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May 12, 2009

Mark Curry
Industrial Economics, Incorporated
2067 Massachusetts Avenue
Cambridge, MA 02140

RE: Margara Reef Repair Project, Project Site Wave Data and Reef Repair Stability Analysis

Dear Mark:

This letter is provided to present the results of the wave data and stability analysis for the reef repair to be performed at the T/V Margara Grounding Site, located along the outer portion of Bahia de Tallaboa, Commonwealth of Puerto Rico. We have completed our engineering analysis of the various potential wave conditions at the reef repair site, and determined the minimum required weight for each independent reef repair unit. We assumed a water depth of 35 feet at the repair sites, which provides the critical depth for the repair. The stability analysis was based on coastal engineering practice for evaluating the weight of a single limestone boulder placed on the bottom under the design wave conditions. We assumed no active attachment to the bottom, considering that the attachment substrate is variable, and in some cases limited in terms of imparting stability. Attached are several tables that summarize our findings, which are described below.

Wave Analysis

A wave analysis was performed at the site of the reef repair to evaluate potential storm conditions for the stability analysis. Offshore waves were determined from the NOAA Wavewatch data at a depth of 3278 feet (999 meters) and were evaluated for various storm return interval conditions. The mean significant offshore wave heights ranged from 9.8 feet (3.0 meters) for the 1-year return interval storm to 31.4 feet (9.6 meters) for the 100-year return interval storm. The results are provided in the attached tables and plots for the various return interval storm conditions. The data is provided in both feet and meters.

The deep water waves were transformed into the shallow waters of the repair site as there is no continuous long-term recorded wave data at the repair site. Nearshore waves were then evaluated to determine conditions at the project site. The depth of water at the repair site was taken to be 35 feet (10.7 meters). The mean significant nearshore wave heights at this depth range from 9.1 feet (2.8 meters) for the 1-year return interval storm to 34.6 feet (10.5 meters) for the 100-year return interval storm. The results are provided in the attached tables and plots for the various return interval storm conditions.

The maximum storm surge documented in the area was recorded to be 2.44 feet above the normal water level on September 6, 1928 (CHL, 2000). Therefore, during storm conditions, the water depth at the site could be up to 38 feet, which translates to a maximum wave height of about 30 feet. Based on the wave data described above and attached, a 30 ft wave at the repair site is approximately equivalent to the 40-year storm event. Larger waves generated by bigger storms would be forced to break in deeper water than exists at the site. Of course, smaller storms would yield smaller waves and lower design forces.

Stability Analysis

An evaluation of limestone boulders placed on the reef surface was used to conduct the reef repair stability analysis. It is recognized, however, that the actual reef repair will likely include a repair unit consisting of limestone boulders and/or rock bound together with concrete. At the reef repair site, the stability of boulders placed underwater is governed by storm conditions. Storm wave conditions at the repair site are based on storm events and depth-limited waves. As described above, the water depth at the repair site during storm conditions could be up to 38 feet. The depth limited wave for this condition is about 30 feet, which approximates the 40-year storm event. The results for the 5, 10, 20 and 50 year return interval storms are attached. A range of storm conditions were analyzed by the following methodology to evaluate boulder stability.

Limestone boulders with a minimum density of 140 pounds per cubic foot (saturated, surface dried) were assumed in the evaluation of the reef repair. We used 140 pounds per cubic foot (pcf) because we understand that the available limestone of southern Puerto Rico generally has densities of 140 pcf or greater. The boulders were evaluated for stability with average diameters of 2.5, 3.0, 3.5 and 4.0 feet. Table 1 is provided which presents the values used in conducting the stability analysis.

TABLE 1
REEF REPAIR STABILITY ANALYSIS
EVALUATION VALUES

Density of Seawater (ρ)	1.99	slugs/ft^3	(SPM, 1984)
Weight Density of Seawater (g_{sw})	64	pcf	(SPM, 1984)
Drag Coefficient (C_D)	0.4		(Torum, 1994)
Added Mass Coefficient (C_M)	1.5		(SPM, 1984)
Lift Coefficient (CL)	0.4		(Torum, 1994)
Coefficient of Static Friction Rubble Stone (μ)	0.75		(CEM, 2006)

Sliding Stability

Wave forces acting on the boulder are due to friction (drag) of the water on the boulder surface and the acceleration of the fluid around the structure. For this study the drag force is calculated as:

$$F_D = 0.5\rho C_D A u^2 \quad (1)$$

Where ρ is the density of water, C_D is the coefficient of drag, u is the horizontal wave particle velocity determined using stream function theory. The inertia force is then calculated as:

$$F_I = \rho C_M V du/dt \quad (2)$$

Where C_M is the 'added mass' coefficient assumed to be equal to 1.5 (SPM, 1984). V is the volume of the boulder assumed to be $0.65D^3$ (SPM, 1984), and *du/dt* is the wave particle horizontal acceleration acting at the depth of the boulder centroid.

The total force acting on the boulder is the sum of the drag and inertia forces:

$$F_T = F_D + F_I \quad (3)$$

Since both the drag and inertia forces are functions of time, the forces have been evaluated numerically over the wave period for the input wave conditions to determine the maximum force.

The resistance to motion of the boulder is calculated in terms of a restoring force. For this analysis a value of 0.4 has been adopted for the coefficient of drag (Torum, 1994). Boulder resistance to sliding is due to friction between the boulder and the bottom and is calculated by:

$$F_{fric} = \mu F_N \quad (4)$$

Where μ is the coefficient of static friction and F_N is the normal force of the boulder acting on the boulder/bottom interface. A value of 0.75 has been adopted for μ (CEM, 2006). The normal force is determined by:

$$F_N = W_{im} - F_L \quad (5)$$

Where W_{im} is the immersed weight of the boulder:

$$W_{im} = (\gamma_W - \gamma_{SW})V \quad (6)$$

γ_W is the dry weight density of the boulder, and γ_{SW} is the weight density of seawater. F_L is the wave induced lifting force acting on the boulder:

$$F_L = 0.5\rho C_L A u^2 \qquad (7)$$

Where the coefficient of lift (C_L) is assumed to be 0.4 (Torum, 1994).

For this study the stability of the boulder is cast in terms of a safety factor, which relates the resisting forces to the wave forces:

$$FS_{sliding} = F_{fric} / F_T \qquad (8)$$

The safety factor provides an assessment of the relative stability of the boulder. A safety factor of less than one implies boulder instability and the likelihood of boulder movement. Safety factors greater than one imply relative stability of the boulder with the level of certainty increasing with the value of the safety factor.

Tumbling Stability

Tumbling (or rolling) of the boulder will occur if the moment of the wave forces acting on the boulder is greater than the restoring moment. The wave-induced moment acting on the boulder is calculated as:

$$M_T = F_T l_T \qquad (9)$$

Where l_T is the moment arm distance between the boulder center of gravity and the center of pressure of the wave induced pressure field acting on the boulder. In order to simplify the moment arm calculation, the moment arm is assumed to be the distance from the boulder center of gravity to the bottom of the boulder (approximately ½ of the stone diameter).

Resistance to tumbling is due to the weight of the boulder and is calculated as:

$$M_N = F_N l_N \qquad (10)$$

Where the restoring moment arm l_N is taken as the horizontal distance between the center of gravity and the boulder corner (taken as approximately ¼ of the stone diameter). The relative stability of the boulder against tumbling has again been expressed in terms of a factor of safety which relates the relative magnitudes of the restoring and wave induced moments:

$$FS_{tumbling}=M_N/M_T \qquad (11)$$

Similar to the sliding factor, a safety factor of less than one implies boulder instability and the likelihood of boulder tumbling under critical wave conditions. Safety factors greater than one imply relative stability of the boulder with the level of certainty increasing with the value of the safety factor.

Results

Based on wave analysis, an approximate 40 year storm event creates the most critical wave condition at the reef repair site. The most critical wave to effect the site is an approximate 30 foot wave with a 2 to 3 foot storm surge in 35 feet of water. The analysis considers the placement of a single limestone boulder on the bottom, and assumes no active attachment such as rebar attachment. We recognize that a single boulder will likely not be used, but this analysis can be applied to a "repair unit" in place of a single boulder.

The attached results indicate that a boulder with a minimum nominal dimension 3.5 feet will be stable with respect to sliding and tumbling during a 40-year storm event as the safety factors are greater than one. The estimated weight of each boulder or repair unit is 2 tons assuming a density of 140 pounds per cubic foot. Less dense rock or less dense repair unit would result in an increase in the size in order to meet weight requirements for stability. The stability analysis was performed based on these parameters and resulted in a safety factor for sliding of 1.4 and a safety factor for tumbling of 1.1. If a repair unit is employed and includes the use of concrete to bind the unit, an added factor of safety will be provided by the concrete binding to the reef surface because friction between the unit and the reef surface would be greater than that of a limestone boulder surface.

Assuming the use of a boulder, the least dimension of each boulder should not be less than one-third (1/3) of the greatest dimension of that boulder. Each boulder should be placed with its greatest dimension parallel to the bottom. Similarly, a reef repair unit of a combination of limestone boulders (small) and concrete should be stable in configuration and relatively low relief.

For the purposes of this evaluation, the boulders were not considered to be attached to the bottom with rebar or by any other means. The analysis included the evaluation of friction to prevent movement of the repair unit under a variety of storm events. However, it was determined that the 40 year interval storm at the 35 foot depth is a likely worst case scenario, as it provides about a 30 foot wave to the repair site. Larger storms will likely result in larger waves and a wave break occurring in deeper water. Smaller storms deliver less energy to the bottom at 35 foot depth. Therefore, the 40-year storm event provides the critical design criterion.

As previously stated, the actual repair can consist of a unit comprised of boulders and/or smaller rock bound together with concrete. Concrete used to bind boulders together will introduce adherence to the bottom further increasing the stability of the repair unit. The repair unit must include a cumulative weight of at least 2 tons in boulders or stones firmly bound together with concrete in a relatively low profile form to be stable under all storm conditions. The unit can consist of at least 4 half ton boulders or at least 8 quarter ton boulders, etc. bound firmly together as a single unit in a fairly low profile shape. A unit of greater weight than the minimum 2 tons will provide a greater factor of safety in terms of reef repair unit stability. The appropriate engineering evaluation of each of the units will address the stability factors of importance.

If you should have any questions, please call me.

Sincerely,

COASTAL PLANNING & ENGINEERING, INC.

Richard H. Spadoni
Senior Vice President

cc: Tom Pierro, P.E., CPE
Andrew Wycklendt, CPE

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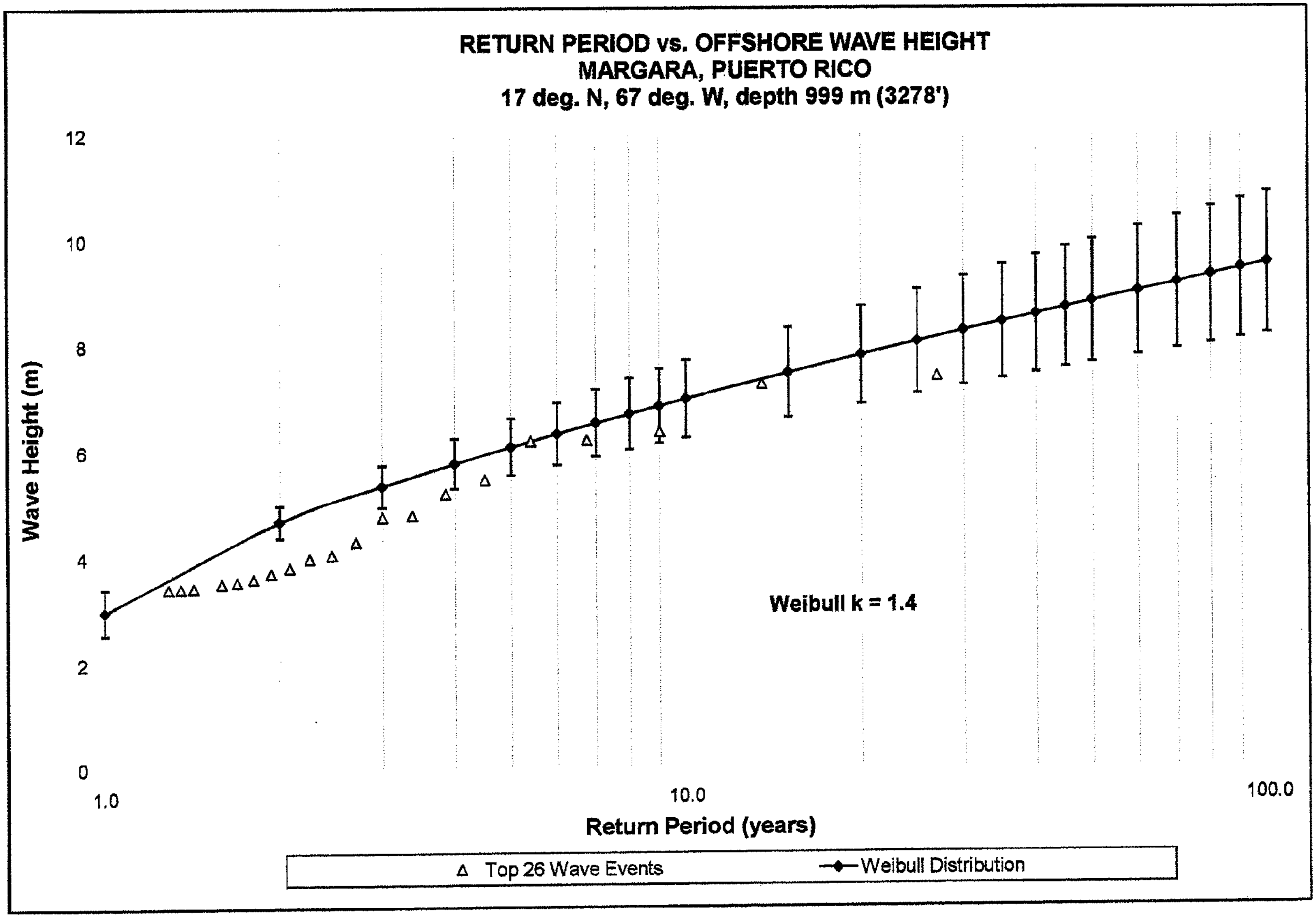
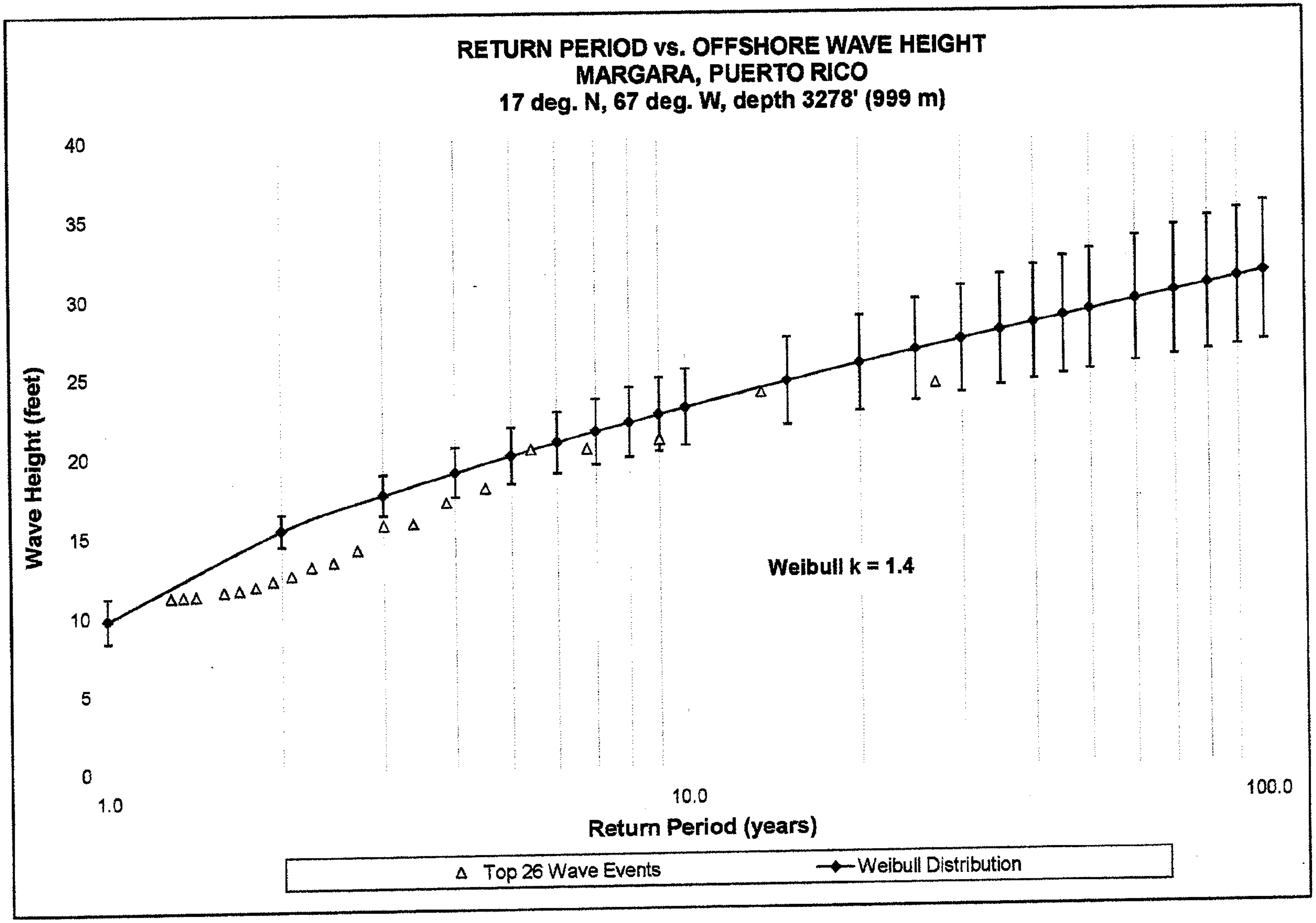
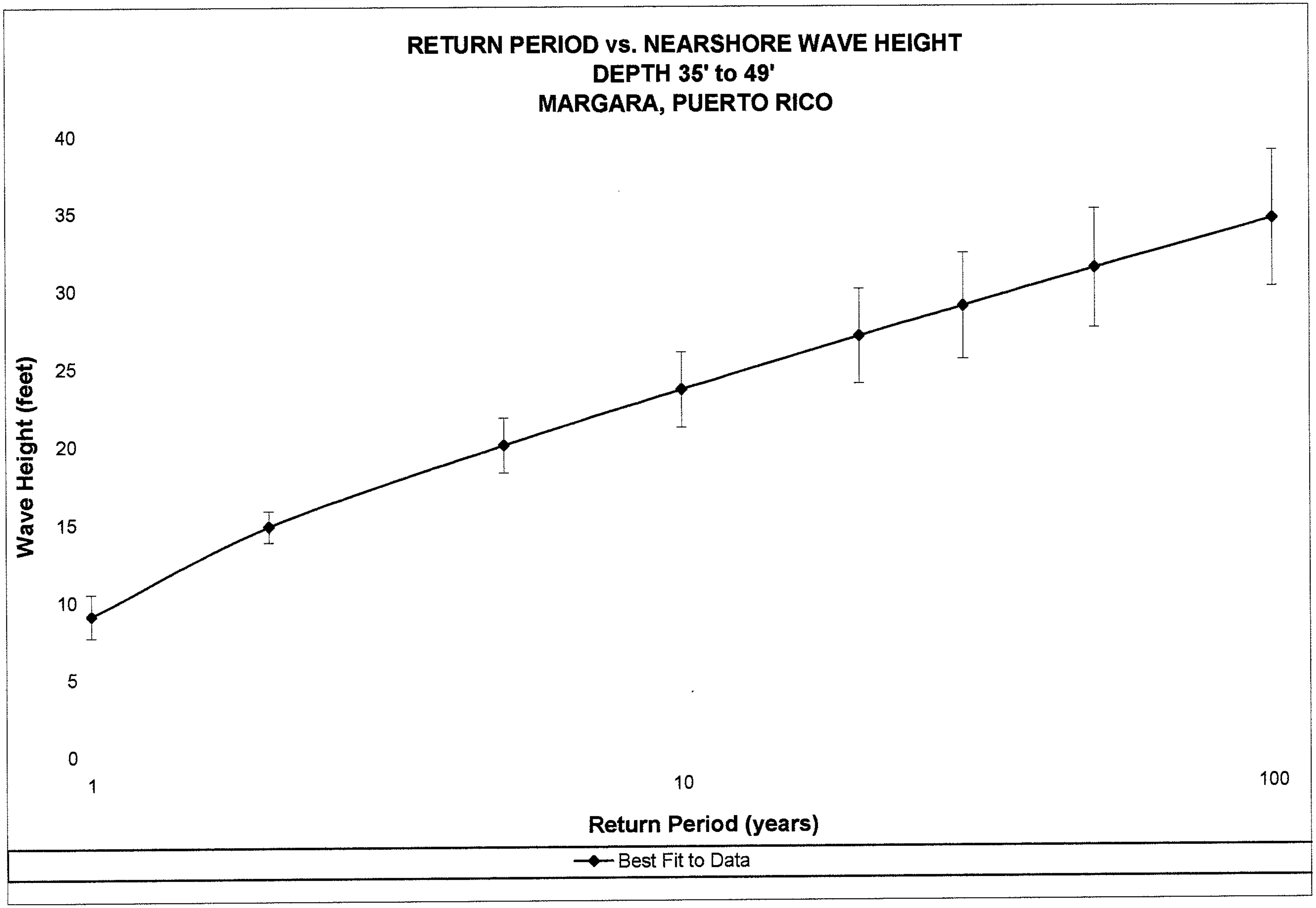
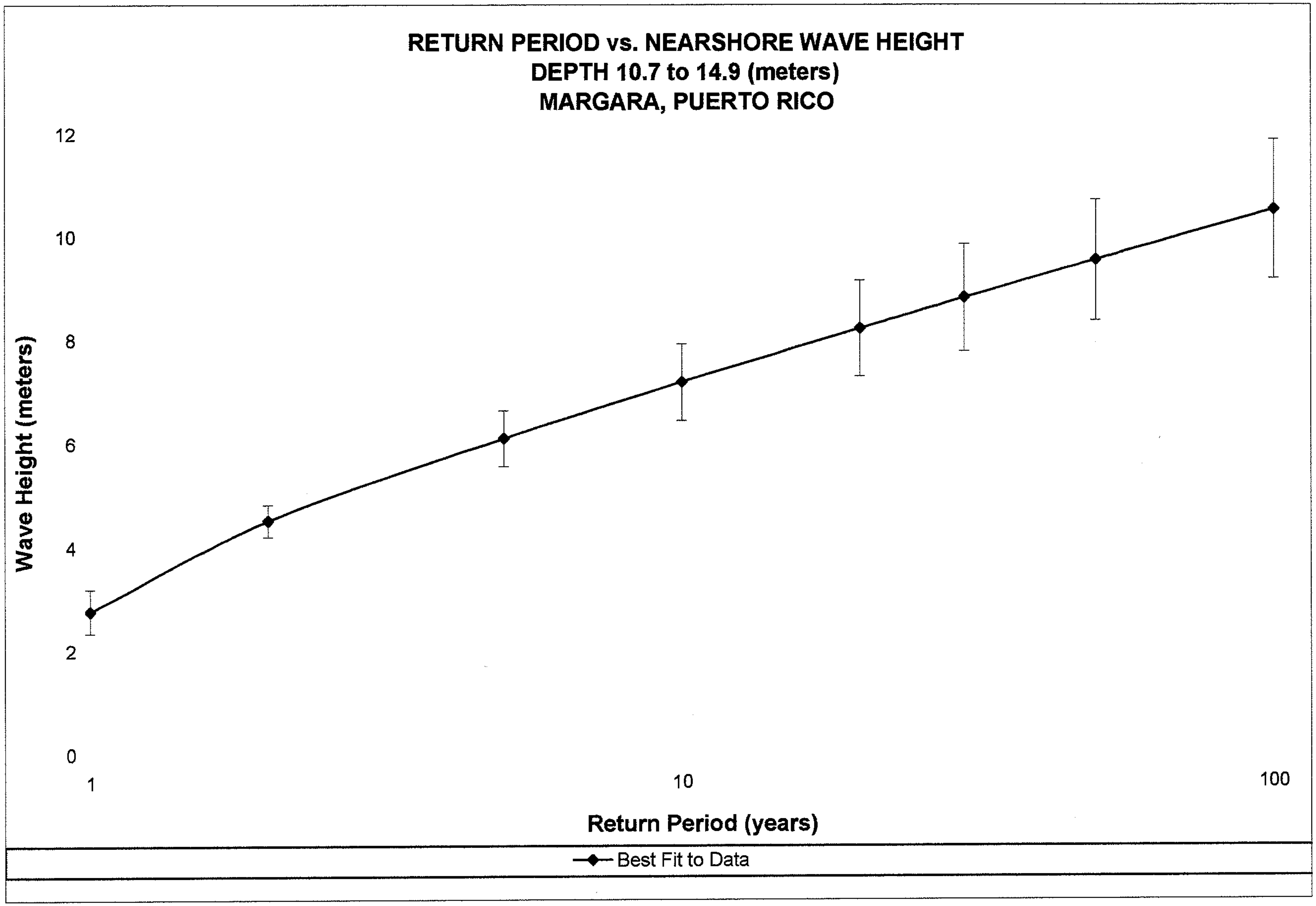

RETURN PERIOD vs. OFFSHORE WAVE HEIGHT
MARGARA, PUERTO RICO
17 deg. N, 67 deg. W, depth 999 m (3278')
Wave Height (m)
12
10
8
6
4
2
0
1.0
10.0
100.0
Return Period (years)
Weibull k = 1.4
Top 26 Wave Events
Weibull Distribution


RETURN PERIOD vs. OFFSHORE WAVE HEIGHT
MARGARA, PUERTO RICO
17 deg. N, 67 deg. W, depth 3278' (999 m)
Wave Height (feet)
40
35
30
25
20
15
10
5
0
1.0
10.0
100.0
Return Period (years)
Weibull k = 1.4
Top 26 Wave Events
Weibull Distribution


RETURN PERIOD vs. NEARSHORE WAVE HEIGHT
DEPTH 35' to 49'
MARGARA, PUERTO RICO
Wave Height (feet)
40
35
30
25
20
15
10
5
0
1
10
100
Return Period (years)
Best Fit to Data


RETURN PERIOD vs. NEARSHORE WAVE HEIGHT
DEPTH 10.7 to 14.9 (meters)
MARGARA, PUERTO RICO
Wave Height (meters)
12
10
8
6
4
2
0
1
10
100
Return Period (years)
Best Fit to Data

RETURN PERIOD, OFFSHORE WAVE HEIGHT, AND PERIOD
MARGARA, PUERTO RICO

Return Period (years)	Significant Wave Height (feet)		Significant Wave Height (meters)		Peak Wave Period (seconds)	
	Mean	σ	Mean	σ	Mean	σ
1	9.8	1.4	3.0	0.4	8.2	0.4
2	15.4	1.0	4.7	0.3	9.8	0.3
5	20.0	1.8	6.1	0.5	11.1	0.5
10	22.9	2.4	7.0	0.7	11.9	0.7
20	25.7	3.0	7.8	0.9	12.7	0.9
30	27.2	3.4	8.3	1.0	13.1	1.0
50	29.0	3.8	8.8	1.2	13.7	1.1
100	31.4	4.4	9.6	1.3	14.3	1.3

Notes:

1. Location: Latitude 17 deg. N, Longitude 67 deg. W.
2. Depth is 3278 feet (999 meters).
3. NOAA Wavewatch forecast reference:
   http://polar.ncep.noaa.gov/waves/download.shtml
   ftp://polar.ncep.noaa.gov/pub/history/waves

RETURN PERIOD, NEARSHORE WAVE HEIGHT, AND PERIOD
MARGARA, PUERTO RICO

Return Period (years)	Significant Wave Height (feet)		Significant Wave Height (meters)		Peak Wave Period (seconds)	
	Mean	σ	Mean	σ	Mean	σ
1	9.1	1.4	2.8	0.4	8.2	0.4
2	14.9	1.0	4.5	0.3	9.8	0.3
5	20.1	1.8	6.1	0.5	11.1	0.5
10	23.6	2.4	7.2	0.7	11.9	0.7
20	27.0	3.0	8.2	0.9	12.7	0.9
30	29.0	3.4	8.8	1.0	13.1	1.0
*50	31.4	3.8	9.6	1.2	13.7	1.1
*100	34.6	4.4	10.5	1.3	14.3	1.3

Notes:

1. Depth is at site is 35 feet (10.7 meters).
2. Maximum Storm Surge is 2.44 feet recorded on September 6, 1928 (CHL, 2000).
3. * Indicates wave height exceeds depth limited breaking wave height, therefore wave would break further offshore.
4. NOAA Wavewatch forecast reference:
   http://polar.ncep.noaa.gov/waves/download.shtml
   ftp://polar.ncep.noaa.gov/pub/history/waves

REEF REPAIR STABILITY ANALYSIS
MARGARA, PUERTO RICO

Return Period (years)	Nominal Boulder Dimension (feet)	(meters)	Rolling Safety Factor (M_N/M_T)	Sliding Safety Factor (F_{fric}/F_T)
5	2.5	0.76	1.7	2.3
	3.0	0.91	1.9	2.6
	3.5	1.07	2.0	2.8
	4.0	1.22	2.2	5.4
10	2.5	0.76	1.2	1.7
	3.0	0.91	1.5	2.0
	3.5	1.07	1.6	2.2
	4.0	1.22	1.7	3.8
20	2.5	0.76	0.9	1.2
	3.0	0.91	1.1	1.5
	3.5	1.07	1.3	1.7
	4.0	1.22	1.4	2.8
*50	2.5	0.76	0.7	0.9
	3.0	0.91	0.9	1.2
	3.5	1.07	1.1	1.4
	4.0	1.22	1.2	2.1

Notes:

1. Depth at site is 35 feet (10.7 meters).
2. * Indicates wave height exceeds depth limited breaking wave height, therefore wave would break further offshore.
3. Design boulder density is 140 pcf.
4. Rolling Safety Factor ($M_{Rolling}$) = M_N/M_T; if $M_N/M_T < 1$ not stable.
5. Sliding Safety Factor ($F_{Sliding}$) = F_{fric}/F_T; if $F_{fric}/F_T < 1$ sliding occurs.
6. Estimated boulder weight:

Nominal Diameter (feet)	Weight (lbs)	(tons)
2.5	1422	0.71
3.0	2457	1.23
3.5	3902	1.95
4.0	5824	2.91