

## CHAPTER 51

### STABILITY OF QUADRIPOD COVER LAYERS \*

by

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#### ABSTRACT

The purpose of this paper is to present the results of a four-year study of the stability of a prototype breakwater armor layer composed of 28-ton concrete quadripods. The study was conducted by measuring the incident wave height and the quadripod movements during this period. The ultimate goal of this study is the verification of empirical breakwater design equations.

#### INTRODUCTION

In the past decade considerable effort has been expended to derive rational methods for the design of cover layers for rubble-mound structures. Generally, these methods have been reduced to formulas based on dimensional or theoretical analysis, but contain experimentally determined coefficients for each armor shape. Due to the relatively large size of prototype breakwater armor units, model tests under carefully controlled conditions are generally used to determine these coefficients. In order to verify the results of model tests, the seaward end of the Santa Cruz Harbor West Jetty, which contains 28-ton concrete quadripods, was instrumented so that the incident wave heights and quadripod displacements could be measured. This paper provides information on the design and construction of the jetty, the instrumentation, and the results of measurements taken over the past four years. The quadripod armor unit is protected by patents owned by Etablissements Neyric and Societe d'Exploitation de Brevets Pour Travaux a la Mer, Grenoble, France.

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BASIS FOR DESIGN

Santa Cruz Harbor is located at the northerly end of Monterey Bay about 65 miles south of the entrance to San Francisco Bay. A location map and a plan of the harbor are shown on Plate 1. The harbor was formed by development of Woods Lagoon, a shallow fresh water pond near the eastern boundary of the City of Santa Cruz. The shoreline in the immediate vicinity consists of sandy beaches backed with a relatively high marine terrace. Harbor elements include an entrance channel, protected by jetties, 100 feet wide and 20 feet deep; an interior access channel 150 feet wide and 15 feet deep reducing to 10 feet within the principal harbor area; a turning basin 250 feet by 300 feet and 10 feet deep; and mooring basins with an initial capacity of almost 400 recreational craft. Wave approach from the ocean is limited to the south to southwest sector by Point Cypress, a projecting headland south of Monterey Bay and by Point Santa Cruz, which is about one and one-half miles to the southwest. Accordingly, the jetties are aligned slightly east of south, the east jetty about 800 feet in length and the west jetty 1,200 feet in length with the outer 250 feet turned 50 degrees easterly to protect the entrance channel and harbor from all storm waves.

Wave Analysis

Based on deep water wave studies, relatively large (25 feet or greater) deep water waves from the south through southwest direction have been produced during storms in the past decade. A refraction analysis was made for waves of various periods and directions which may approach the harbor. The analysis consisted of the construction of refraction-fan diagrams diverging from the head of the jetties. With deep water directions determined, companion orthogonals were projected shoreward to determine the refraction coefficients. The maximum theoretical height of wave that would reach the jetties was then determined taking into account the refraction coefficient, the depth of water, the shoaling coefficient, and the seaward slope of the bottom. The maximum breaker height at the jetties was determined to be 21.2 feet and could be produced by a 16 second wave from the SSW with deepwater significant heights of 24.8 feet. This value was rounded to 21 feet and selected as the design wave.

Jetty Design

Design of the structure was based on available criteria published by the Corps of Engineers, principally "Shore Protection Planning and Design, Technical Report No. 4." Based on comparative costs of a number of alternatives, quadripod-rubble-mound construction was determined to be the most economical. The quadripod armor layer was limited to the outer 400 feet of the west jetty.

Armor Layer

Determination of the weight of the armor unit was based on the Hudson or WES equation. The equation is:

$$W_r = \frac{\gamma_r H^3}{K_\Delta (Sr-1)^3 \cot \alpha}$$

where  $W_r$  = the weight of armor unit in primary cover layer, lbs,  $\gamma_r$  = specific weight of armor unit, lbs/ft<sup>3</sup>; H = design wave height ft.,  $K_{\Delta}$  = experimentally determined coefficient,  $S_r$  = specific gravity of the armor unit relative to the water in which it is immersed, and  $\alpha$  = angle of breakwater slope measured from the horizontal.

For the quadripod sections, the selected design called for two layers of 25-ton quadripods (pell mell) placed on a 1 on 2 slope along the trunk and on a 1 on 3 slope around the conical head section. The quadripods were backed by a concrete cap, essentially 18 feet wide and 10 feet thick to prevent displacement of armor units from the cap by overtopping waves. The quadripods were underlaid by a 6 foot B stone layer (50% greater than 6,000 lbs., minimum 4,000 lbs.) and a C stone core 4,000 lbs to 4" (50% greater than 500 lbs.). Crest height was established at +16.0 M.L.L.W. datum. Typical quadripod dimensions are shown in Plate 2. A typical cross section is shown in Plate 3

Substituting actual constructed values (e.g., 28 ton quadripods) and currently accepted  $K_{\Delta}$  values in the foregoing stability equation indicates that the structure would be stable for a design wave of 25 feet.

#### QUADRIPOD CONSTRUCTION

Construction of the jetties, employing standard equipment and methods, was noteworthy principally for the ease and simplicity of quadripod construction and placement. Steel forms, comprising 8 top sections and 48 bottom sections were utilized in the casting of the quadripods. A 6-man crew, working a 9-hour day, cast the required 900 quadripods in 114 working days extending from 27 July 1962 to 5 February 1963. One quadripod was cast the first day, three the third day, and eight on all other days. The average time to strip eight top forms and connect to bottom forms was 1.77 hours; casting eight quadripods required approximately 5.0 hours, and average time for stripping bottom forms and storing was 2.12 hours. The daily operation provided for removal of top forms with a minimum time lapse of 18 hours after casting and removal of the quadripods from the bottom forms after a minimum 5-day cure period. A special lifting sling was used at the casting yard to keep all legs in compression. Transit-mix concrete (6-1/2 cubic yards truck capacity) was employed with placement utilizing one Link Belt crawler crane and two 3-1/2 cubic yards concrete buckets. Each quadripod was numbered in the order cast.

Hauling and placing started 2 November 1962 and was completed 5 March 1963, with a total of 122 working days. Quadripods were not placed continuously throughout the job. On days when quadripods were placed, daily placement ranges from a maximum of 69, with an overall daily average of 41. The quadripods were loaded at the storage yard by a crane onto a tractor drawn (40-ton capacity) low-boy trailer. At the jetty, a Lima Crawler crane, Series 2400, with a 100-foot boom, using a double cable sling with a quick release hook attachment lifted the quadripods from the trailer and placed them on the seaward slope of the west jetty.

INSTRUMENTATION AND MEASUREMENTS

Upon completion of the structure, detailed surveys were conducted to serve as a basis for measurement of future displacements. These surveys consisted of establishment (horizontally and vertically) of 5 standard brass disks in the concrete cap. Steel pins were set in each corner of concrete cap pours and in 44 numbered quadripods throughout the upper layer. Repeat measurements of all monuments and pins have been taken annually and of selected quadripod pins after stormy periods. Horizontal and vertical distances are measured from the cap by standard surveying techniques. Vertical displacements recorded during the 4-year period to April 1967 are summarized in the table following. All quadripods above water are also identified in aerial photographs of the seaward portion of the jetty.

Vertical Displacement (feet)		QUADRIPOD VERTICAL DISPLACEMENT			
		Number of Quadripods			
		June 63 to June 64	June 64 to June 65	June 65 to May 66	May 66 to April 67
0	- 0.05	21	21	21	22
0.06	- 0.10	8	5	12	5
0.11	- 0.20	6	6	5	2
0.21	- 0.40	5	2	3	2
0.41	- 0.60	1		1	1
0.61	- 0.80				1
0.81	- 1.00				1
>	- 1.00	2		1	1
		43	34	43	33

With the exception of a few quadripods near the jetty head, no significant movements have occurred. The maximum cap settlement is about 0.1 foot, near the seaward end. Quadripods on the head section are also moving, however, the largest displacements occurred during the initial measurements and with but few exceptions the displacements are extremely small. The armor units appear to be consolidating in predicted manner in that, with settlement, the individual units tend to interlock thus providing for maximum stability. In general, movement of a few units is not indicative of failure in the structure. Horizontal and vertical displacements are shown on Plates 4 and 5, respectively.

Design waves for coastal structures are calculated for the condition before the structure has been built. Thus in any attempt to verify the design formulas a wave for a similar condition must be obtained. In order to measure the waves at the structure as they would be without the structure in place, a wave gage was located 400 feet seaward off the end of the west jetty in an area of low reflected waves. In this location it was impractical to construct a platform at the desired gauging location so it was necessary to use a subsurface pressure transducer connected with a cable to a wave gage on shore. The wave sensor installed initially was one which

permitted detection of pressure fluctuations such as sea and swell waves, but canceled out long period pressure fluctuations such as those resulting from tides. One advantage of this system is that the sea and swell waves are clearly shown without the effect of the tides and additionally results in better utilization of chart paper. After the first year's operation a check of the overall accuracy of the system, independent of the theoretical and electrical calibration built into the wave recorder, was developed through bypassing the filter. Thus the sensor responds to absolute pressure less the static head including the tides. On days when the sea is essentially calm, the recorder trace is due to the tides alone and may be quickly checked by comparison with predicted values. In addition, a portable tide recorder occasionally placed in operation inside the harbor permits comparison of records. This comparison is considered to be an independent check. Atmospheric pressure fluctuations are neglected in this study.

The shore based equipment consists of a strip chart type recorder and a "Beach Erosion Board" magnetic tape recorder. Normally, the significant wave height is read from the strip chart every six hours at the U. S. Weather Bureau synoptic interval. During periods of high waves, detailed spectral analyses are made by the U. S. Army Coastal Engineering Research Center from the magnetic tapes.

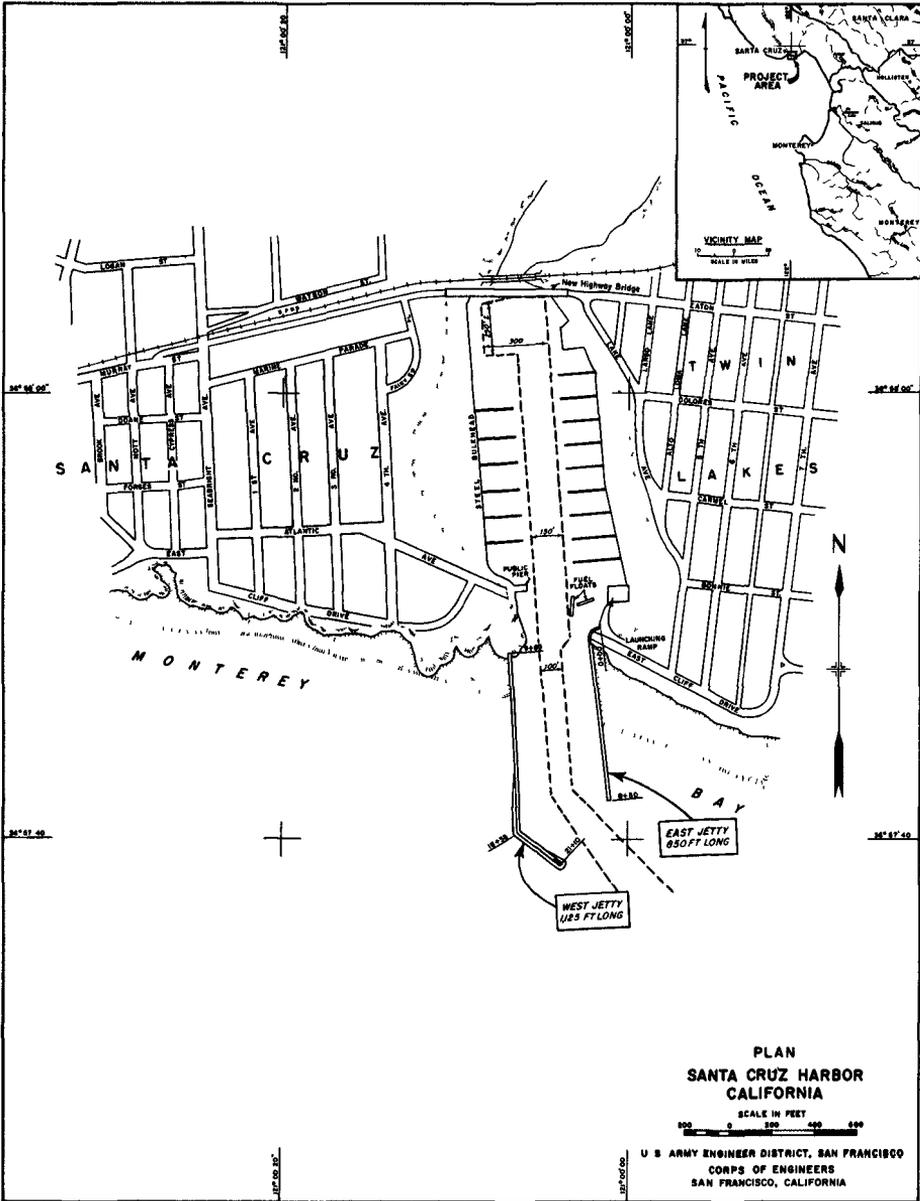
The maximum monthly significant wave heights recorded to date are given in the table following. The highest wave recorded during the study was recorded on 12 December 1967 when the significant wave height reached 12.7 feet. It is obvious that these values are well below that expected to cause displacement or failure.

MAXIMUM SIGNIFICANT WAVE HEIGHTS  
RECORDED AT SANTA CRUZ

Months	Years						Average
	1963	1964	1965	1966	1967	1968	
January	5.9	10.3	6.7	-	-	4.0	6.7
February		3.5	2.8	6.0	-	-	4.1
March		3.4	2.1	4.5	-	-	3.3
April		3.8	1.4	1.0	-	-	2.1
May		3.5	1.5	-	-	-	2.5
June		4.2	1.3	-	-	8.4	4.6
July		3.0	-	3.4	-	3.1	3.2
August		2.6	-	-	-	3.8	3.2
September		4.1	-	-	-	4.2	4.1
October	5.0	-	-	-	-	6.8	5.9
November	5.3	7.8	-	-	-	5.2	6.1
December	4.2	8.7	-	-	12.7	-	8.5

#### CONCLUSIONS

Based on repeated measurements of selected points in the seaward portion of the Santa Cruz West Jetty, it is concluded that no displacements have occurred that approach those to be expected from failure, thus no verification of the breakwater stability equation is possible at this time. The measurements taken to date, however, provide a record of progressive reaction of the structure to storm waves.





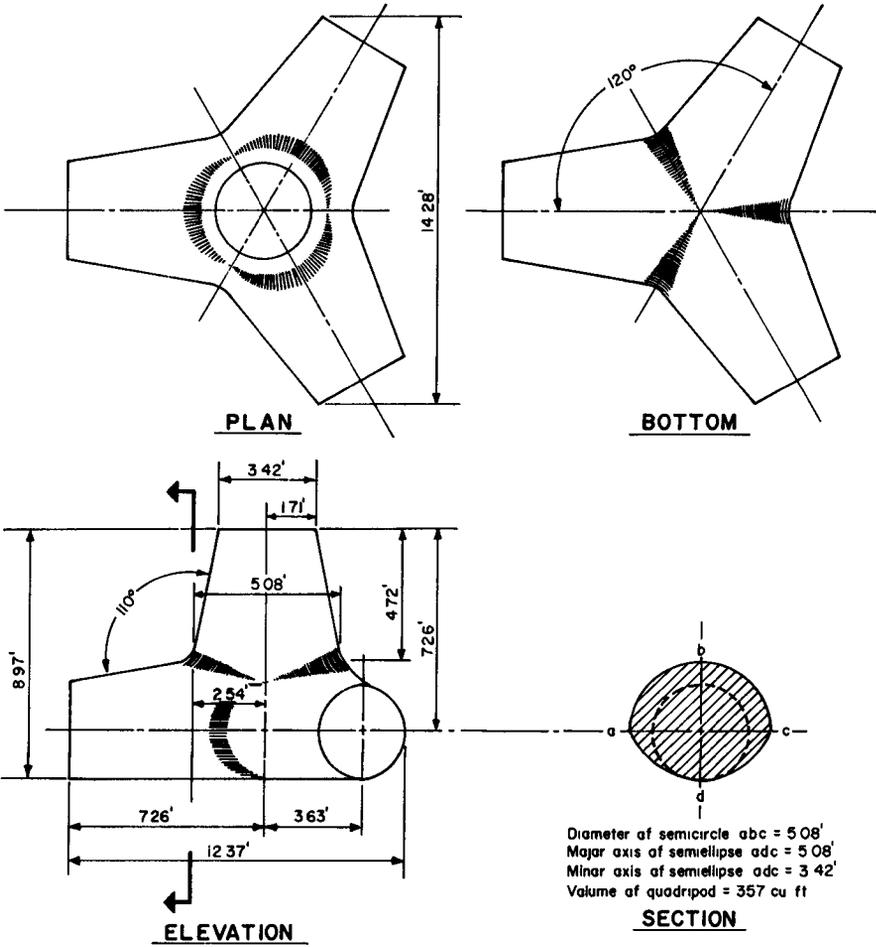


PLATE 2

SANTA CRUZ HARBOR  
CALIFORNIA  
QUADRIPOD DIMENSIONS

U.S. ARMY ENGINEER DISTRICT, SAN FRANCISCO  
CORPS OF ENGINEERS  
SAN FRANCISCO, CALIFORNIA



