Probabilistic Shoreline Change Simulation for Risk Estimation of Shoreline Erosion

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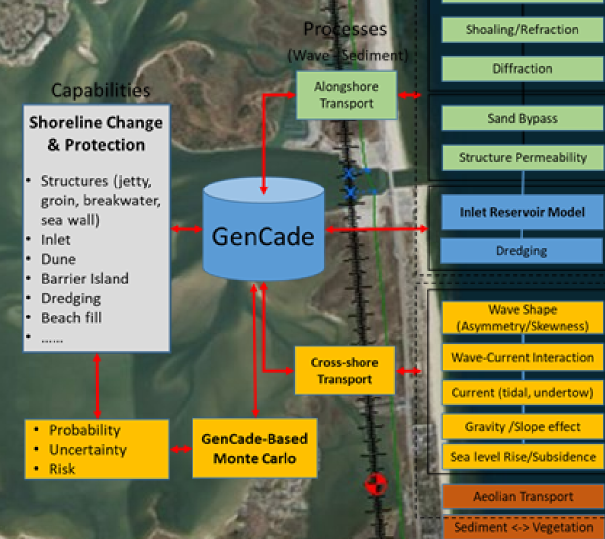

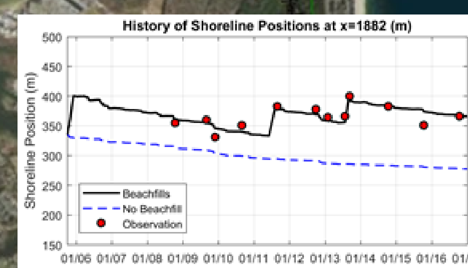

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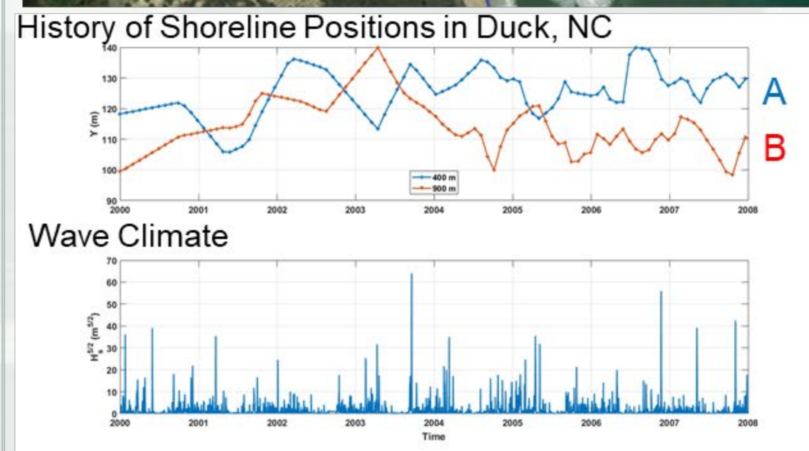
Outline

- Introduction: Motivation, Objectives, and GenCade
- GenCade-based Monte-Carlo Simulation for Risk Estimation of Shoreline Change
- Case Studies for Risk and Uncertainty of Long-Term Shoreline Changes
  - Idealized Coast
  - Duck coast at FRF, NC
  - Fenwick Island, DE (Uncertainty by Beach Fill)
- Remarks

Risk and Uncertainty in Long-Term Shoreline Changes

- Quantifying erosion risk and uncertainty in simulating long-term shoreline changes is an important task in risk-based 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**, etc.
- **Coastal development:** structure installation, beach refill, beach recreation, etc.
- Shoreline changes induced by natural physical processes in general are highly irregular. And uncertainty in coastal protection practice exists
- **Probabilistic shoreline change (Monte-Carlo) simulation** is an effective way to quantify risk and uncertainty of shoreline changes driven by physical processes and coastal protection practices.



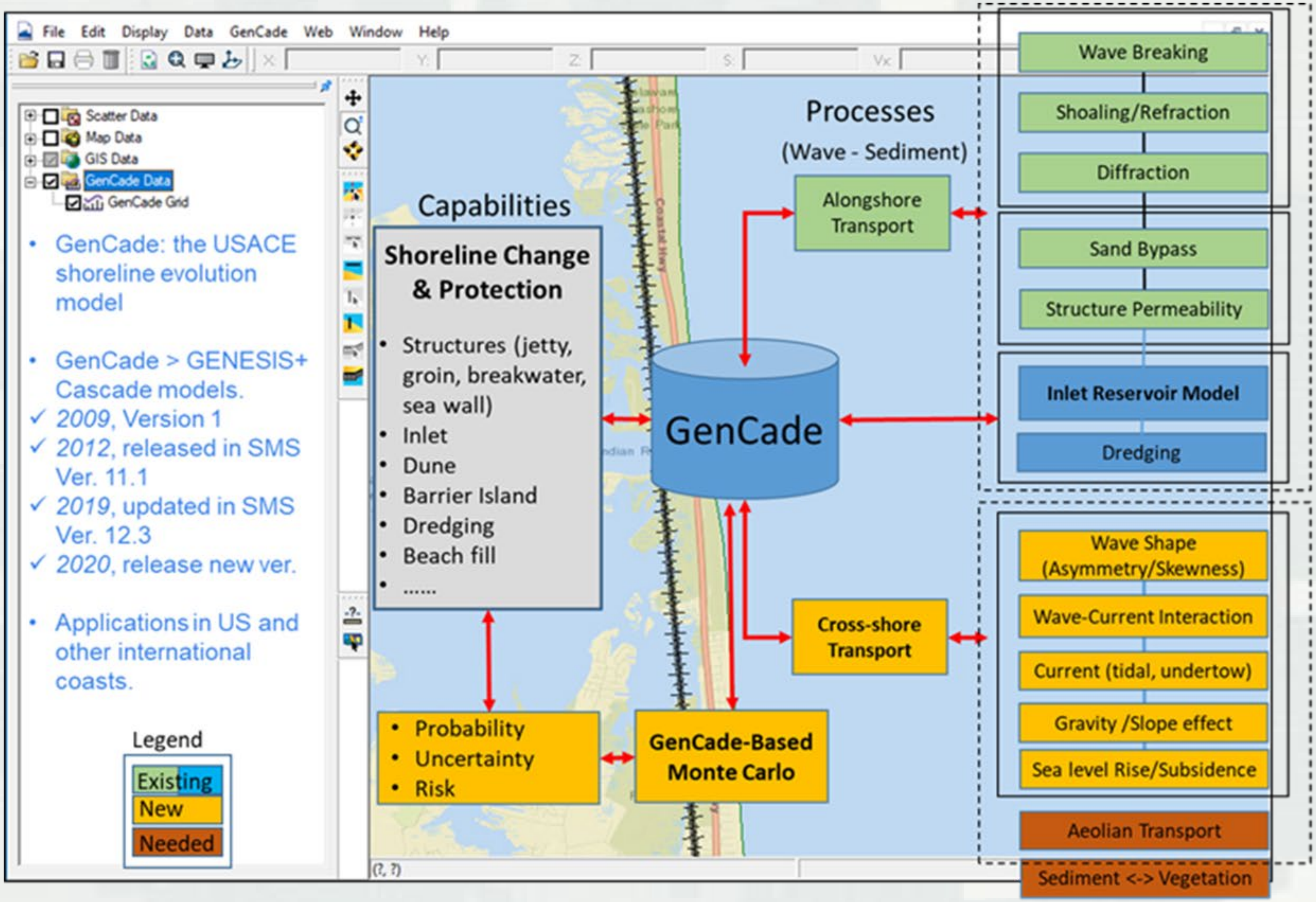
Uncertainties in Shoreline Changes due to Coastal Management Practices

- 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

GenCade for Simulating Shoreline Evolution



GenCade-Based Monte Carlo Simulation: Estimation of Uncertainty and Risk

$$p(x) = \begin{cases} R(x) & x \in [0, x_0) \\ \varepsilon W(x) & x \in (x_0, +\infty) \end{cases}$$

Random Signals (e.g. Waves)

GenCade

Statistic Analysis

- Maximum Likelihood Estimation

Input wave conditions for setting up the probability density functions, i.e. wave heights, periods, angles

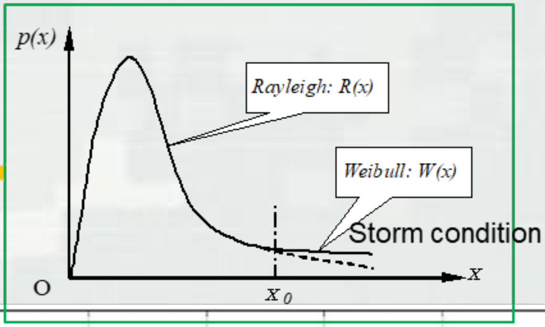
Generate time series of wave heights and angles based on probability density functions (pdfs)

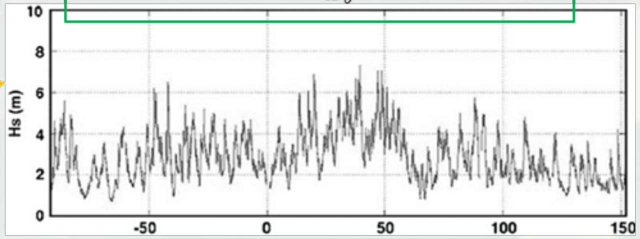
Simulation of shoreline changes by the one-line model, GenCade

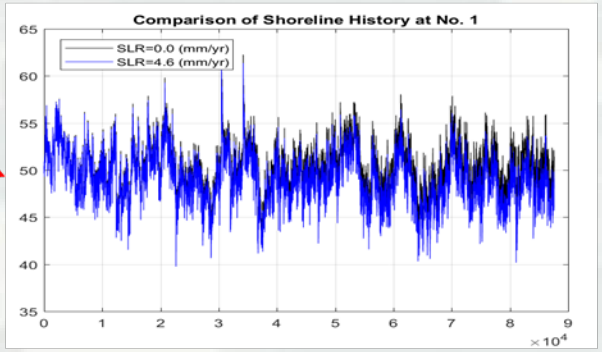
Repeat N times

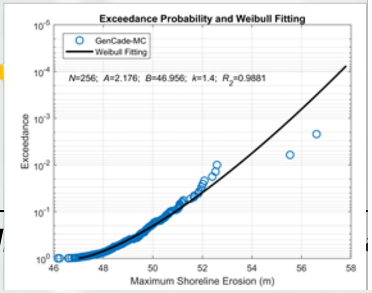
Statistic analysis of shoreline changes

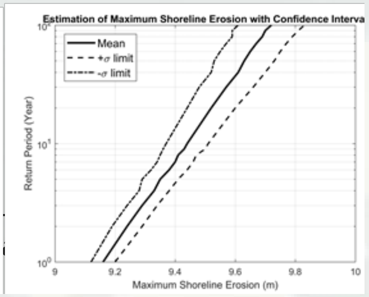
Stop







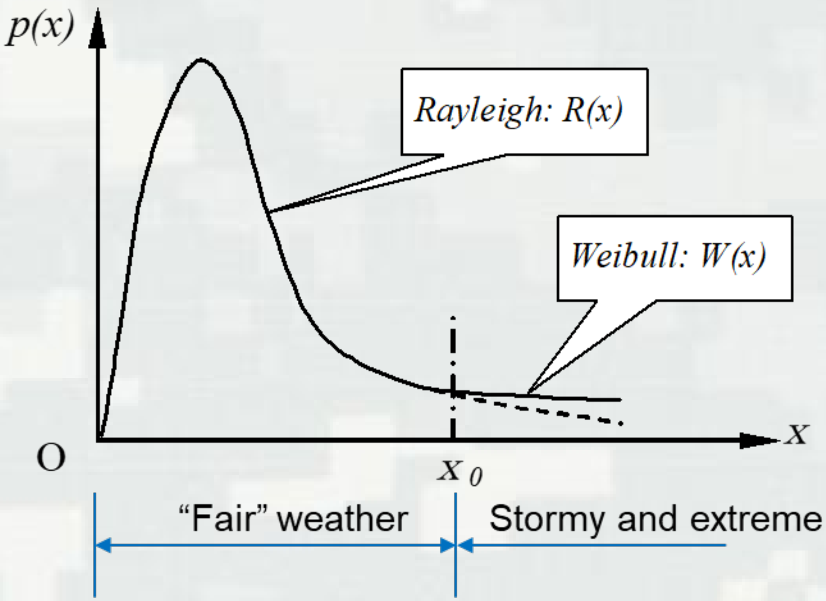




The more test samples (N), the better statistic results

Generate Random Wave Signals Using Probabilistic Density Function (PDF) of Wave Height

Consider waves in "fair" weather and storms:
Non-Gaussian PDF with a fat-tail shape



$$\int_{-\infty}^{+\infty} p(x) = 1 \;\Rightarrow\; \varepsilon = \frac{e^{-\frac{\pi}{4}x_0^2}}{e^{-(\frac{x_0-B}{A})^K}}$$

$$p(x:\varepsilon,R,W) = \begin{cases} R(x) & x \in [0, x_0) \\ \varepsilon W(x) & x \in (x_0, +\infty) \end{cases}$$

where $x = {}^{H}/_{\overline{H}}$, $\overline{H}$: mean wave height
ε: parameter
x_0: a truncated extreme value of wave height

Rayleigh Distribution (for normal waves) :

$$R(x) = -\frac{\pi}{2} x \exp\left(-\frac{\pi}{4}x^2\right) \qquad x \le x_0$$

Weibull Distribution ("fat-tail" for extreme waves):

$$W(x:k,A,B) = \frac{1}{k}\left(\frac{x-B}{A}\right)^{k-1} \exp\left(-\left(\frac{x-B}{A}\right)^k\right)$$

$$x > x_0$$

How to Determine the "fat-tail" PDF? Wave Observation Data: An Example

Density distribution of wave height is fitted as mixing distribution of Rayleigh and Weibull distributions

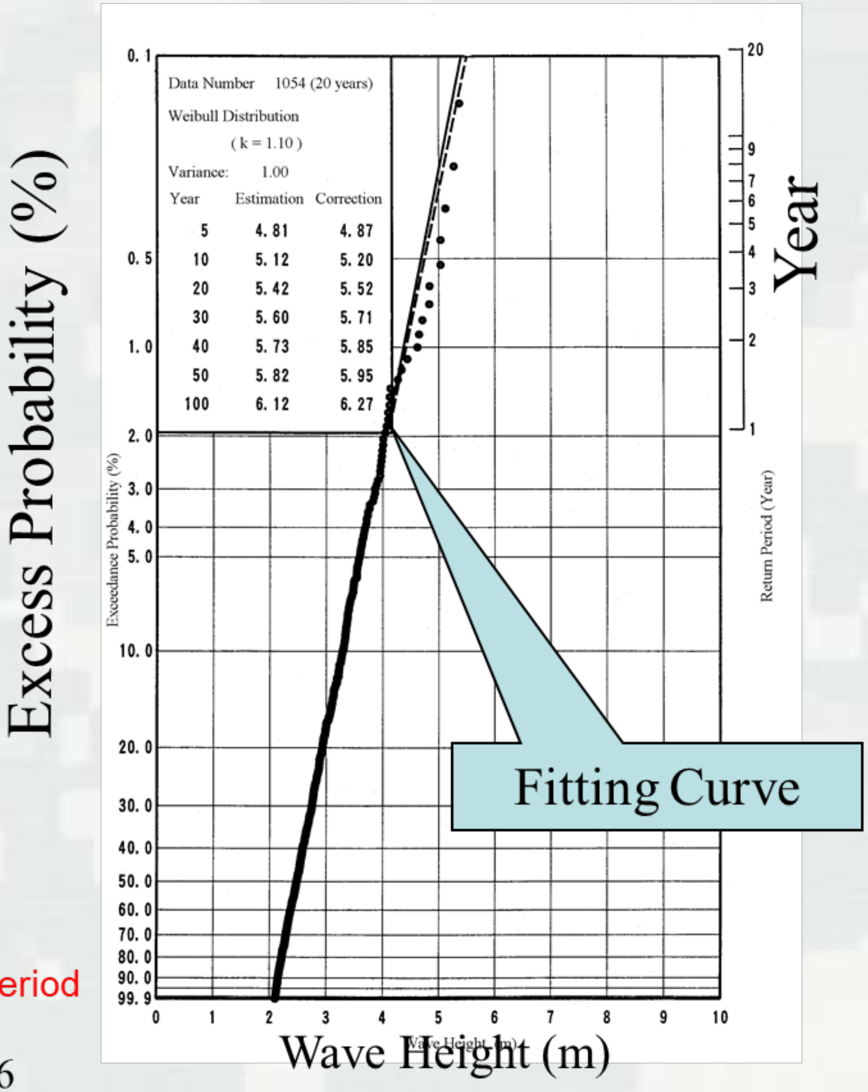
$$p(x) = \begin{cases} R(x) & x \in [0, x_0) \\ \varepsilon W(x) & x \in (x_0, +\infty) \end{cases}$$

where $x = H / H_{mean}$,
in $W(x)$, $k = 1.1, A = 0.5792, B = 2.0554, x_0 = 2.1$

$\bar{H} = 1.19$ m

Observation data: H=4.0 m wave height for one-year return period

Observation data at Naka Port, Japan, from 1980 to 1996



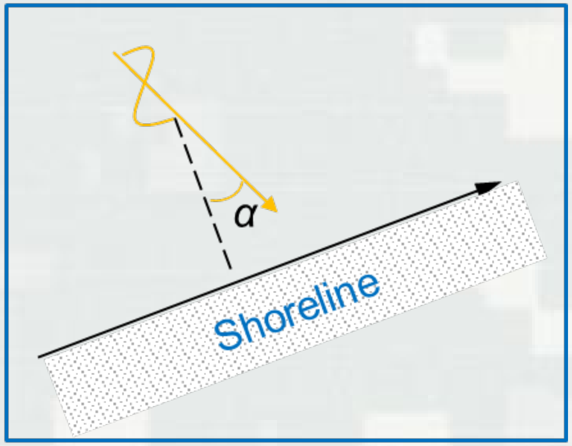
Wave Direction and Period

Incident Wave Angle (α): Gaussian Distribution

$$p(\alpha) = N(\alpha \mid \mu, \sigma) = \frac{1}{\sqrt{2\pi\sigma}} \exp\left(-\frac{(\alpha-\mu)^2}{2\sigma^2} \right) \qquad \alpha \in [-\frac{\pi}{2}, +\frac{\pi}{2}]$$

σ: Standard deviation of wave direction

μ : Mean value of direction



Significant Wave Period: based on Pierson-Moskowitz Spectrum

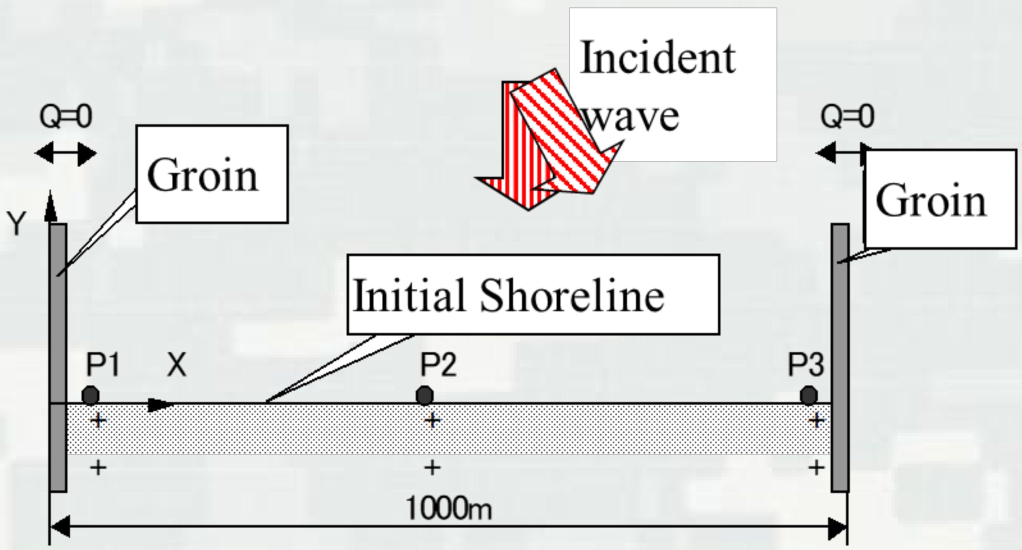
$$T_s = 5\sqrt{H_s}$$

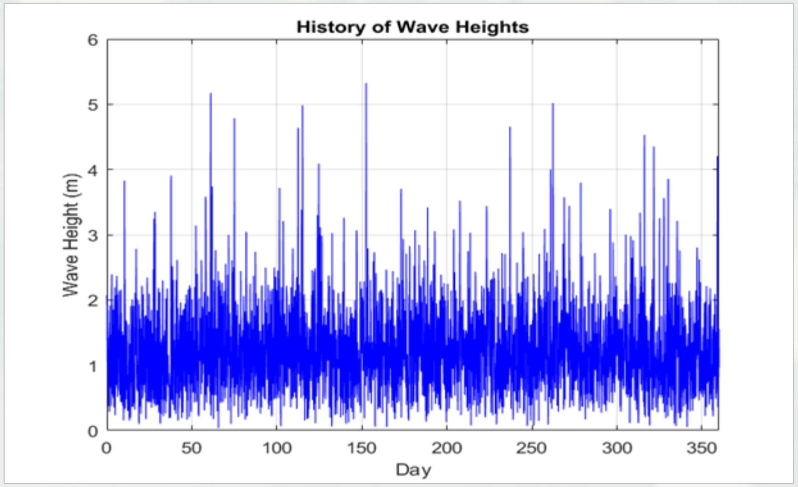
Probabilistic Shoreline Change Modeling in an Idealized Coast: Sensitivity Study

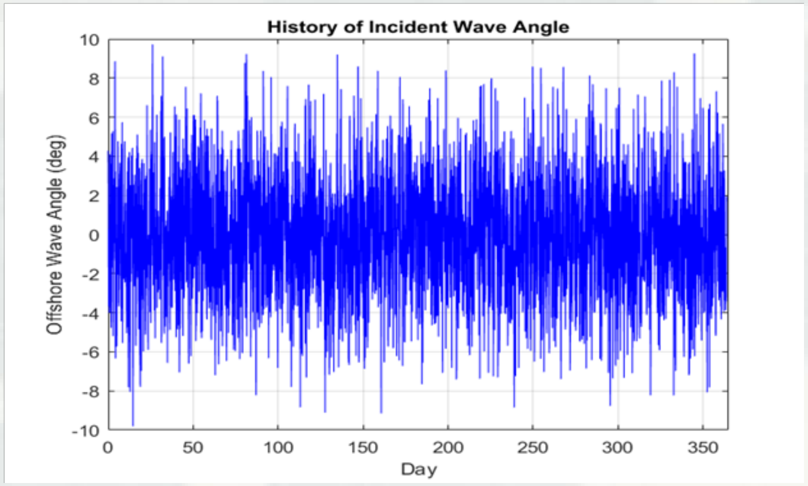
Two Test Cases:

(1) Case 1 (α_{mean}=0.0°)

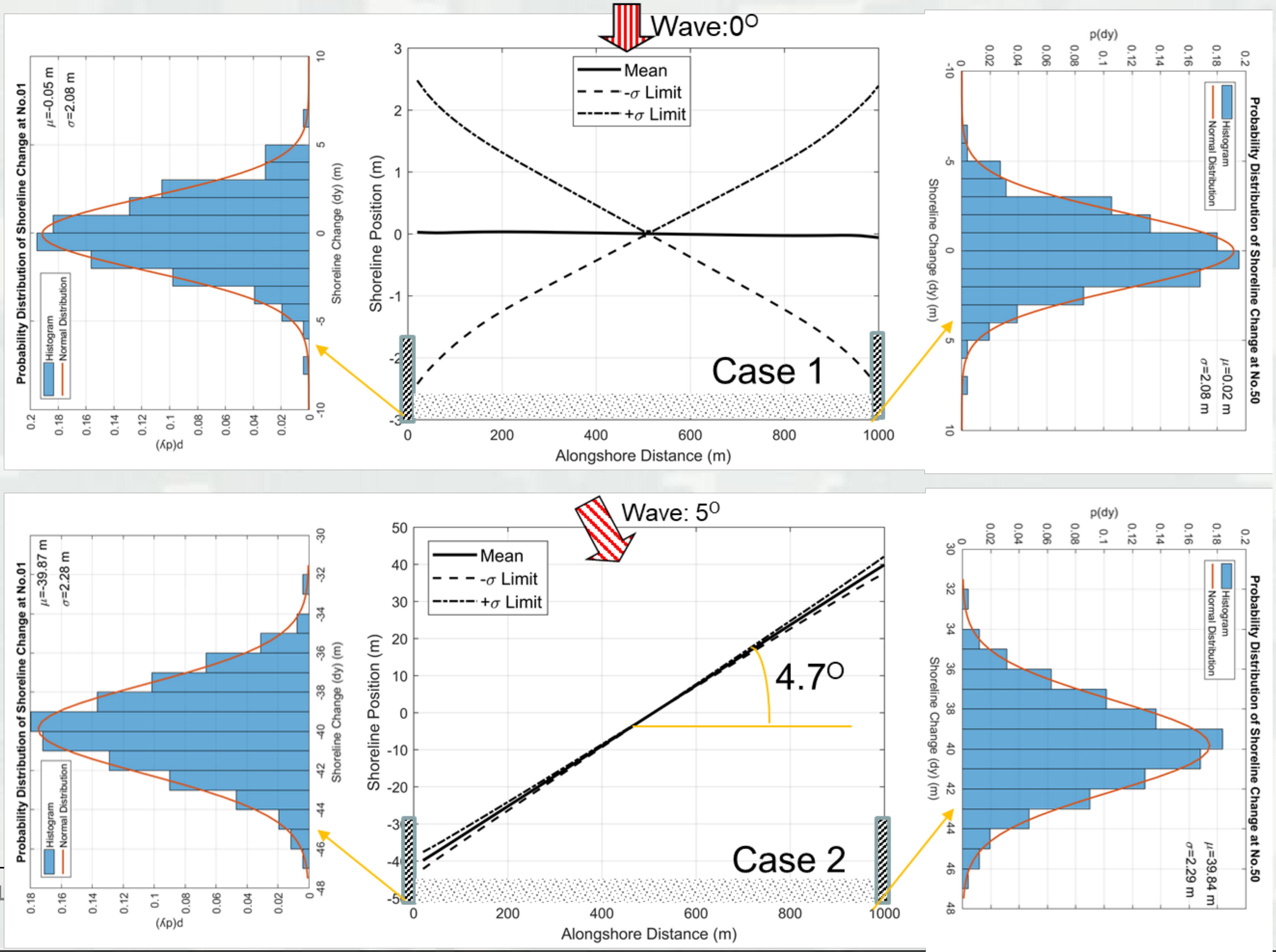
(2) Case 2 (α_{mean}=5.0°)





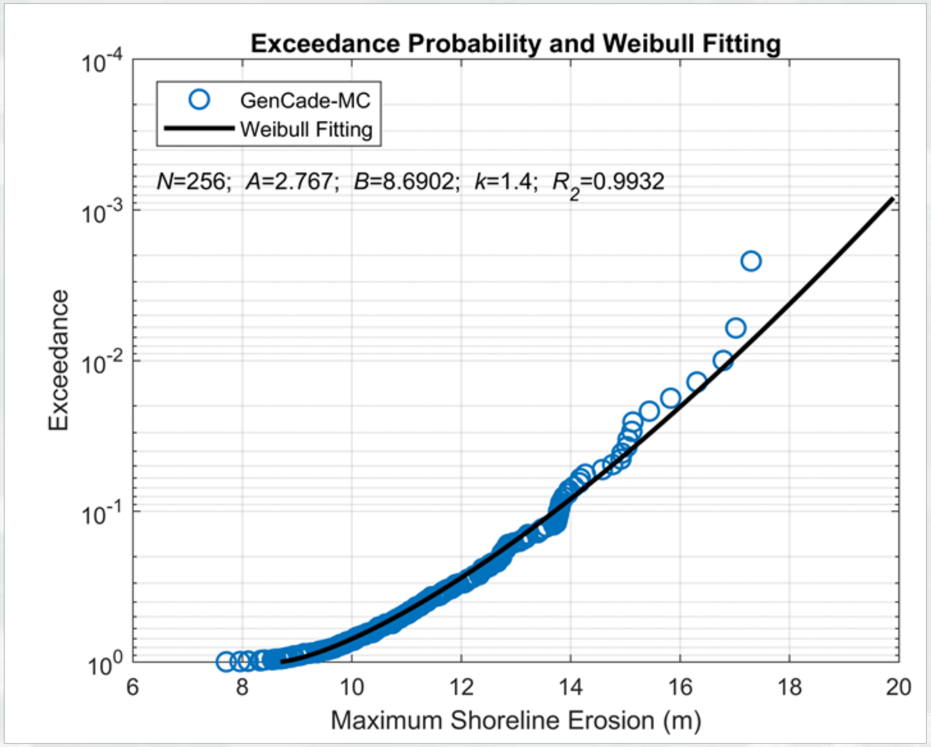


Predictions of Mean Shoreline Changes after 10 Years

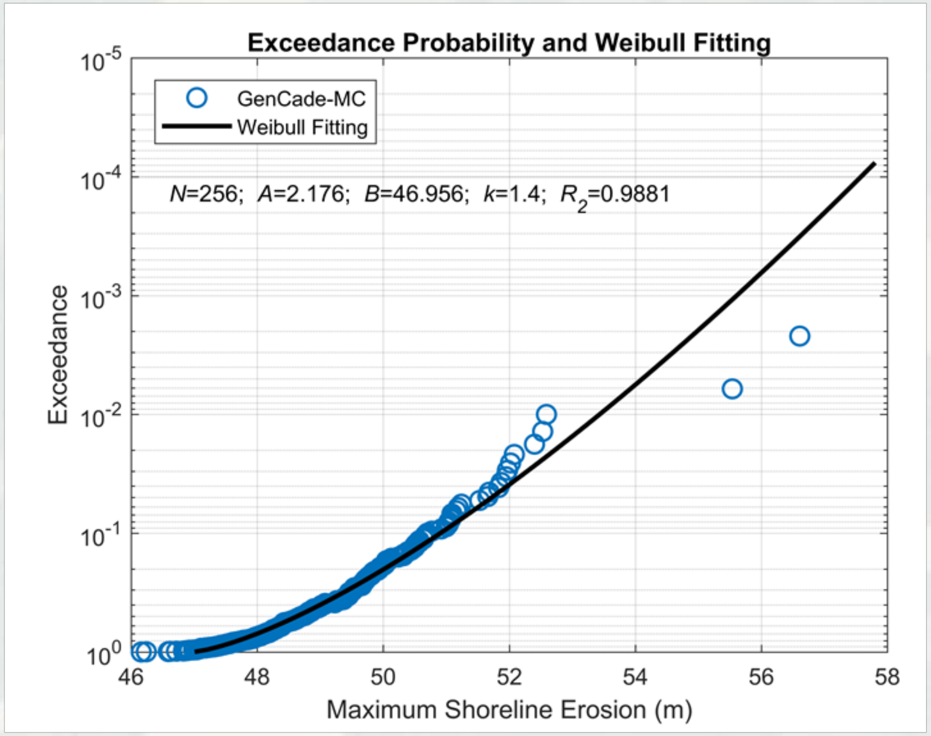


BUIL

Estimation of Maximum Shoreline Erosion (Landward most) in the Future: Maximum Likelihood Estimation



(1) Case 1 (α_{mean}=0.0°)



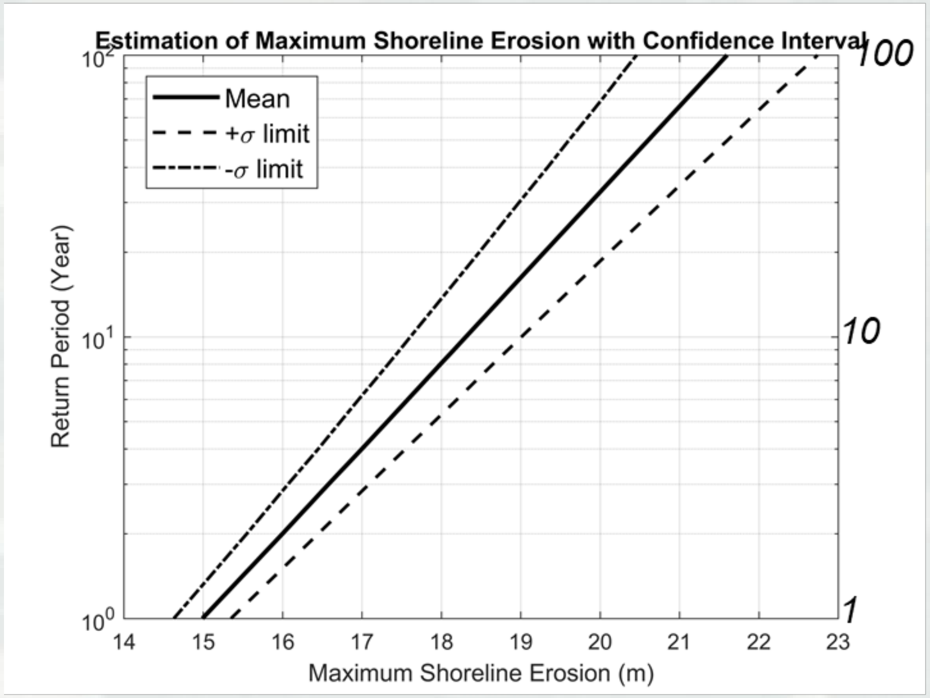
(2) Case 2 (α_{mean}=5.0°)

Weibull Function Best Fitting

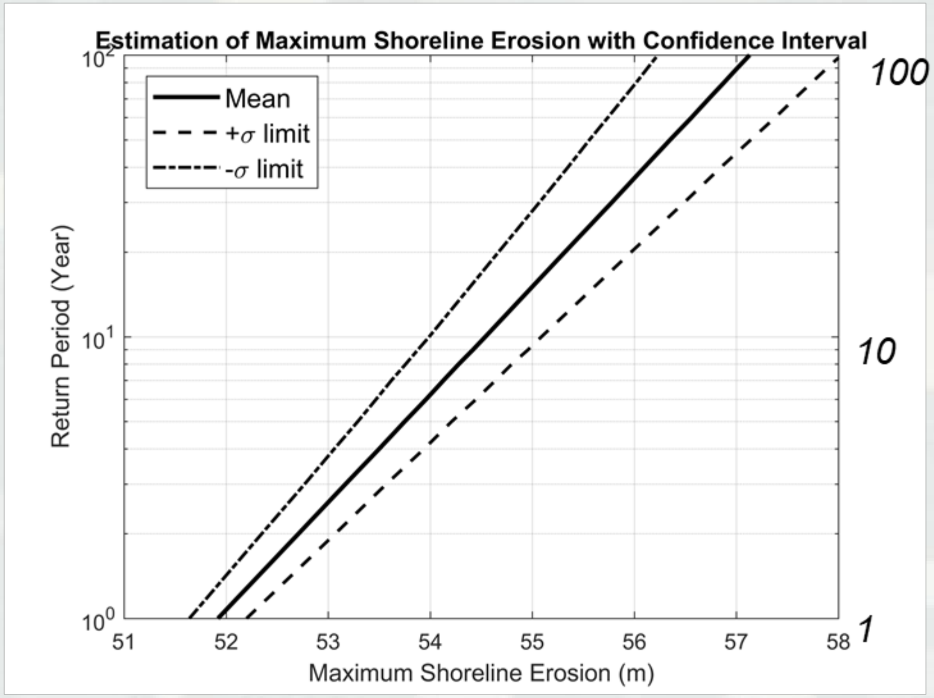
$$F(\Delta y) = 1 - \exp\left[-\left(-\frac{\Delta y - B}{A}\right)^k\right]$$

(k=0.75~2.0)

Prediction of Maximum Shoreline Erosion (Landward most) near Groin - Maximum Erosion in the Future



(1) Case 1 (α_{mean}=0.0°)

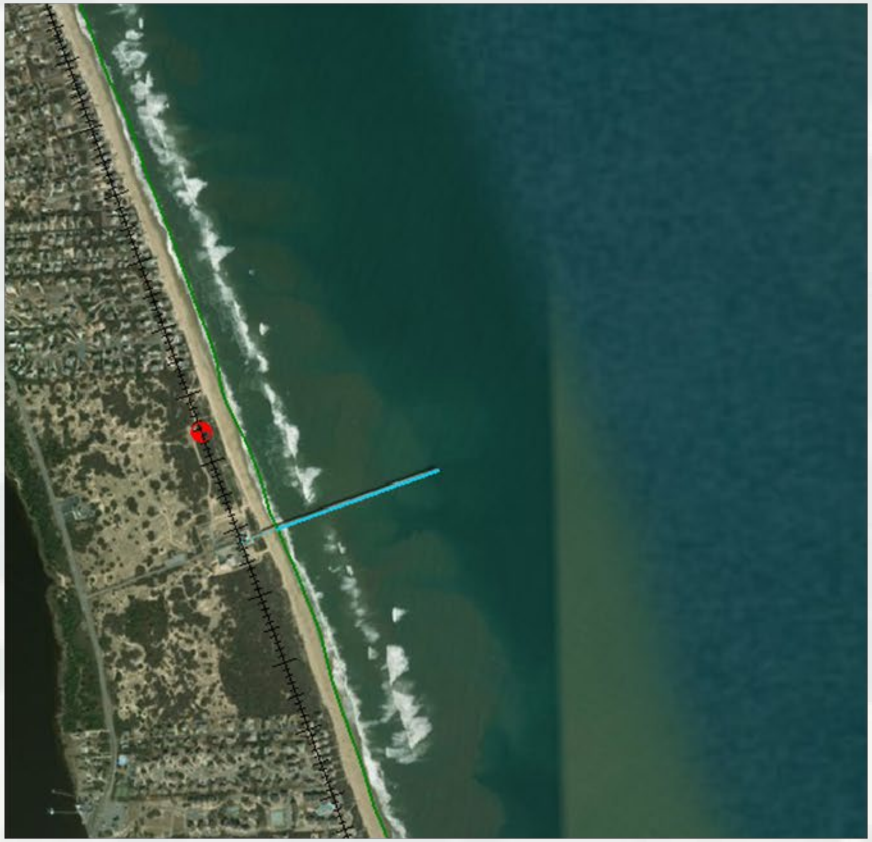


(2) Case 2 (α_{mean}=5.0°)

Return Period (year): R $R = \dfrac{1}{\lambda(1 - F(\Delta y))}$ (λ: mean rate of date samples)

Goda, Y., (1988). On the methodology of selecting design wave height. In: B.L.Edge, Proc. of the 21st ICCE. ASCE, pp. 899–913.

Monte Carlo Simulation of Shoreline Change in Duck, NC



FRF in Duck, NC

Number of Monte Carlo = **128**

Wave Conditions:

- **Wave Height: Rayleigh+Weibull**
- **Direction: Gaussian**
- **Period: PM Spectrum**
- **Truncated Wave Height: 2.0 m**

Computational Period: 6 years

1999/10/23 0:00 - 2005/10/23 0:00

time step = 3 minutes

K1 = 0.40; K2 = 0.25

Grain size = 0.20 mm

Berm Height = 1.0 m

Closure depth = 7.0

Sea Level Rise Rate = 4.55 mm/year

Smooth parameter = 1 (no smoothing)

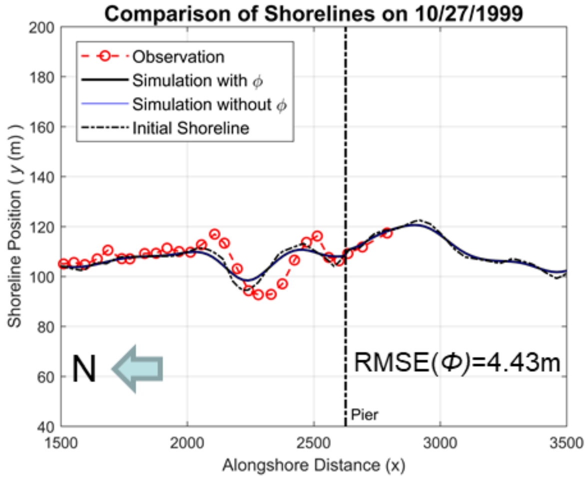
Boundary Conditions: Pined

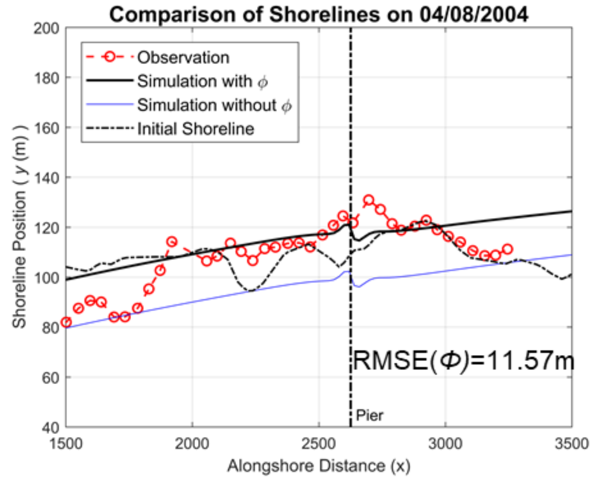
Grid Size = 20 m

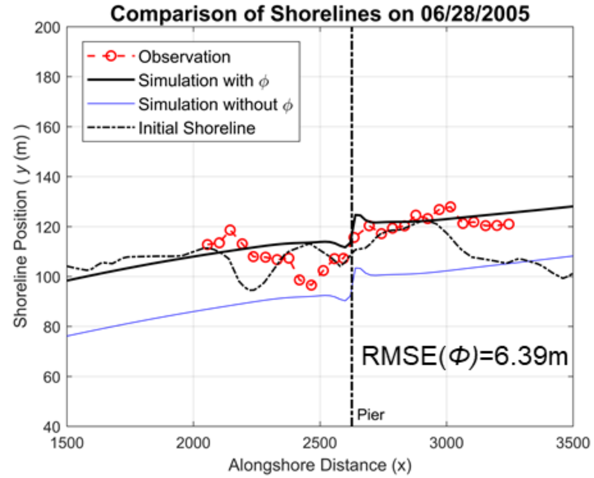
Permeability of Pier = 0.6 (no diffracting)

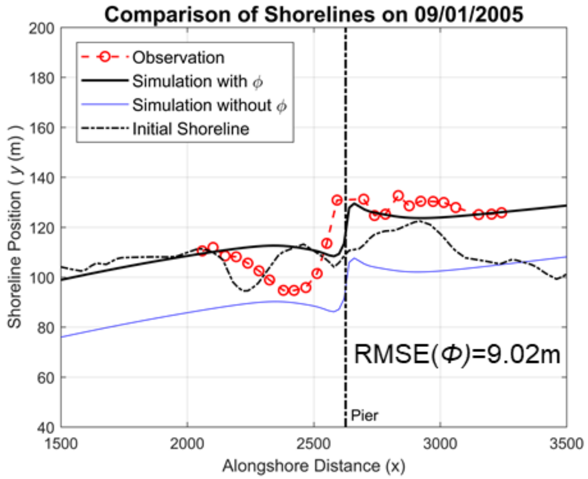
Scaling parameter of cross-shore transport: 0.182

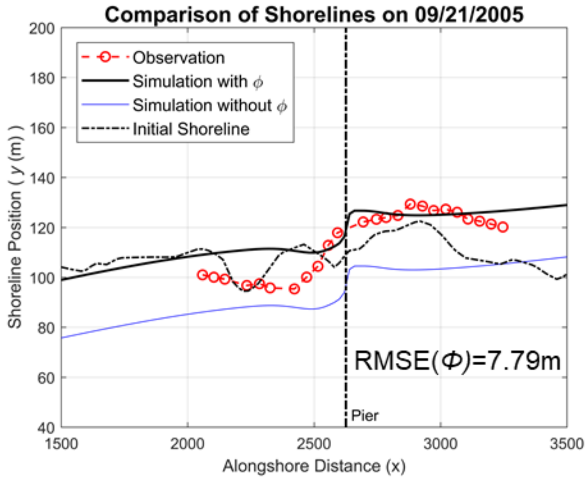
Model Validation -Determine System Errors

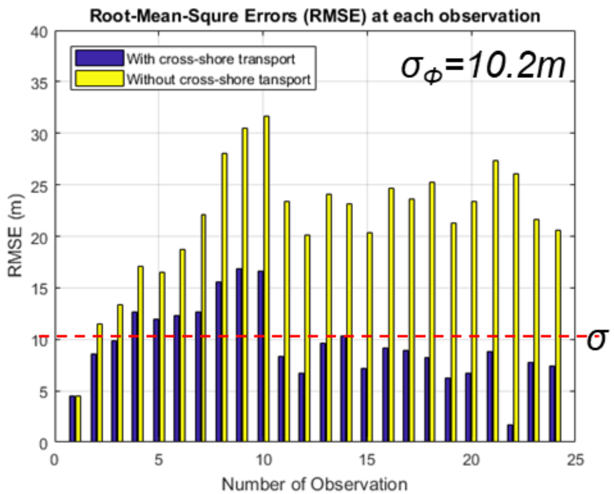




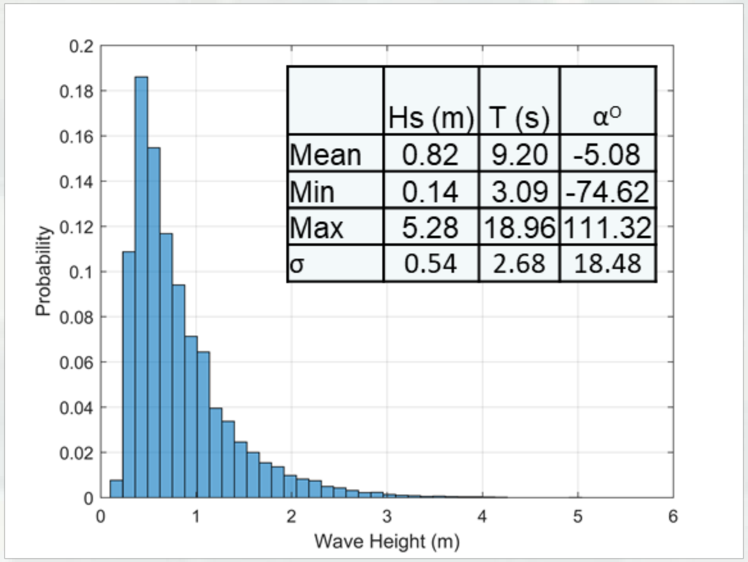




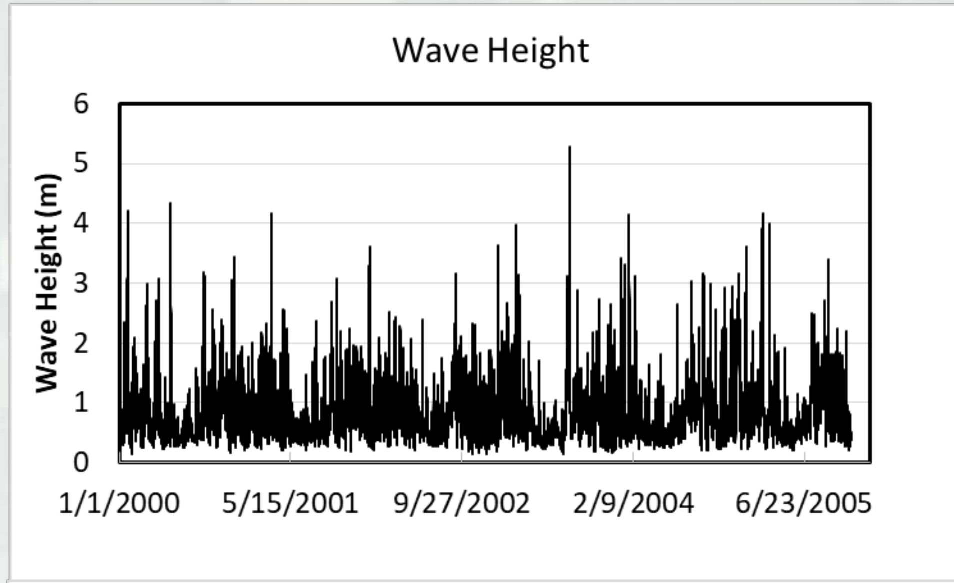


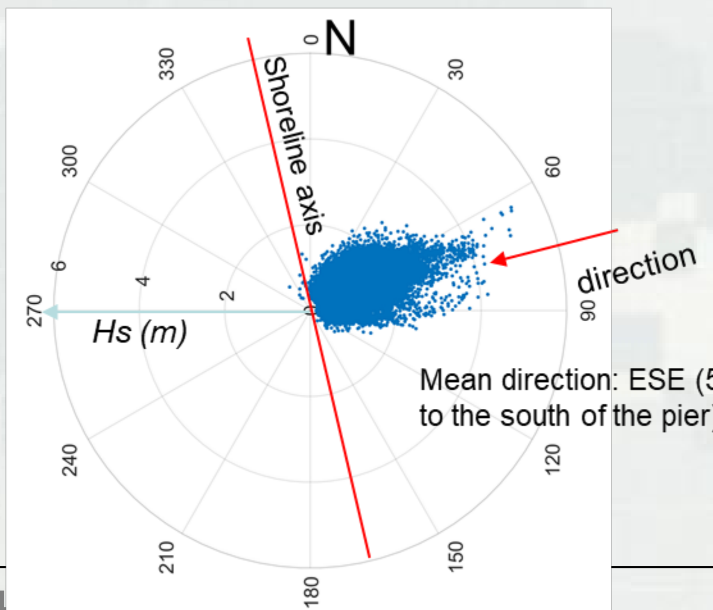


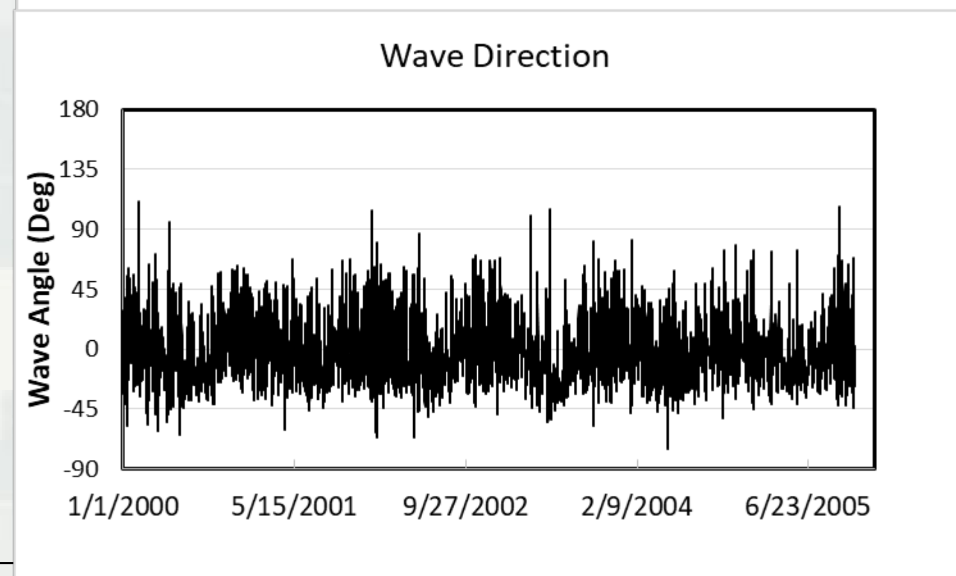
Wave Data for Creating PDFs



	Hs (m)	T (s)	α°
Mean	0.82	9.20	-5.08
Min	0.14	3.09	-74.62
Max	5.28	18.96	111.32
σ	0.54	2.68	18.48

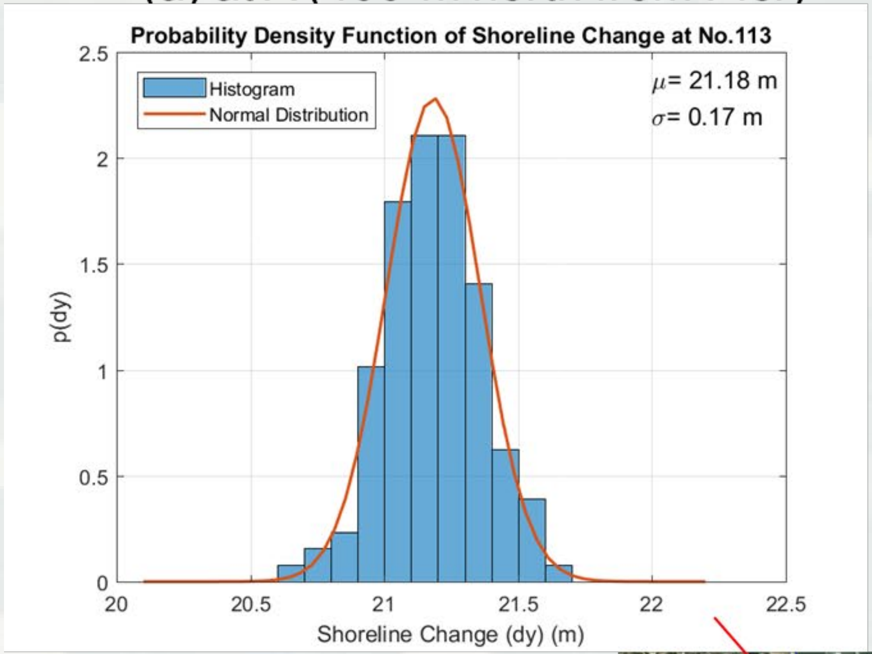




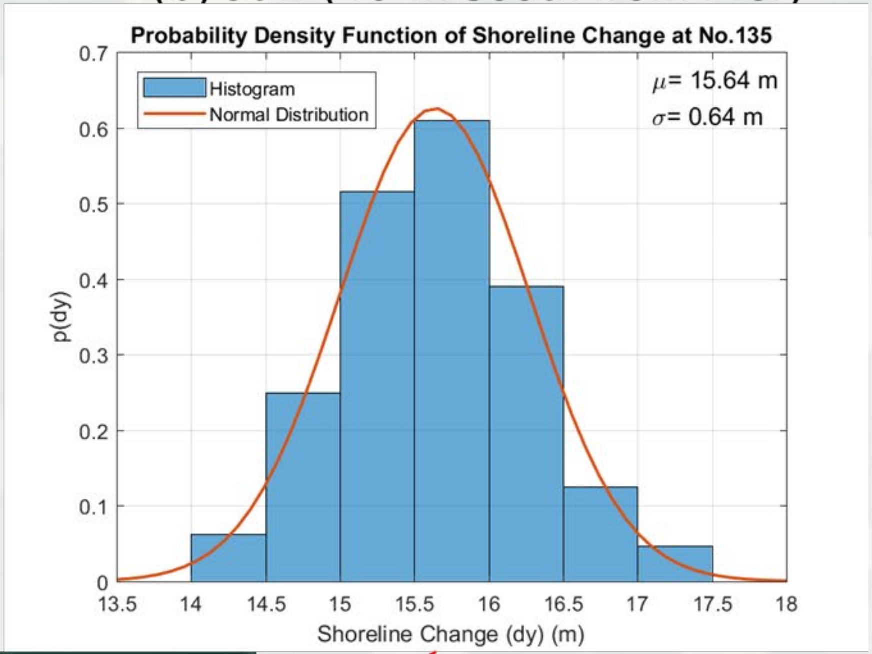


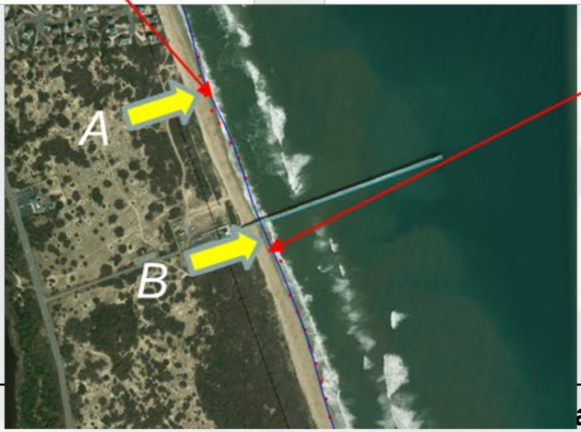
Probability Density Functions: 6-Years Shoreline Change

(a) at A (400-m north from Pier)

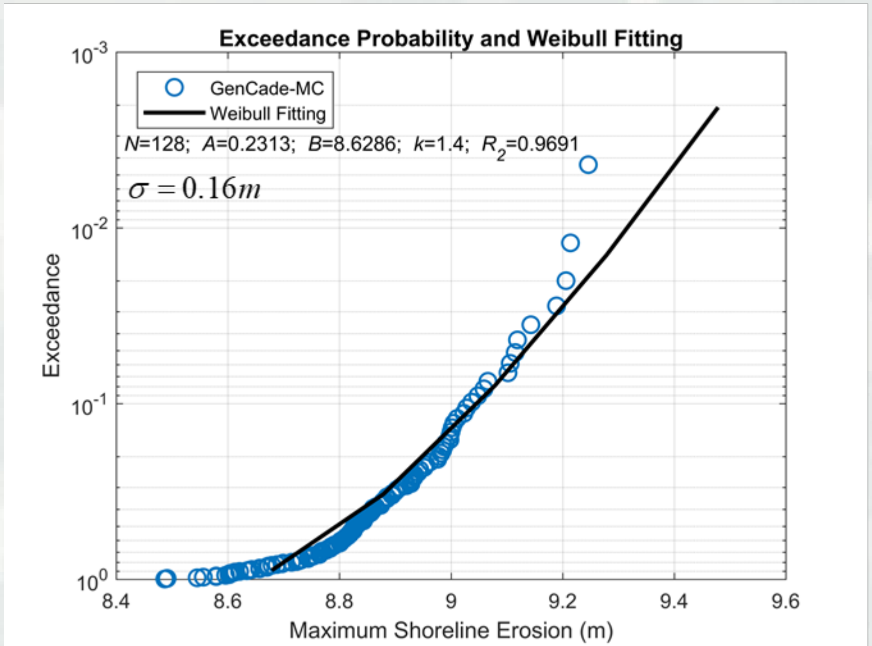


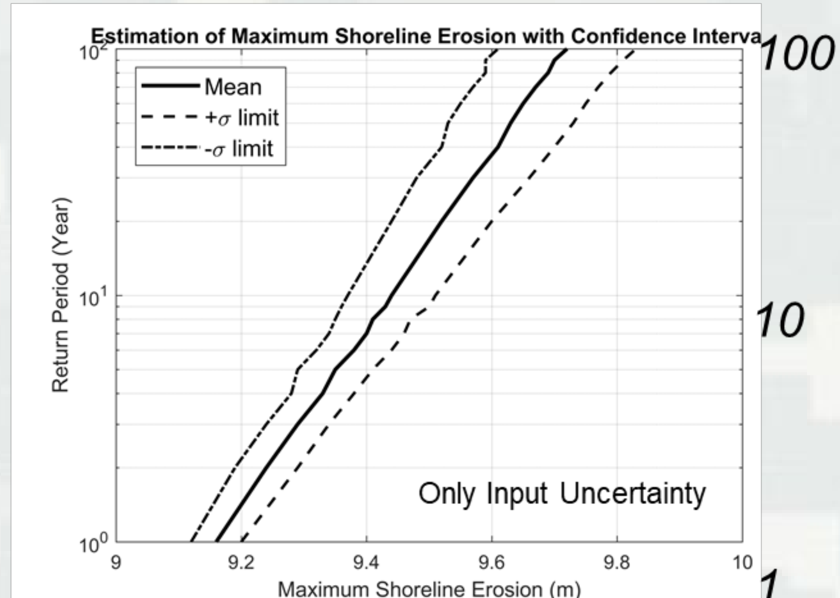
(b) at B (40-m south from Pier)

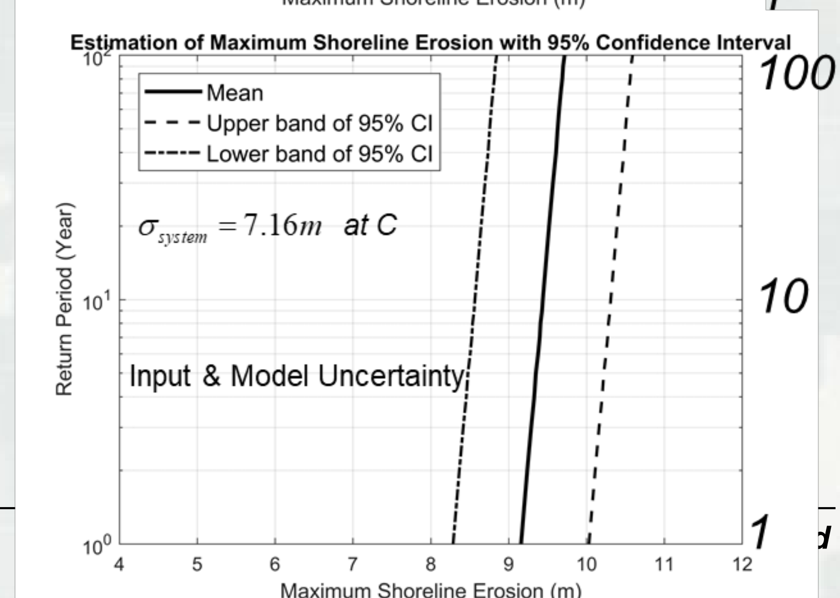




Uncertainty Estimation of Maximum Erosion at Point C

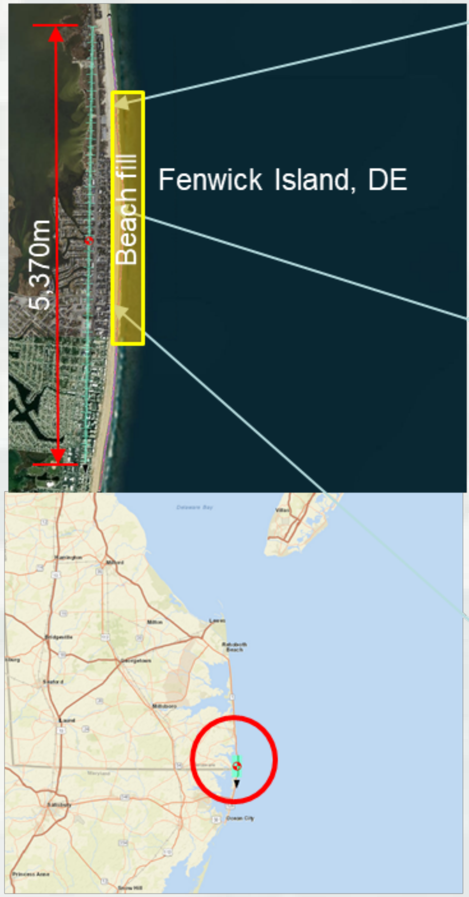


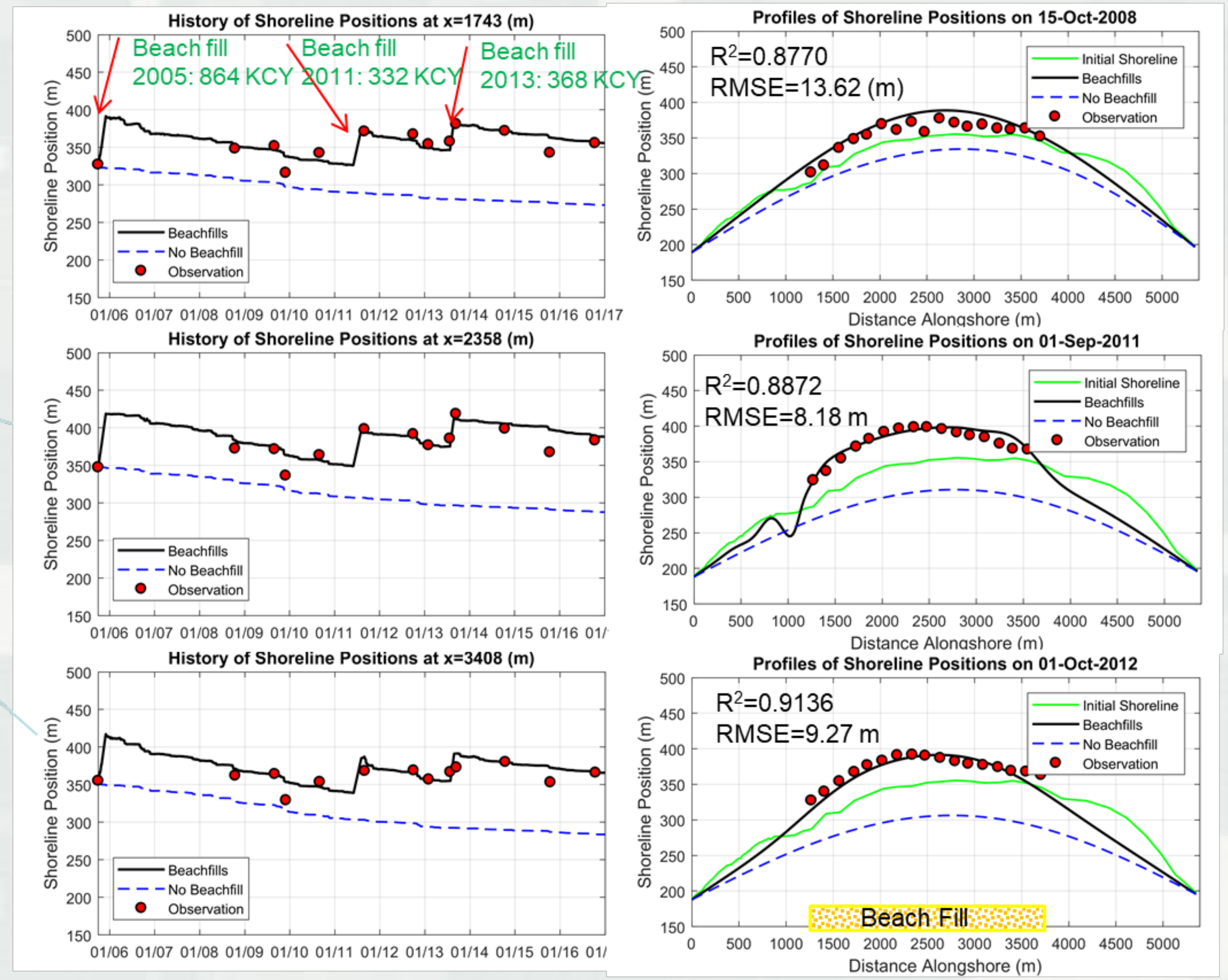




Long-term Shoreline Change in Fenwick Island, DE

- 12-year Shoreline Changes (2005-2017)
- Periodical beach fills : 2005, 2011, & 2013

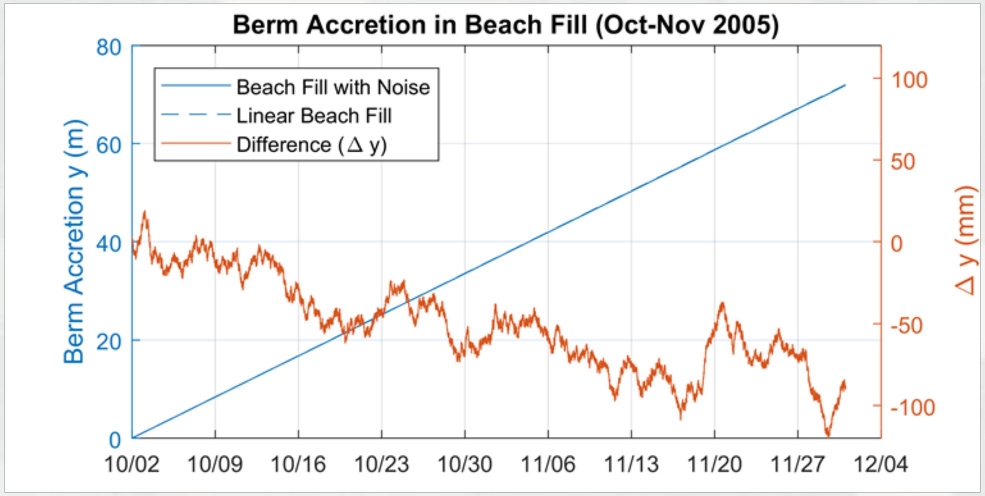


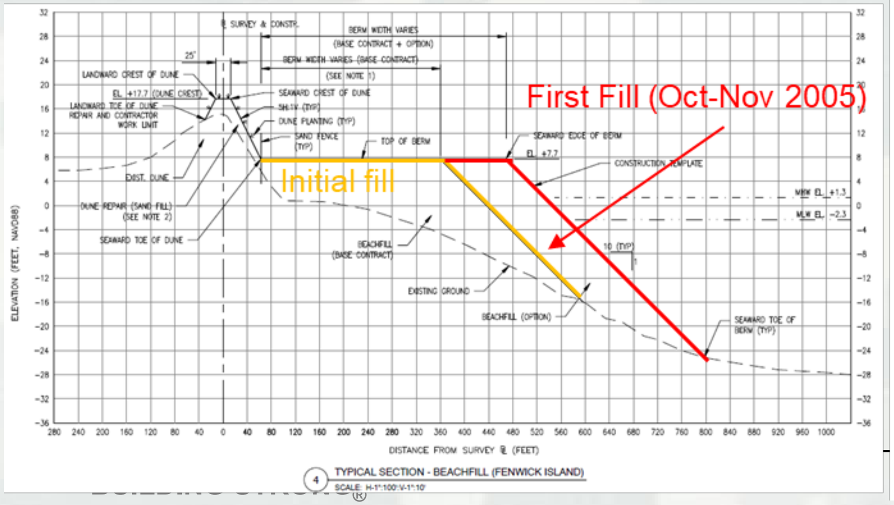


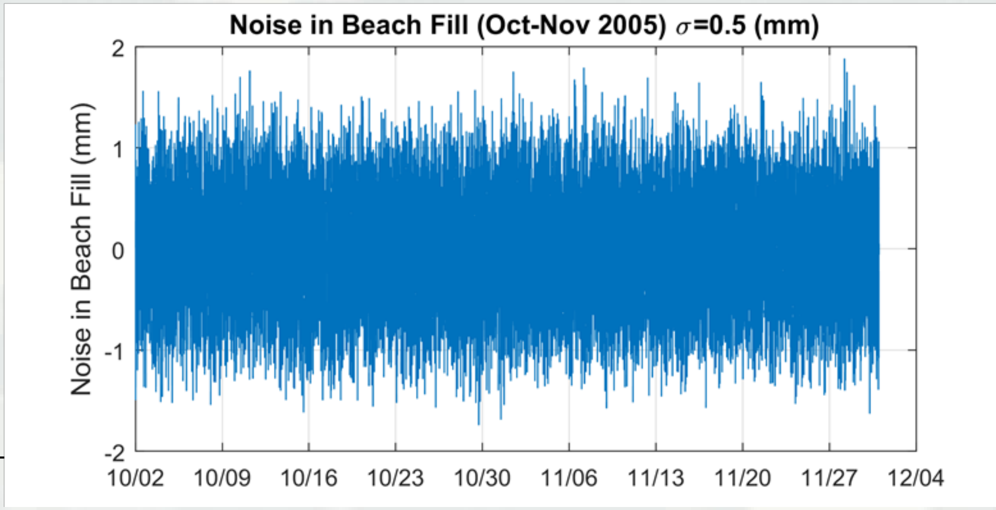
Uncertainty due to Beach Fill ($\Delta y(t)$)

Beach fill (Δy) = Planned Beach Fill ($\overline{\Delta y}(t)$)+ White Noise

$$\Delta y(t) = \overline{\Delta y}(t) + N(0, \sigma^2)$$

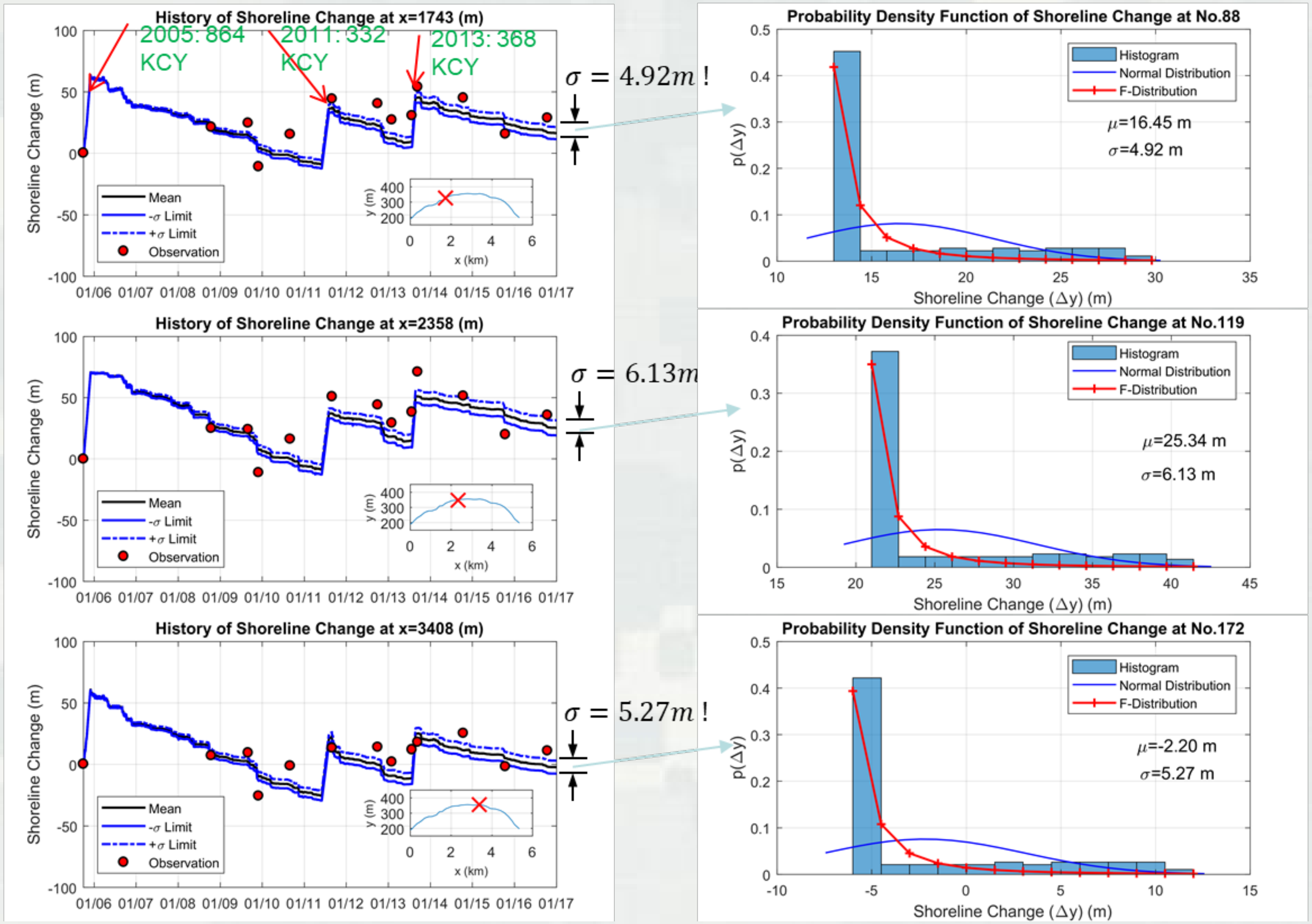






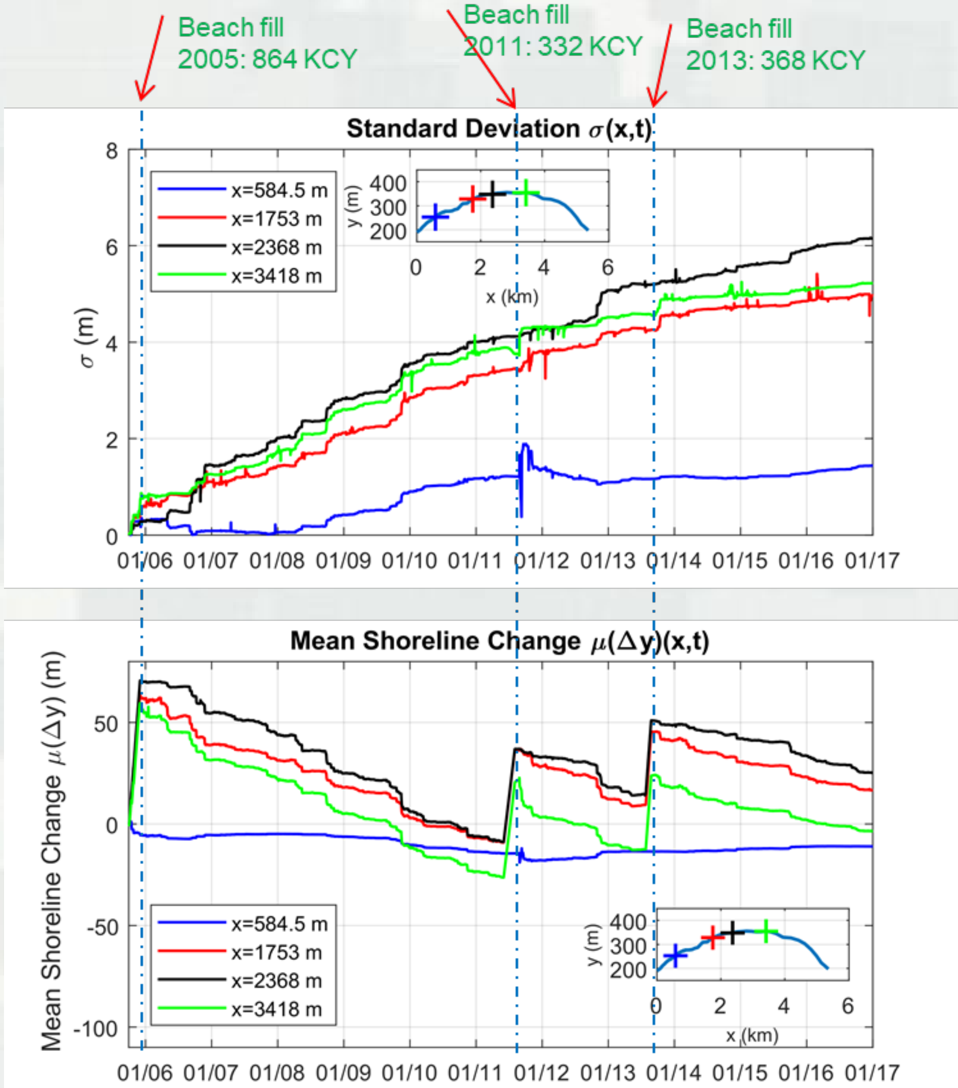
Variation of Shoreline Changes with Uncertainty in Beach Fill (1)

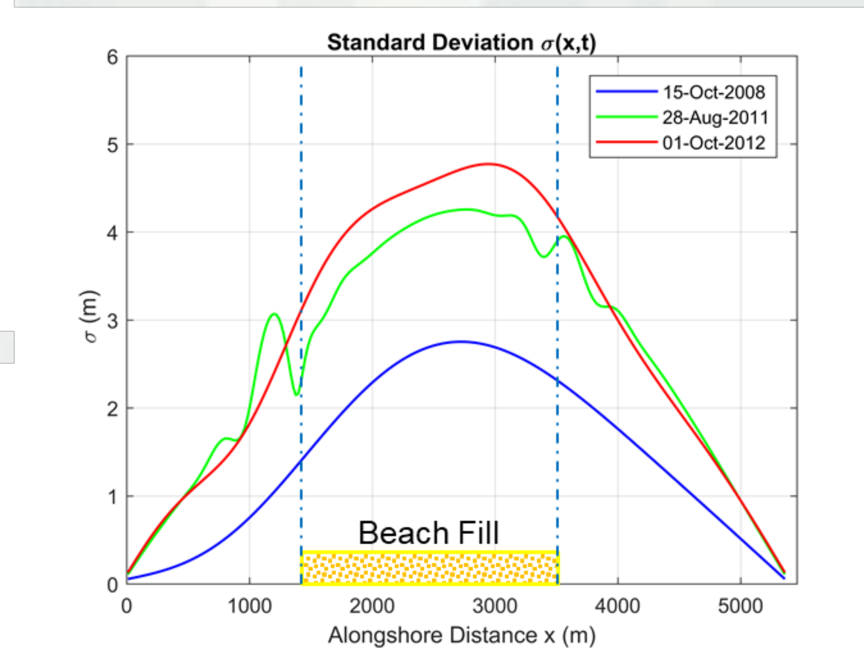
(a) Shoreline change with errors (b) Pdf at the end of simulation



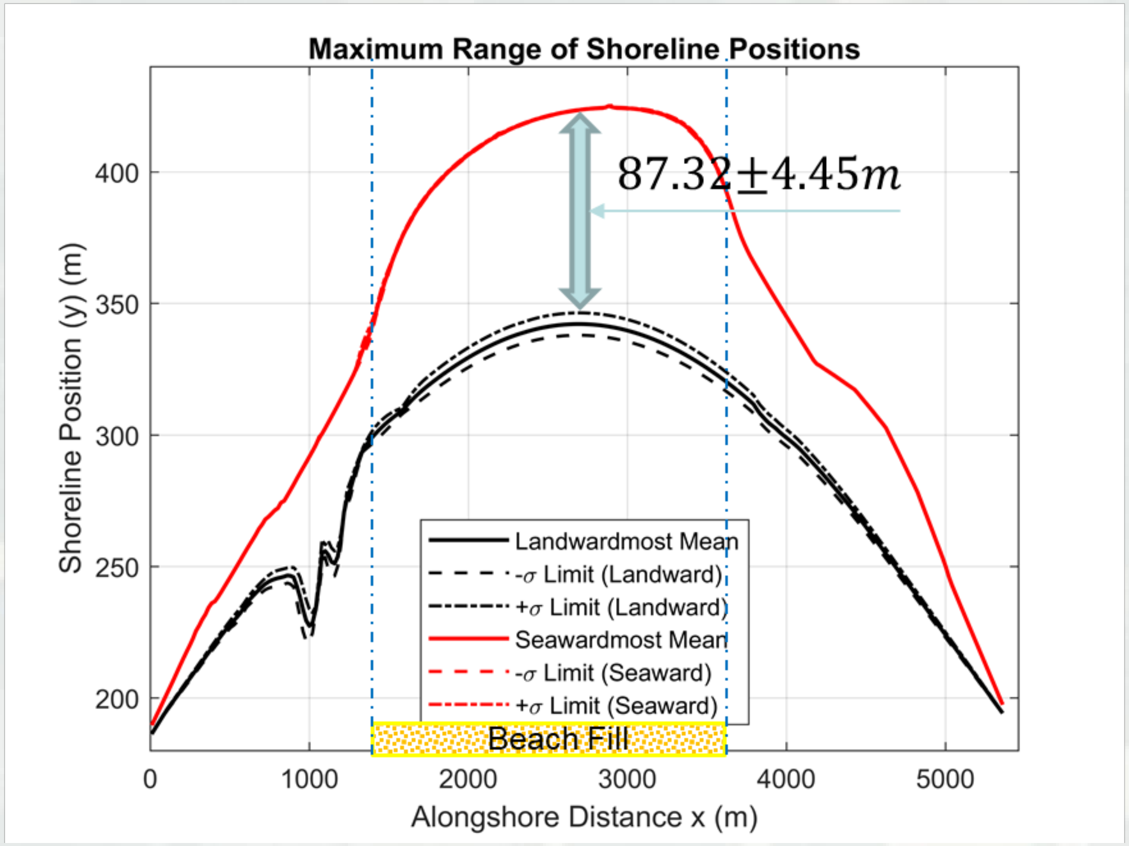
- Uncertainty propagates with time!
- Skew pdf, not Gaussian!
- F-Distribution

Errors/Uncertainty Propagating in Space (Beach) and Time





Maximum Range of Shoreline Changes: from Landwardmost to Seawardmost



Remarks

- GenCade-based Monte-Carlo (GenCade-MC) simulation provides a useful approach to assess uncertainty of shoreline change driven by waves.
- Maximum likelihood estimation of extreme shoreline changes predicts risk of erosion, which is essential for risk-based coast design.
- GenCade-MC is applicable to assess uncertainty of shoreline changes due to uncertainty in coastal protection practices (e.g. beach fill, nourishment).
- Further investigation of uncertainties by other factors (model parameters, boundary conditions, etc.) will be done.

Thank you for your attention!

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