sand sharing, beach nourishment, structure effect, etc.

- Combines the engineering power of GENESIS with the regional processes capability of the Cascade model.

- Development began in 2009, GenCade Version 1 in SMS Ver. 11.1 was released in 2012.

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Top: Onslow Bay, NC (for SAW)
Bottom: Galveston, TX (Galv. Park Board)
New Features of GenCade for Shoreline Evolution Model with Cross-Shore Transport and SLR

- Shoreline Change Equation with Sea Level Rise (SLR)

\[
\frac{\partial y}{\partial t} + \frac{1}{D_s} \left( \frac{\partial Q}{\partial x} - q - \phi \right) + \frac{R + S}{\tan \beta} = 0
\]

\( \phi \) : Cross-shore sediment transport rate

\( R \) : Sea Level Change Rate

\( S \) : Subsidence Rate

\( \tan \beta \) : beach slope

\( D_s = d_c + d_B(t) \) : Total closure depth

- Berm height varies with sea level change

\[
d_B(t) = d_{B0} - (R + S)t
\]
Model Validation: Shoreline Changes (1999-2005) at FRF, Duck, NC

- **Model Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d_c$ (m)</td>
<td>7.0</td>
</tr>
<tr>
<td>$d_b$ (m)</td>
<td>1.0</td>
</tr>
<tr>
<td>$d_{50}$ (mm)</td>
<td>0.2</td>
</tr>
<tr>
<td>$R+S$ (mm/yr)</td>
<td>4.55</td>
</tr>
<tr>
<td>$K_1$</td>
<td>0.40</td>
</tr>
<tr>
<td>$K_2$</td>
<td>0.25</td>
</tr>
<tr>
<td>$\Delta t$ (min)</td>
<td>3.0</td>
</tr>
<tr>
<td>$\Delta x$ (m)</td>
<td>20.0</td>
</tr>
</tbody>
</table>

Wave: Senso-Metric 8m Array  
Boundary Conditions: Pined  
Permeability of Pier = 0.6 (no diffracting):  
Parameters for Cross-Shore Transport  
Scaling parameter $\alpha_D$ = 1.50  
$C_w$, $C_C$, $\varepsilon_B$, $\varepsilon_S$ by Fernández-Mora et al. (2015)
Determining Shoreline Positions from FRF Survey Data of Beach Profiles

- Beach profile locations dating back to 1985 illustrating the cross-shore and temporal coverage
- 14 Survey groups (total 965 data surveys) based on projects

Representative beach profile coverage area along the FRF property.
CRAB = Coastal Research Amphibious Buggy
LARC = Lighter Amphibious Resupply Cargo

Bathymetric contour plot showing the relatively straight and parallel contours except in the vicinity of the pier.
Wave Data (2000/1/1 – 2006/1/1)

The wave measurements at the 8-m array during the six year study period (1999-2005) include a blend of low-energy periods and energetic storm conditions.

<table>
<thead>
<tr>
<th></th>
<th>H (m)</th>
<th>T (s)</th>
<th>alfa (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>0.82</td>
<td>9.18</td>
<td>-5.06</td>
</tr>
<tr>
<td>Min</td>
<td>0.14</td>
<td>3.09</td>
<td>-74.62</td>
</tr>
<tr>
<td>Max</td>
<td>5.28</td>
<td>18.96</td>
<td>111.32</td>
</tr>
<tr>
<td>σ</td>
<td>0.53</td>
<td>2.68</td>
<td>18.52</td>
</tr>
</tbody>
</table>

Wave Height

Wave Direction
Model Validation: Comparisons of Shoreline Positions (1999-2005)

Comparison of Shorelines on 10/27/1999

Comparison of Shorelines on 04/08/2004

Comparison of Shorelines on 06/28/2005

Comparison of Shorelines on 09/01/2005

Comparison of Shorelines on 09/21/2005

Comparison of Shorelines on 10/19/2005

RMSE(Φ)=4.43m

RMSE(Φ)=11.57m

RMSE(Φ)=6.39m

RMSE(Φ)=9.02m

RMSE(Φ)=7.79m

RMSE(Φ)=6.84m
Model Validation: (w or w/o xshore) Comparisons of Shoreline Changes (1999-2005)

- Comparison of Shoreline Changes on 10/27/1999: RMSE(Φ)=4.43m
- Comparison of Shoreline Changes on 04/08/2004: RMSE(Φ)=11.57m
- Comparison of Shoreline Changes on 06/28/2005: RMSE(Φ)=6.39m

- Comparison of Shoreline Changes on 09/01/2005: RMSE(Φ)=9.02m
- Comparison of Shoreline Changes on 09/21/2005: RMSE(Φ)=7.79m
- Comparison of Shoreline Changes on 10/19/2005: RMSE(Φ)=6.84m

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Predicted Cross-Shore Transport Rate ($\Phi$) (1999-2005)

(a) $\Phi$ vs Hs

(b) $\Phi$ vs $\alpha$ (angle)
Annual Cross-Shore Transport Rate

(1) Annual Average $\Phi$

(2) 6-year Average $\Phi$
Model Skill Assessment: Root-Mean-Square Errors at Observation Times (1999-2005)

Root-Mean-Square Error (RMSE) at each observation

\[ RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (m_i - O_i)^2} \]

\( m_i \): model values
\( O_i \): Observation data

Normalized Bias (NB) at each observation

\[ NB = \frac{1}{N} \sum_{i=1}^{N} \frac{(m_i - O_i)}{\sum_{i=1}^{N} |O_i|} \]
Model Validation (Impact of SLR)  
Comparisons of Shoreline Changes (1999-2005)
Modeling of Shoreline Change in Fenwick Island, DE with Beachfill Event

Objectives: (1) to validate the GenCade model by using shoreline survey data provided by NAP and DNREC, and (2) to evaluate shoreline erosion after beach fill completed in Sept. 2013.

Computational Parameters

- Computational Period: 3.5 years
  - 2013/07/13 0:00 - 2017/01/01 0:00
  - starting before the beach fill in Sept. 2013

- Beachfill $= 356,000\text{yd}^3$ Jul-Sept, 2013

- Time step = 3 minutes
- Grain size = 0.30 mm
- Berm Height = 1.0 m
- Closure depth = 10.0 m
- Smooth parameter = 1 (no smoothing)
- No regional contour
- Boundary Conditions: Moving (retreat 2.5 ft/year)
- Grid Size = 20 m
- Sea Level Rise rate: 4.50 mm/year (based on tide gauges)
- Subsidence: included

Calibrated Model Parameters:
- $K_1 = 0.90$
- $K_2 = 0.35$

- Cross-shore transport included
- Scaling parameter $a_D = 0.16$
- $C_{wp}, C_{C}, \epsilon_B, \epsilon_S$ by Fernández-Mora et al. (2015)
History of Shoreline Positions in Fenwick Island, DE

Beachfill = 356,000 yd$^3$
Jul-Sept, 2013

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Comparisons of Shoreline Positions on 09/13/2013 and 10/15/2016

Profiles of Shoreline Positions on 13-Sep-2013
- Initial
- Simulation
- Observation

Profiles of Shoreline Positions on 15-Oct-2016
- Initial
- Simulation
- Observation

Beachfill = 356,000yd³
Jul-Sept, 2013
Annual Longshore Sediment Transport Rate in Fenwick Island, DE
Annual Crossshore Sediment Transport Rate in Fenwick Island, DE
Conclusion

- One-line shoreline evolution model such like GenCade is an engineering application tool with a unique capability for making long-term prediction of shoreline changes in spatio-temporally varying conditions of waves and beach morphology. Inclusion of long-term signal driving net sediment transport alongshore and cross-shore is critical to improve one-long model predictability.

- GenCade’s new capabilities (Cross-shore sediment transport and SLR effect) are important in simulating shoreline evolution. Nonlinearity of wave dynamics plays an important role in estimating net cross-shore sediment transport.

- The values of empirical parameters ($C_w$, $C_C$, $\varepsilon_B$, and $\varepsilon_S$) which were calibrated in Duck coast, NC, by Fernández-Mora et al (2015) are appropriate for another Atlantic coast (e.g. the Fenwick Island coast in DE). Parametric cross-shore transport model is capable of estimating cross-shore transport rate in different coasts. So this parametric model is not site-specific.

- Further investigation of uncertainties by other factors (model parameters, boundary conditions, etc) is needed. As an ongoing research, we are developing a GenCade-Based Monte-Carlo simulation model for estimating shoreline changes probability and uncertainty.
References

Thank you for your attention!

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http://cirp.usace.army.mil/pubs/