Briefing Document: Dynamics of Wave Breaking and Nearshore Water Levels

Executive Summary

This document synthesizes the core principles governing ocean wave transformation in nearshore environments, focusing on the phenomena of wave breaking, the formation of the surf zone, and the resulting changes in mean water level known as wave set-down and set-up.

Wave breaking is the final, nonlinear stage of a wave's life cycle as it moves into shallow water. This process is triggered when a wave becomes too steep to maintain its form, causing its crest to collapse forward. The physical mechanism involves the wave slowing down and its height increasing (shoaling) due to the decreasing water depth, leading to instability. Breaking converts organized wave motion into turbulent, dissipative flow, which is fundamental to shaping coastal morphology.

The type of wave breaking—spilling, plunging, collapsing, or surging—is primarily determined by the beach slope. This breaking process creates the surf zone and dissipates significant wave energy, transforming it into turbulence, mean currents such as undertow and longshore currents, and heat. These effects are critical drivers of sediment transport and nearshore water quality.

A direct consequence of wave transformation is the variation in the mean water level. As waves approach the shore and their energy increases, a slight lowering of the mean water level, or **wave set-down**, occurs. Following the breaking point, within the surf zone, the rapid dissipation of wave energy and momentum causes a rise in the mean water level, known as **wave set-up**. The magnitude of this set-up can be significant, especially during storms, contributing to the total water level and exacerbating coastal flooding. These phenomena are of paramount importance in coastal engineering, influencing the design of coastal structures, prediction of wave runup and overtopping, and the calibration of numerical models.

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1. Fundamental Wave Characteristics

Ocean waves and tides represent two distinct forms of marine energy. Their characteristics differ significantly in terms of periodicity, predictability, and the nature of the energy they carry.

Feature	Wave Energy	Tidal Energy
Energy Source	Wind and storms transferring energy to the water surface.	Gravitational pull of the Moon and Sun.
Energy Type	- **Kinetic Energy:** From the oscillatory surface motion of water particles. -	- **Potential Energy:** From the elevation difference between high and low

	Potential Energy: From the differences in wave height.	tides. - **Kinetic Energy:** From horizontal tidal currents.
Flow Dynamics	Irregular and oscillatory with high-frequency periods (5–20 seconds).	Predictable and periodic with long-frequency periods (e.g., 12.42 hours).

2. The Phenomenon of Wave Breaking

Wave breaking is the process by which a wave's form becomes unstable, causing its crest to collapse. It represents the end stage of wave transformation, where wave energy is converted into turbulence, currents, and mixing.

2.1. Physical Mechanism

As waves propagate from deep to shallow water, a sequence of four physical changes leads to breaking:

1. **Decreased Celerity (C):** The wave speed decreases as the water depth (h) becomes shallower, governed by the relation $C = \sqrt{(gh)}$.
2. **Increased Wave Height (H):** Due to energy conservation, the wave height increases in a process known as shoaling.
3. **Increased Wave Steepness (H/L):** The combination of increasing height and decreasing wavelength causes the wave to become steeper.
4. **Instability and Collapse:** Eventually, the wave crest travels faster than the trough beneath it. This instability causes the crest to collapse forward, resulting in the wave "breaking." The back of the wave moves faster than the front, pushing the wave to become too high and break.

2.2. Breaking Criteria

A wave will break when its steepness exceeds a critical value. This is defined by two primary criteria based on water depth:

- **Deep Water Criterion:** Breaking occurs when the ratio of wave height (H) to wavelength (L) reaches its maximum value. $(H/L)max \approx 1/7$
- **Shallow Water Criterion:** At the point of breaking, the breaking wave height (Hb) is a function of the local water depth (hb). $Hb / hb \approx 0.78$ This indicates that a wave in shallow water breaks when its height is approximately 78% of the local water depth.

An additional common empirical formula for predicting the breaking height is: $Hb / L_0 = 0.39 \tanh(2\pi hb / L_0)$ where L_0 is the deep-water wavelength.

2.3. Types of Wave Breaking

The morphology of the beach slope is the primary factor determining the type of breaking wave. There are four principal types, as adapted from Galvin (1968):

Type	Characteristics	Typical Slope (tan β)	Examples
Spilling Breaker	The crest spills gently forward down the wave face, leading to a gradual energy loss.	< 0.02	Gentle sandy beaches.
Plunging Breaker	The crest curls over, creating an air pocket, and plunges downward, resulting in strong turbulence.	0.02–0.05	Moderate slopes, classic surf waves.
Collapsing Breaker	The steep front face of the wave collapses without curling.	0.05–0.1	Steep beaches.
Surging Breaker	The wave slides up the slope with no crest breaking.	> 0.1	Very steep or reflective beaches.

Figure: Conceptual diagrams showing spilling, plunging, and surging breakers based on beach slope steepness.

3. The Surf Zone and Nearshore Dynamics

The surf zone is the nearshore area where waves break. As waves enter shallower water, they slow and begin to crowd together. Wave energy and decreasing water depth push water upwards, increasing wave height until breaking occurs.

Within the surf zone, the breaking process generates significant forces and currents. The force of the breaking wave can be resolved into two components:

- A component perpendicular to the shore, which produces **wave set-up**.
- A component parallel to the shore, which produces a **longshore current**.

The velocity of the longshore current is typically highest near the breaking point and decreases towards the shore and further offshore.

4. Wave Set-down and Set-up

Wave set-down and set-up are changes in the mean water level (MWL) caused by variations in wave radiation stress as waves approach the shore.

- **Wave Set-down:** A slight *lowering* of the MWL that occurs *before* the breaking point (seaward of the breaker).
- **Wave Set-up:** A *rise* in the MWL that occurs *inside* the surf zone, driven by the loss of wave momentum during breaking and dissipation.

4.1. Physical Explanation and Governing Equations

As waves move from deep to shallow water, their height increases (shoaling), which also changes the wave energy and momentum flux (radiation stress). The gradient in radiation stress induces an adjustment in the mean water surface to balance momentum.

- **Increased radiation stress (offshore)** leads to a **lower mean level (set-down)**.
- **Decreased radiation stress (inside surf zone)** leads to a **higher mean level (set-up)**.

The mechanism can be summarized as follows:

Region	Behavior	Radiation Stress Gradient	Water Level Response
Outside breaker	Waves shoal, energy flux ↑	$dSxx/dx > 0$	Set-down (η ↓)
Inside surf zone	Waves break, energy ↓	$dSxx/dx < 0$	Setup (η ↑)

The depth-averaged, steady cross-shore momentum equation governs this process: $\rho gh(d\eta/dx) + dSxx/dx = 0$, where η is the mean water surface displacement and Sxx is the radiation stress.

4.2. Magnitude and Impact

The maximum wave set-up at the shoreline can be estimated for a uniform beach slope under steady conditions: $\eta(setup,max) \approx (5/16) * (Hb^2 / hb)$

The magnitude of the set-up is directly related to the wave conditions:

Wave Height (Hb)	Depth (hb)	Setup (cm)	Comments
1.0 m	1.3 m	2–4 cm	Mild setup
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	Significant coastal flooding effect

5. Effects and Engineering Importance of Wave Breaking

Wave breaking is a critical process in coastal science and engineering due to its wide-ranging effects on energy, sediment, and structures.

5.1. Energy Dissipation

Breaking converts the wave's potential and kinetic energy into other forms:

- **Turbulent Kinetic Energy (TKE)**
- **Mean Current Energy** (e.g., undertow, longshore current)
- **Heat and Mixing**

The local energy dissipation rate per unit surface area (ε) can be expressed as: $\varepsilon = (1/8)\rho gHb^2Cgb$, where Cgb is the group velocity at breaking.

5.2. Broader Coastal Effects

Effect	Description
Energy Dissipation	Reduces wave height and energy shoreward of the breaking point.
Sediment Transport	Drives surf-zone currents and is a primary agent of beach morphology changes.
Mixing and Oxygenation	Enhances nearshore water quality and aeration through turbulence.
Hydrodynamic Loading	Generates significant dynamic impact forces on coastal structures.

5.3. Engineering Importance

Understanding wave breaking and set-up is crucial for coastal engineering applications:

- **Determines surf-zone width and wave setup on beaches.**
- **Critical for coastal structure design**, informing calculations for wave runup and overtopping on seawalls and revetments.
- **Governs nearshore circulation**, affecting rip currents and setup-driven flow.
- **Used to calibrate breaking dissipation models** in numerical tools such as SWAN, MIKE21, SWASH, and XBeach.
- **Defines the upper limit of wave height** at any given water depth.
- **Combines with storm surge** to define the total water level (TWL) that impacts coastlines, which is essential for flood risk assessment.