Briefing Document

Dynamics of Wave Breaking and Nearshore Water Levels

Executive Summary

This briefing synthesizes the fundamental processes governing **wave transformation in the nearshore zone**, with emphasis on:

- Wave breaking mechanisms
- Surf zone dynamics
- Mean water level changes (wave set-down and set-up)

Wave breaking represents the final, nonlinear stage of a wave's evolution as it shoals into shallow water. As depth decreases:

1. Wave speed decreases,
2. Wave height increases (shoaling),
3. Wave steepness increases,
4. Instability develops and the crest collapses.

Breaking converts organized wave motion into turbulence, currents, and mixing — processes that fundamentally shape coastal morphology and sediment transport.

The type of breaking (spilling, plunging, collapsing, surging) depends primarily on **beach slope**.

A critical consequence of wave transformation is the change in **mean water level (MWL)**:

- **Wave set-down**: slight lowering of MWL before breaking.
- **Wave set-up**: rise in MWL within the surf zone due to momentum dissipation.

During storms, wave set-up can contribute substantially to total water level (TWL), exacerbating coastal flooding.

These processes are central to coastal engineering design, including:

- Runup and overtopping prediction
- Coastal structure design
- Numerical model calibration
- Flood risk assessment

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1. Fundamental Wave Characteristics

Ocean waves and tides represent distinct forms of marine energy.

Feature	Wave Energy	Tidal Energy
Energy Source	Wind and storms	Gravitational pull of Moon & Sun
Energy Type	Kinetic (oscillatory motion) Potential (wave height differences)	Potential (tidal elevation differences) Kinetic (tidal currents)
Periodicity	High-frequency (5–20 s)	Long-period (~12.42 hr)
Predictability	Irregular	Highly predictable

Waves are short-period, wind-driven surface gravity waves.
Tides are long-period gravitational oscillations.

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2. The Phenomenon of Wave Breaking

Wave breaking marks the transition from organized wave motion to turbulent flow.

2.1 Physical Mechanism

As waves propagate from deep to shallow water:

(1) Decreased Celerity

$$C = \sqrt{gh}$$

Wave speed decreases with depth.

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(2) Increased Wave Height (Shoaling)

Energy conservation causes wave height to increase as depth decreases.

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(3) Increased Steepness

$$\text{Steepness} = \frac{H}{L}$$

Height increases while wavelength shortens → instability grows.

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(4) Instability and Crest Collapse

Eventually:

- Crest velocity exceeds underlying particle velocity
- The crest outruns the trough
- The wave overturns and breaks

Breaking converts wave energy into:

- Turbulent kinetic energy
- Mean currents
- Mixing and heat

2.2 Breaking Criteria

Deep Water Criterion

$$\left(\frac{H}{L}\right)_{max} \approx \frac{1}{7}$$

A wave breaks when steepness reaches its limiting value.

Shallow Water Criterion

$$\frac{H_b}{h_b} \approx 0.78$$

Breaking wave height is approximately 78% of local depth.

Empirical Formula

$$\frac{H_b}{L_0} = 0.39\tanh\left(\frac{2\pi h_b}{L_0}\right)$$

Where:

- H_b= breaking height
- h_b= breaking depth
- L_0= deep-water wavelength

2.3 Types of Wave Breaking

Breaker type depends primarily on **beach slope (tan β)**.

Type	Characteristics	Typical Slope (tan β)	Examples
Spilling	Gentle crest spilling forward	< 0.02	Flat sandy beaches
Plunging	Curling crest, air pocket	0.02–0.05	Classic surf waves
Collapsing	Front face collapses	0.05–0.1	Steep beaches
Surging	Wave slides up slope	> 0.1	Reflective shorelines

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3. The Surf Zone and Nearshore Dynamics

The **surf zone** is the region where waves continuously break.

As waves shoal:

- Wave energy increases
- Wave spacing decreases
- Breaking begins
- Turbulence dominates

Breaking generates two primary force components:

- **Cross-shore component** → Wave set-up
- **Alongshore component** → Longshore current

Longshore current velocity:

- Maximum near breaker line
- Decreases shoreward and offshore

Undertow develops as a compensating offshore-directed current beneath breaking waves.

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4. Wave Set-down and Set-up

Wave set-down and set-up describe changes in **mean water level (MWL)** due to gradients in radiation stress.

4.1 Governing Mechanism

The steady, depth-averaged cross-shore momentum equation:

$$\rho g h \frac{d\eta}{dx} + \frac{dS_{xx}}{dx} = 0$$

Where:

- η= mean water level displacement
- S_{xx}= radiation stress
- ρ= density

Regional Behavior

Region	Radiation Stress Gradient	MWL Response
Outside breaker	$dS_{xx}/dx > 0$	Set-down (η ↓)
Inside surf zone	$dS_{xx}/dx < 0$	Set-up (η ↑)

4.2 Maximum Set-up Estimate

For uniform beach slope:

$$\eta_{max} \approx \frac{5}{16}\frac{H_b^2}{h_b}$$

Typical Magnitudes

Breaking Height	Depth	Setup	Interpretation
1.0 m	1.3 m	2–4 cm	Mild
2.0 m	1.5 m	8–10 cm	Moderate
3.0 m	2.0 m	15–20 cm	Strong
Storm waves	—	> 0.5 m	Major flooding contribution

During storms, wave set-up can significantly increase total water level.

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5. Energy Dissipation and Coastal Impacts

5.1 Energy Dissipation

Energy dissipation per unit surface area:

$$\varepsilon = \frac{1}{8}\rho g H_b^2 C_{gb}$$

Where:

- C_{gb}= group velocity at breaking

Breaking transforms wave energy into:

- Turbulent kinetic energy
- Longshore current energy
- Undertow
- Heat and mixing

5.2 Broader Coastal Effects

Effect	Description
Energy Reduction	Decreases wave energy shoreward
Sediment Transport	Drives beach morphology change
Mixing & Oxygenation	Enhances nearshore water quality
Structural Loading	Produces dynamic impact forces

5.3 Engineering Importance

Understanding wave breaking and set-up is critical for:

- Surf zone width prediction
- Wave runup and overtopping design
- Seawall and revetment stability
- Rip current analysis
- Flood hazard mapping
- Total Water Level (TWL) assessment

TWL includes:

$$\text{Storm Surge} + \text{Wave Set-up} + \text{Wave Runup}$$

Breaking dissipation models are implemented in widely used numerical tools such as:

- SWAN
- MIKE 21
- SWASH
- XBeach

Concluding Perspective

Wave breaking is not merely a surface phenomenon — it is a fundamental transformation of energy and momentum that:

- Shapes beaches
- Drives sediment transport

- Controls nearshore circulation
- Raises coastal water levels

During storms, wave set-up becomes a critical contributor to flooding and structural loading.

For coastal engineers, understanding the physics of breaking waves and nearshore water level adjustment is essential for:

- Climate-resilient infrastructure design
- Accurate numerical modeling
- Coastal flood risk assessment