Hard Coastal Structures: Engineering Principles and Design Considerations

Executive Summary

This briefing document synthesizes the core principles, design considerations, and environmental forces relevant to hard (grey) coastal structures. These engineered defenses are implemented to protect coastal assets and populations from erosion and flooding, reflecting a traditional "hold-the-line" strategy driven by economic, urban, and navigational imperatives.

Hard structures exist on a continuum with "green" (nature-based) and hybrid approaches. While effective at resisting forces, they exhibit low adaptability and ecological value compared to green solutions that work with nature. The design of these structures is critically dependent on a thorough understanding of the hydrodynamic environment, which includes the combined forces of waves, astronomical tides, storm surge, and long-term sea-level rise (SLR). Accurate load estimation, based on these factors, is paramount for ensuring both safety and cost-effectiveness.

Key engineering calculations involve determining a design water level by summing components like tide, surge, and SLR, and establishing a design wave height based on a specific return period (e.g., 100-200 years for critical barriers). A central concept in wave-structure interaction is the Breaker Parameter (Iribarren number, ξ), a ratio of structure slope to wave steepness. This dimensionless number dictates whether waves will spill, plunge, or surge, which in turn governs wave run-up, overtopping rates, and the magnitude of impact pressures on the structure. Final design elements, such as crest elevation, are determined by detailed run-up calculations that account for the structure's slope, material roughness, and other geometric factors.

1.0 Introduction to Hard Coastal Structures

1.1 Rationale and Context

Hard coastal structures are engineered solutions designed to defend shorelines where significant assets and populations are at risk from coastal hazards like erosion and flooding. The primary drivers for their implementation are the protection of high economic value, urban density, navigational channels, and cultural heritage. This approach represents a historic focus on physical security through a "hold-the-line" philosophy.

1.2 The Grey-Green-Hybrid Continuum

Coastal protection strategies are often categorized along a spectrum from "grey" (hard structures) to "green" (nature-based solutions). Grey approaches are characterized by their function of resisting forces, while green approaches aim to work with natural processes.

Approach	Function	Adaptability	Ecological Value
Grey	Resist forces	Low	Low
Hybrid	Combine grey + green	Medium	Medium
Green	Work with nature	High	High

1.3 Common Types of Coastal Works

A variety of hard structures are used for coastal defense, each with a specific engineering function. They are often used in conjunction with "soft" measures like beach nourishment.

Structure Type	Description	Primary Function	Classification
Artificial Headlands	Large rock or concrete structures built out from the coast, creating stable bays between them.	Stabilize the shoreline by forming artificial bays.	Hard
Groynes	Structures (timber, rock, masonry) built perpendicular to the shore to interrupt longshore sediment transport.	Trap sand moving along the coast to build up a beach.	Hard
Offshore Breakwaters	Rock or concrete structures built parallel to the shore, in the water, to break waves before they reach the beach.	Reduce wave energy reaching the shoreline, promoting sediment deposition.	Hard
Stepped Sea Wall	A sloped wall, often with steps, backed by support piles and a promenade. Typically includes a wave return wall.	Protect the land behind it from direct wave attack and overtopping.	Hard
Rip-rap Sea Wall	A sloped revetment constructed from large, angular stones (armour stone) over a filter layer.	Dissipate wave energy and protect the underlying slope from erosion.	Hard
Beach Nourishment	Placing sand on an eroding beach to widen it.	Widen the beach to provide a buffer against storm waves.	Soft

2.0 The Hydrodynamic Design Environment

The design of any coastal structure must account for the complex and powerful forces of the marine environment. Accurate estimation of these loads is fundamental to safety and cost. The key inputs for design include the Design Wave (height, period, length), Water Level (η), and the statistical Return Period.

2.1 Key Environmental Forces

Coastal structures must be engineered to withstand the cumulative effects of:

- **Waves:** The primary source of dynamic energy and pressure.
- **Tides:** The regular, predictable rise and fall of the sea level due to gravitational forces of the moon and sun.
- **Storm Surge:** An abnormal rise in water level generated by a storm.
- **Wave Setup:** An increase in the mean water level near the shore caused by breaking waves.
- **Sea Level Rise (SLR):** The long-term increase in the average sea level.

2.2 Understanding Storm Surge

Storm surge is a critical factor in coastal flooding and must be differentiated from storm tide.

- **Storm Surge:** "An abnormal rise of water generated by a storm, over and above the predicted astronomical tides."
- **Storm Tide:** "The water level rise due to the combination of storm surge and the astronomical tide."

The most extreme flooding occurs when a large storm surge coincides with a high tide. The primary cause of storm surge is the force of strong winds pushing water toward the shore. The impact of a storm's low atmospheric pressure is minimal in comparison. As the wind-driven water approaches land, it "piles up," creating the surge.

2.3 Wave Dynamics and Run-up

As waves travel from deep water toward the coast, they undergo a transformation. In deep water, their motion is unaffected by the seabed. As the water shallows, the waves begin to "feel" the bottom, causing them to slow, steepen, and eventually break in the surf zone.

- **Wave Runup (R):** The time-varying elevation of the water level at the shoreline. It is measured relative to the still water level (SWL) and is a function of wave height (H) and beach slope (β). It comprises two components:
    - **Wave Setup (η):** The time-averaged elevation of the water level.
    - **Swash:** The time-varying component of the run-up.

2.4 Sea Level Rise (SLR) Projections

Long-term sea-level rise is a critical design consideration that elevates the baseline water level for all other forces.

- **Global Projections (1800-2100):** Global sea level rise projections range from 1 to 8 feet by 2100. The likely range is considered to be between 1 and 4 feet, depending on future emissions scenarios.
- **New Jersey Projections (2000-2150):** Regional projections provide more localized data. For New Jersey, under a moderate emissions scenario, the median (50% chance) projection for SLR is 1.4 feet by 2050 and 3.3 feet by 2100. The high-end projection (less than a 5% chance SLR exceeds) is 2.6 feet by 2050 and 6.9 feet by 2100.

Year	At least a 66% Chance of SLR (ft)	Median (~50% Chance) SLR (ft)	High End (Less than 5% chance exceeds) (ft)
2050	0.9 - 2.1	1.4	2.6
2100	2.0 - 5.1	3.3	6.9
2150	3.1 - 8.3	5.2	13.8
All values are relative to a 1991-2009 baseline.			

3.0 Core Engineering Design Principles

3.1 Establishing Design Parameters

The design process begins by defining the conditions the structure must withstand. This involves statistical analysis and the combination of multiple environmental factors.

Design Water Level (η)

The Design Still Water Level (SWL) is calculated by summing the contributions from various sources:

- **Formula:** $\eta = \eta_{tide} + \eta_{surge} + \eta_{setup} + \eta_{SLR}$
- **Typical Ranges:**
  - **Tide:** ±1–3 m (±3–10 ft)
  - **Surge:** 0–5 m (0–16 ft)
  - **Setup:** 0.1–0.5 H_s
  - **SLR:** 0.3–1 m (1–3 ft)
- **Example Calculation:** For a scenario with tide = 1.2 m, surge = 2.0 m, setup = 0.9 m, and SLR = 0.5 m, the design water level is η = 4.6 m (15 ft) above Mean Sea Level.

Return Periods and Design Wave Height

The severity of design conditions is linked to a return period (T_R), which is the average recurrence interval of an event. The choice of return period depends on the structure's importance.

Structure	Return Period (TR) in years	Use
Barrier	100–200	Critical
Seawall	50	Moderate
Temporary	25	Low

The design significant wave height ($H_{s,design}$) is calculated using the Gumbel distribution based on the chosen return period.

3.2 The Breaker Parameter (ξ): A Critical Determinant

The Iribarren number, or Breaker Parameter (ξ), is a fundamental dimensionless value in coastal engineering that describes how a wave will break on a slope. It quantifies the relationship between the structure's slope steepness and the incoming wave's steepness.

- **Formula:** $\xi = (\tan \alpha) / \sqrt{(H_{m0} / L_0)}$
    - **tan α:** Structure slope angle
    - **H_{m0}:** Significant wave height
    - **L_0:** Deep-water wavelength

The value of ξ predicts the type of wave breaking, which directly controls run-up, reflection, overtopping, and the pressure exerted on the structure.

ξ Range	Breaking Type	Description	Design Implication
< 0.5	Spilling	Gentle slope, low energy dissipation per wave	Low run-up, less reflection
0.5–3.3	Plunging	Intermediate slope, powerful breaking jet	High impact pressure
> 3.3	Surging / Reflecting	Steep slope, wave runs up without breaking	High run-up, overtopping risk

- **Typical Values:** Natural beaches often have $\xi < 1$, rubble revetments typically have ξ = 1-2, and vertical walls have $\xi > 3.3$.

3.3 Calculating Wave Run-up ($R_{u,2\%}$)

Wave run-up is the maximum vertical extent that waves reach on a slope. The 2% exceedance run-up ($R_{u,2\%}$), meaning the height reached or exceeded by only 2% of waves, is a standard design parameter.

A simple approximation for run-up on smooth, permeable slopes is:

- For $\xi < 1.8$: $R_{u,2\%} / H_{m0} = 1.65 * \xi$
- For $\xi \geq 1.8$: $R_{u,2\%} / H_{m0} = 3.0$

More detailed calculations incorporate influence factors to adjust for real-world conditions. The general formula is: $\mathbf{R_{u,2\%} = \gamma_b * \gamma_f * \gamma_\beta * f(\xi) * H_{m0}}$ Where γ_b, γ_f, and γ_β are reduction factors for a berm, surface roughness, and oblique wave attack, respectively.

3.4 Roughness Factor (γ_f)

The surface roughness and permeability of a structure significantly affect wave run-up by dissipating energy. The roughness factor (γ_f) adjusts the calculated run-up, with smoother, impermeable surfaces having higher values.

Structure Type / Surface	Typical γ_f Value
Smooth concrete (vertical / sloping)	1.00
Grouted stone / smooth armor units	0.90 – 1.00
Tetrapods / Accropode / Xbloc (single-layer)	0.55 – 0.75
Two-layer rock armour (impermeable core)	0.55
Two-layer rock armour (permeable core)	0.40
Very rough porous rubble mound	0.35 – 0.45

4.0 Hurricane Impact Data

Hurricanes are a primary driver of extreme coastal conditions, generating significant storm surge and large waves that test coastal defenses.

4.1 Storm Surge by Hurricane Category

Category	Winds (mph)	Storm Surge (feet)	Description
Tropical Storm	39–73	0–3	Minor
Category 1	74–95	3–5	Minimal
Category 2	96–110	5–7	Moderate
Category 3	111–130	7–12	Extensive
Category 4	131–155	12–15	Extreme
Category 5	156+	15–20+	Catastrophic

4.2 Costliest Atlantic Hurricanes

Rank	Hurricane	Category	Season	Damage (USD)
1	Katrina	5	2005	$125 billion
2	Harvey	4	2017	$125 billion
3	Ian	5	2022	$113 billion
4	Maria	5	2017	$91.6 billion
5	Irma	5	2017	$77.2 billion
6	Ida	4	2021	$75.3 billion
7	Sandy	3	2012	$68.7 billion
8	Ike	4	2008	$38 billion
9	Andrew	5	1992	$27.3 billion
10	Ivan	5	2004	$26.1 billion

4.3 Deadliest Atlantic Hurricanes

Rank	Hurricane	Category	Season	Fatalities
1	"Great Hurricane"	?	1780	22,000–27,501

2	Mitch	5	1998	11,374+
3	Fifi	2	1974	8,210–10,000
4	"Galveston"	4	1900	8,000–12,000
5	Flora	4	1963	7,193
6	"Pointe-à-Pitre"	?	1776	6,000+
7	"Okeechobee"	5	1928	4,112+
8	"Newfoundland"	?	1775	4,000–4,163
9	"Monterrey"	3	1909	4,000
10	"San Ciriaco"	4	1899	3,855

4.4 Miscellaneous Atlantic Hurricane Records

Record	Value	Name	Category	Season
Distance traveled	6,500 miles (10,500 km)	Alberto	3	2000
Highest forward speed	69 mph (111 km/h)	Six	TS	1961
Largest in diameter	1,150 miles (1,850 km)	Sandy	3	2012
Longest duration (non consecutive)	28 days	"San Ciriaco"	4	1899
Longest duration (consecutive)	27.25 days	Ginger	2	1971
Longest duration (at category 5)	3.6 days	"Cuba"	5	1932