ATTACHMENT 1

Rincon Island and Open Causeway Construction. Journal of Waterways and Harbors Division of the American Society of Civil Engineers (Blume, J. and Keith, J., September 1959)

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RINCON OFFSHORE ISLAND AND OPEN CAUSEWAY

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SYNOPSIS

This paper presents the design problems and the construction techniques involved in creating a man-made island of sand, rock and precast concrete armor in the Pacific Ocean offshore from California. This oil production island with the open causeway which connects it to the shoreline constitutes one of the most unique marine installations in the world. The design included many alternate economic studies, model tests in a wave laboratory, and storm damage and wave runup studies with alternate armor types, materials, densities and slopes. The field operations included skin diving and the use of special fathometers in control operations for underwater placement.

INTRODUCTION

The State of California, through its Lands Commission, called for competitive bids in 1954 for the exploration and development of and the production of oil and gas from an offshore area of 1,175 acres called Rincon Lease. This submarine land lies offshore from existing production walls located on piers constructed many years ago. The oil company bidders were to provide all necessary installations at no cost to the State. Offshore facilities had to be in accordance with the then existing requirements and court rulings which essentially specified "solid man-made islands of natural materials".

Richfield Oil Corporation was pronounced the successful bidder since it offered greater oil royalties to the State than any of the many other oil companies that bid. After some legal delays, Richfield was awarded the lease and told to proceed. The engineering firm, John A. Blume & Associates, Engineers, which had already performed various preliminary offshore studies as consultants to Richfield, was in turn told to proceed with the engineering

Note: Discussion open until February 1, 1960. To extend the closing date one month, a written request must be filed with the Executive Secretary, ASCE. Paper 2170 is part of the copyrighted Journal of the Waterways and Harbors Division, Proceedings of the American Society of Civil Engineers, Vol. 85, No. WW 3, September, 1959.

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phases of the project except those pertaining to oil exploration and production which were to be done by the client. This was the start of a project which not only developed considerable "romantic" appeal to the public and in the press before completion in 1958, but also included new techniques, storm risks without precedent, and unusual economic considerations in marine and offshore construction.

Project Location and General Description

Rincon Lease is located offshore between Santa Barbara and Ventura as shown on Figs. 1 and 2. Rincon Island No. 1 was located by the client within

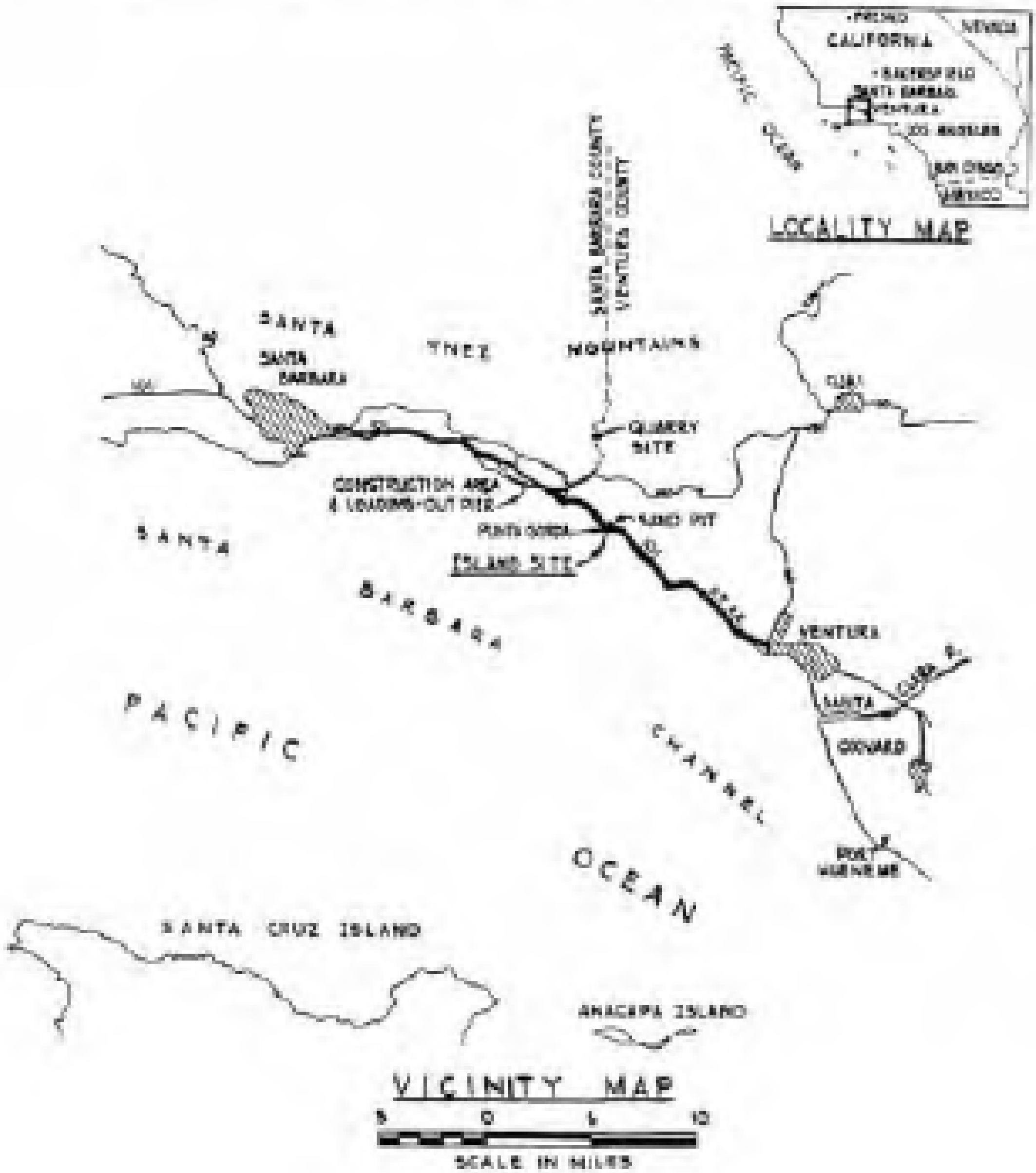


FIG. 1

the lease area to provide for maximum production from the greatest area at the least total cost of installation, drilling, and operation. This was in itself an appreciable engineering problem but one that cannot be included herein. With modern slant drilling techniques, the first or "mother" island as located and with conductor pipes for sixty-eight possible wells will develop an appreciable amount of the entire lease.

The water depth at the island ranges from 41 to 48 feet referred to MLLW as datum, from the most shallow to the deepest toe of the island. Tidal range

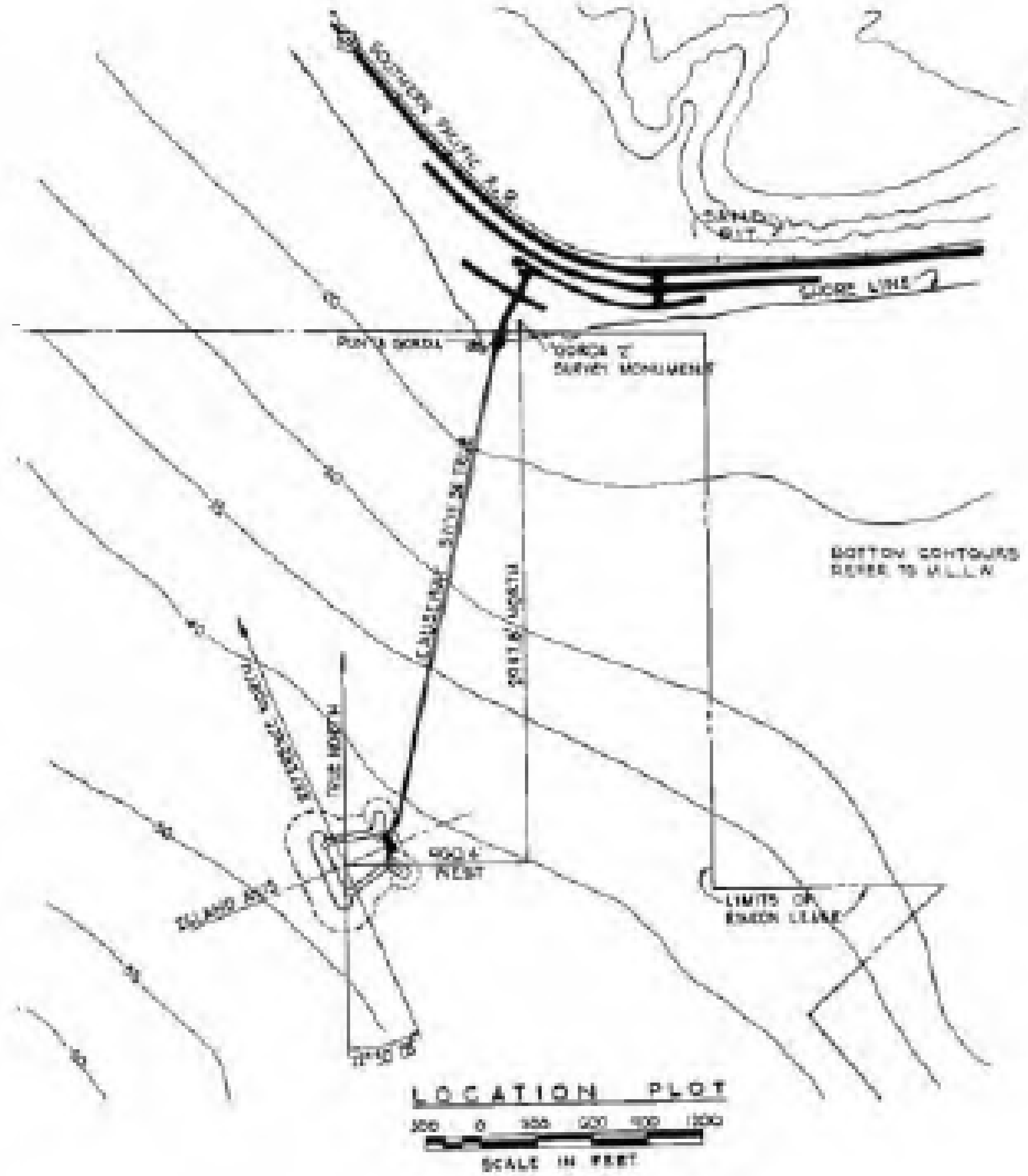


FIG. 2

in this area is as follows:

Extreme High	7.50
MHHW	5.40
MSL	2.58
MLLW	0.00
Extreme Low	-2.5

Although Rincon Island is located in the Santa Barbara Channel which lies between the mainland and the natural offshore islands known as the Channel Islands, it is actually in the Pacific Ocean. These offshore islands do provide some protection to the channel and reduce the energy of many ocean storm swells before they reach shallow water. However, the protection is by no means complete, nor is it very significant for a fixed structure. Many ocean storm swells can enter the channel and proceed easterly with but nominal loss of energy and they can then be further increased by local winds, and perhaps local bottom conditions as well.

The unusual plan shape of the island, which is shown in Fig. 3, was developed to obtain optimum wave protection. The area of construction on the

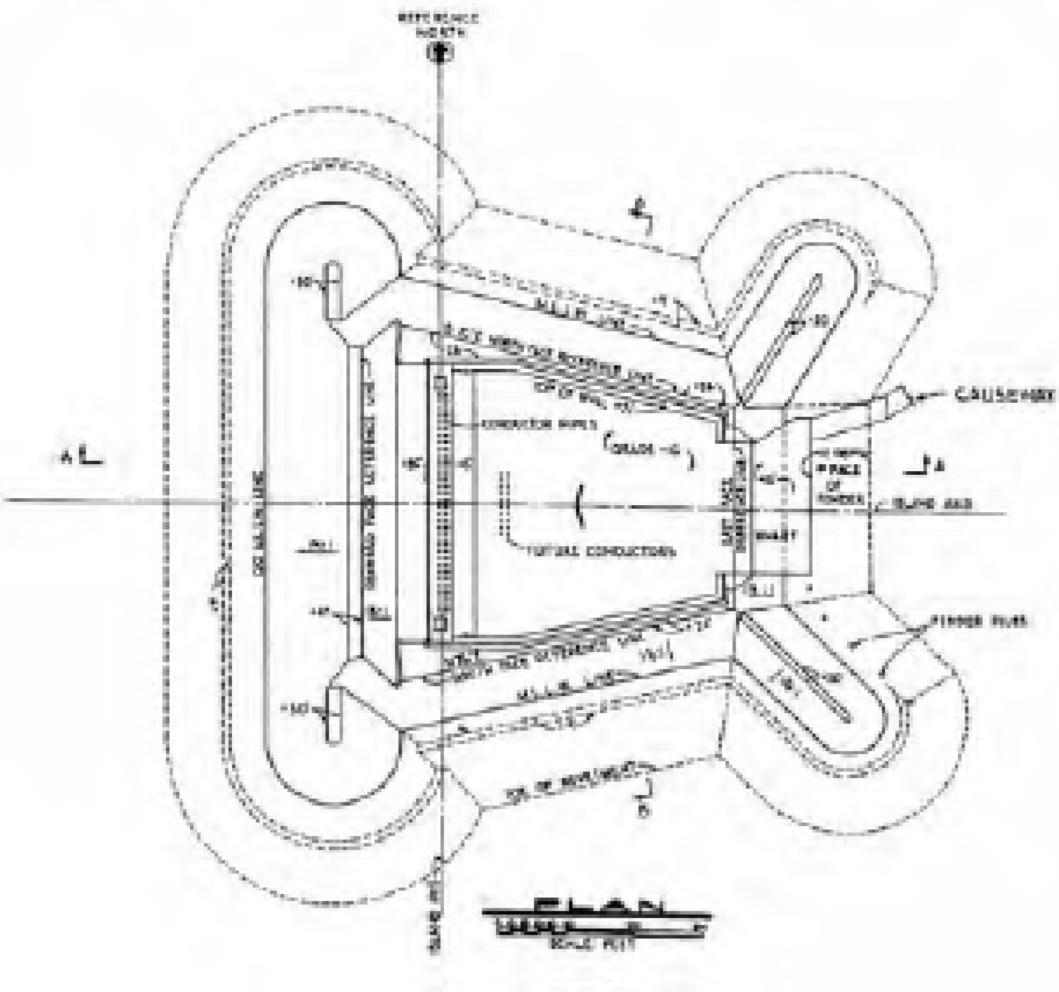


FIG. 3 RINCON ISLAND

ocean floor is about 6.3 acres, at MLLW the area is 3.2 acres, and the gross area at elevation + 16 feet is 2.1 acres. The net usable flat area at this level, exclusive of the wharf, is 1.1 acres, although considerable additional usable space is obtained by effective use of vertical wall surfaces inside the rock armor.

Rincon Island is constructed of rock revetments which contain sand fill. It was constructed in stages (Fig. 4) and contains many types and gradations of rock. The most exposed face is protected with 1,130 concrete tetrapods,* each of 31 tons. The top elevation of the seaward breakwater wall is at + 41, the sides at + 24, and the wharf and working area are at + 16 feet. There are approximately 618,000 tons of material in the island including the 35,000 tons of tetrapods. The exterior side slopes of rock rubble are 1-1/2 to 1 except on the east wings which are at 1-1/4 to 1 and the tetrapod armor is at 1-1/2 to 1. Fig. 5 is a photograph of the island which was taken near the end of the construction period.

A small wharf of prestressed concrete piles, concrete cap, and timber deck is provided at the lee side of the island within a semi-protected harbor created by two "wings" or rock breakwater stubs. A single lane causeway of steel pipe piles and timber decking on steel stringers extends from this wharf to the abutment some 2,730 feet away. Most bents are at 40 feet centers with alternating single-pile and double-battered-pile bents. The deck level climbs sharply from the island and is level for most of its course at 35 feet above MLLW. Fig. 6 shows the island, the open causeway and the coastline in the background.

The development of the island and causeway provided many engineering

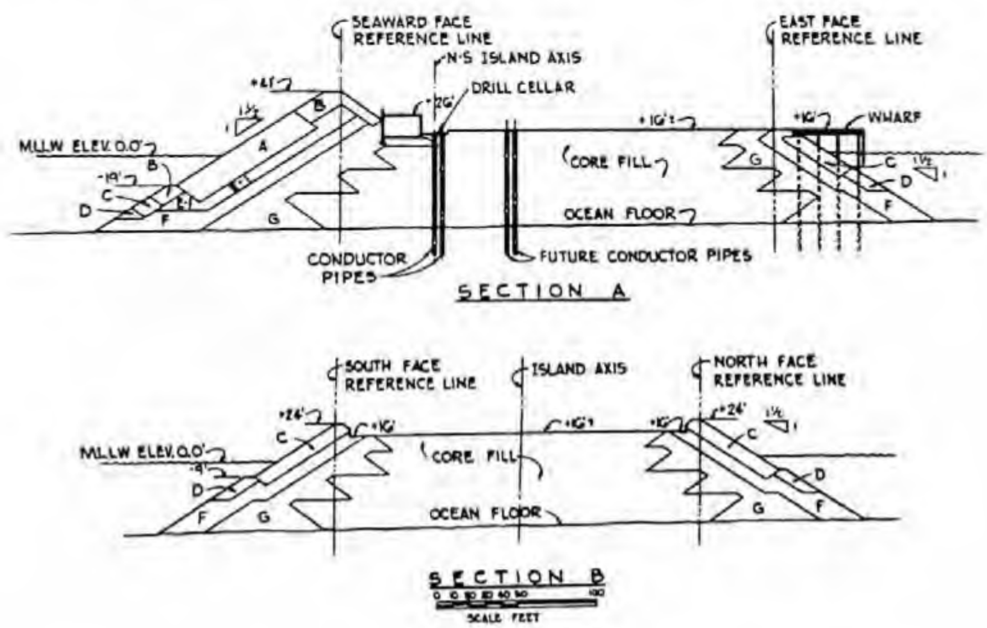


FIG. 4 RINCON ISLAND

* Covered by U. S. Patent No. 2,766,592 issued October 16, 1956, to Establissements Neyrpic which has given Sotramer (Societe d'Exploitation de Brevets pour Travaux a la Mer) an exclusive license to promote and exploit the use of tetrapods throughout the United States.

Fig. 5. Aerial View Looking Northwest

problems which required first-time techniques for their solution. It was by no means a simple matter of dumping rock in the ocean. In order to keep costs low and still provide a satisfactory installation with certain anticipated risks, a great deal of engineering study and many "judgment" type decisions

Fig. 6. Aerial View of Island and Causeway

were necessary. The design is not, and could not be, conservative, but it was thoroughly considered.

The Basic Problem

The Owner's offshore lease from the State stipulated that the area should be drilled either from shore, from existing offshore structures, or from a solid island of natural materials. A comparison of slant drilling costs from shore with rough estimates of island costs indicated an island of natural materials was the economical solution. The Owner's geological studies dictated the general location and the basic problem became the design of an economical, permanent island of natural materials suitable for oil well drilling and production. Moreover, the installation was not to detract from the natural appearance of the coastal area.

The size of the island was to be determined by operational area requirements plus allowance for armor layers and their necessary side slopes. These factors in turn were functions of the optimum number of oil wells on the island, the production functions to be done on the island versus on shore, ocean swell heights, periods, and many other considerations. Many investigations and alternate economical considerations were conducted by the Owner's production department and by their engineering consultants working in close collaboration.

Site Investigation

Bottom contours were obtained from existing maps supplemented by lead line soundings and fathometer runs with one of the Owner's exploratory drilling ships, the "La Ciencia". Soil borings of the ocean bottom were made from the La Ciencia by a variety of methods with two primary purposes. One purpose was to determine the suitability of the ocean floor as a foundation for the island, and the other to determine if a satisfactory source of dredger fill material for the island core was available within economical pumping distance. The simplest sampling device was a "snapper" or small spring loaded clamshell for obtaining samples of the surface material on the ocean floor. The "dart" sampler was a heavily weighted stabbing device which, when dropped to the ocean floor through the water, would recover a cylindrical sample up to three feet in length. A jet-churn rig was used to recover cylindrical samples from various depths by jet-churning to the desired depth and then stabbing samples from the bottom of the hole. This last rig was later replaced by a rotary rig which colud also obtain cylindrical samples by drilling to the desired depth and then stabbing the sample from the bottom of the hole. The first two methods of sampling were used in the search for dredger fill material and the latter two for deeper information near the island site.

Bottom conditions vary uniformly throughout the lease area. Overburden material on the ocean floor is a silty sand ranging into sandy silt, and increasing in thickness as the water depth increases. At the island site it ranges from 14 to 25 feet in thickness. The average slope of the bottom at the island site is 3%.

Table I indicates some of the materials encountered. Underlying the overburden is a geologically recent shale or "siltstone" formation. Consolidation tests on samples of the overburden material indicated a probable

Table I

Typical Overburden Materials at Island Site

Sample depth	surface	5'	12'	18'	24'
Dry wt., lbs./cu.ft.	80	98	99	97	94
Wet wt., lbs./cu.ft.	101	123	123	119	117
Percent moisture	27	26	25	23	25
Percent passing following U. S. Std. sieves					
No. 30	99.7	100.0	100.0	99.8	99.8
No. 50	99.5	-	99.8	-	-
No. 80	99.2	99.8	99.6	99.7	99.5
No. 100	98.9	99.6	99.3	99.5	99.1
No. 140	96.8	98.8	97.6	98.0	95.1
No. 200	59.6	76.6	81.2	80.6	61.3
No. 270	30.9	37.1	56.4	52.9	37.9
Hydrometer tests effective particle size					
.050 mm.				46.0	
.037 mm.				32.5	
.024 mm.				23.0	
.017 mm.				19.1	
.010 mm.				15.9	
.0072 mm.				12.7	
.0050 mm.				11.1	
.0035 mm.				9.5	
.0027 mm.				6.3	

settlement of less than six inches at the ocean floor from the weight of a solid island, most of which settlement should occur during construction. Bottom material shoreward of the island was not as coarse as desirable for dredger fill, but studies indicated that proper control of the discharge location could utilize the ocean currents to separate and waste the fine fractions to leave a satisfactory granular core of dredged material.

Faults are known to exist near the island site, some of which are active and most of which are not. The Santa Barbara area has had appreciable earthquakes in recent decades.

The coastline in this area has appreciable littoral drift and sand transportation. However, the sand movement at the location and in the water depth of the island is negligible. Moreover, the island is so small and so far from the coastline as to have no effect on coastal sand erosion or accretion. The possibility of the loss of existing materials adjacent to the island was, of course, considered. Indications were that some minor changes in natural bottom deposits had occurred in recent years and would again occur.

Oceanographic Studies

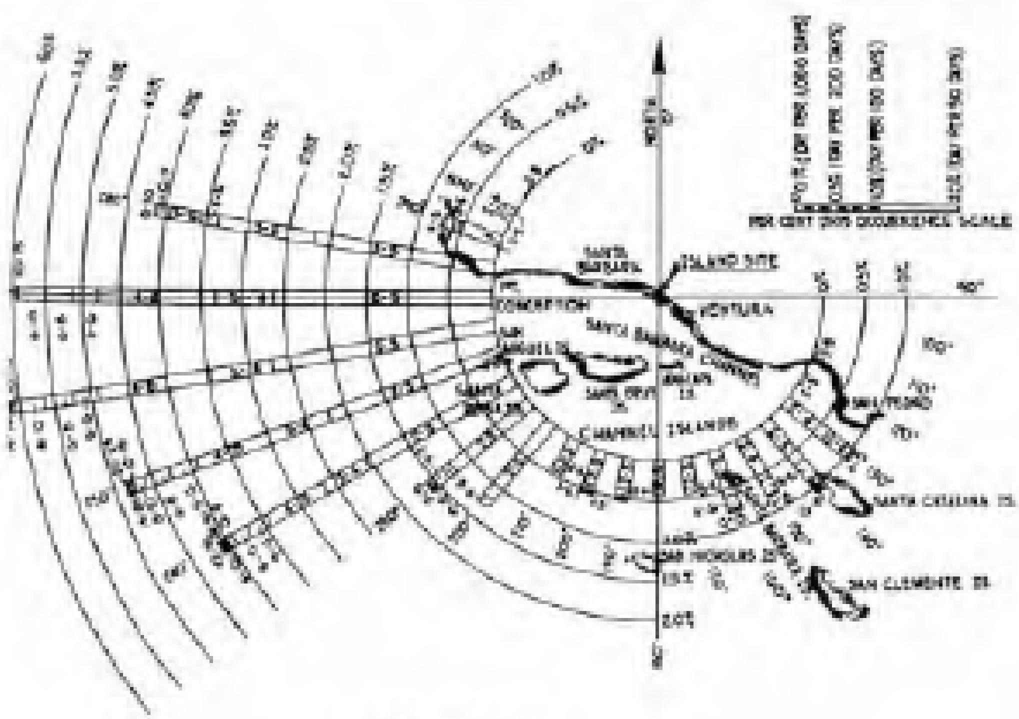
Wave forecasts for the island site were prepared in considerable detail, and covered estimated heights, periods, direction and frequency of occurrence.

Basic data for the wave forecasts were compiled from several sources. Available wave measurements from wave recorders and from trained observers, hindcasting from synoptic weather maps, and past records of severe storms were all utilized. Refraction studies were then required to tailor this information to fit the partially sheltered position of the island. The Channel Islands and the westward trend of the coastline as far as Point Concepcion serve to protect the island site from many, but by no means all, of the Pacific's winter storm waves. The Santa Barbara Channel offers an inviting approach of almost unlimited fetch from the west right up to Rincon Island for the less frequent but still probable storm waves which approach from this critical direction. This "partial" protection serves to confine the approach of really large waves and had considerable influence on selecting the odd configuration of the island as well as its orientation.

The wave studies were also concerned with lower wave heights from all directions, which, though less dramatic still had an influence on the island design. Frequency of occurrence of these lower wave heights is especially important in planning and scheduling marine operations in exposed locations. Figs. 7 and 8 illustrate the manner in which this information was presented in the island bid documents.

Rock Sources

The closest developed quarry site convenient to marine loading facilities was on Catalina Island. Since this represents a barge haul of approximately



ESTIMATED PER CENT DAYS OCCURRENCE OF VARIOUS *WAVE HEIGHTS AND DIRECTIONS AT ISLAND SITE

* WAVE HEIGHT IS "SIGNIFICANT WAVE HEIGHT" WHICH IS DEFINED AS THE AVERAGE HEIGHT OF THE HIGHEST ONE-THIRD OF THE WAVES.

FIG. 7 WAVE ROSE FOR ISLAND SITE

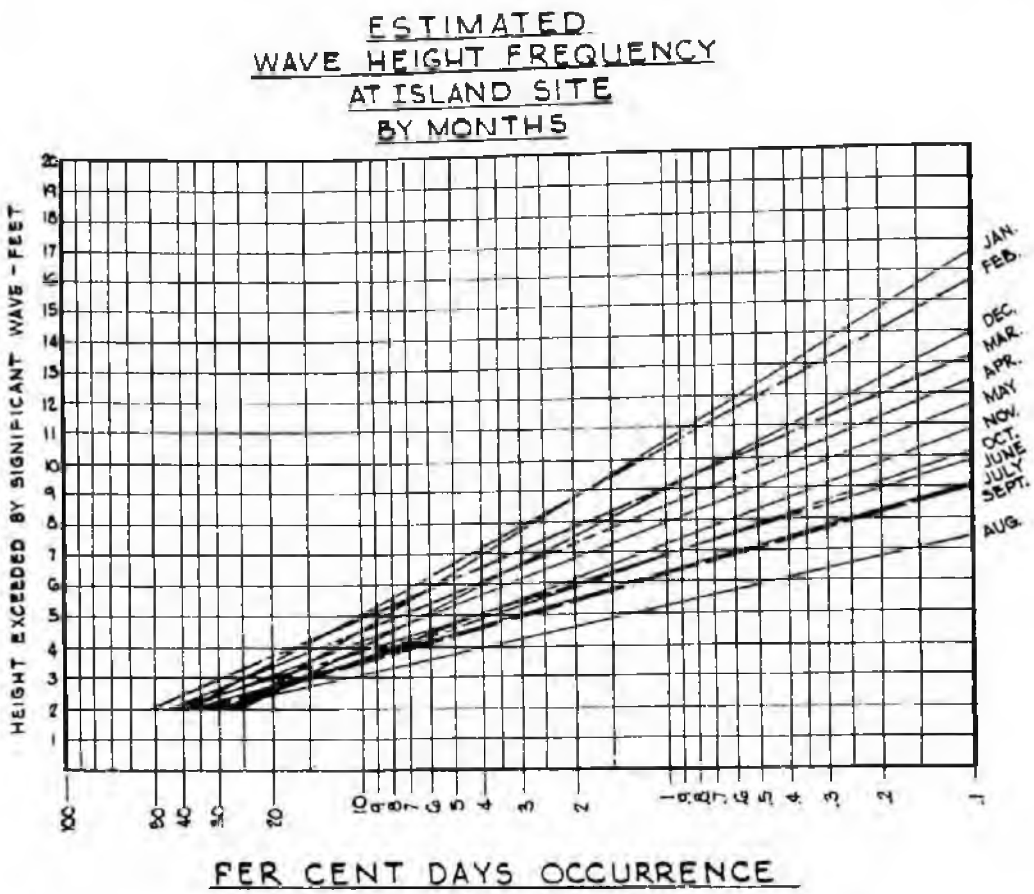


FIG. 8 WAVE FREQUENCY CHART

90 miles to the island site, considerable effort was devoted to locating alternate sources. Rock samples were taken from the vicinity of Prisoner's Harbor on Santa Cruz Island, which was only 27 miles from the island site. Laboratory tests indicated the rock was suitable for use in the island revetments but it was estimated that few units of more than 15 tons could be obtained. The igneous rock appeared very similar to other Santa Cruz Island rock, which was used in the construction of the Santa Barbara breakwater about 30 years ago and which has shown excellent weathering characteristics. The Owner arrived at an agreement with the private owner of this portion of Santa Cruz Island whereby the new quarry site was offered to all bidders as a royalty free source of rock and gravel. Exploratory blasting was financed by the Owner and witnessed by all the interested bidders. Other existing quarries on the mainland involved either very long hauls with transfers to barges or produced materials not suitable for the sea water and wave exposure.

The bidding documents were prepared so as to allow any source of rock on a specification basis for quality, density, size, and gradation, Various alternate sized armor rock units were specified depending upon the rock specific gravity.

Precast Concrete Armor

Studies of the use of precast concrete armor revealed several factors which made it desirable to provide for the use of precast concrete armor as an alternate to the use of large rocks for the class A or largest rock category. Recent research in the use of tetrapods showed that for a given weight and specific gravity they have more stability against wave action than quarried rocks. Practically, this meant that lighter units would be required for the seaward face of the island and hence a smaller crane would be required for placing the armor. Equally important was the lessened risk to any contractor planning to open a new quarry site for the island project by elimination of the necessity for producing and transporting very heavy rocks. It is usually difficult to predict what maximum size of rock it is possible to produce economically from a quarry site until actual operations are under way. In addition to tetrapods, the design included tetrahedrons as optional precast concrete armor.

The alternate of using precast concrete armor also made it practical for a contractor to build the island from an onshore quarry since the next maximum required size of quarried rock, the B grade, could be hauled over public roads with normal equipment. The various sizes of the tetrapod Class A armor and other armor rock classifications are shown in Table II.

Preliminary Island Designs

During the preliminary design stages many elements of the island underwent a considerable number of changes. Basically the evolution of the final shape and size was the result of joint studies by the Owner concerning his requirements from an oil production viewpoint and the engineer's design search for the most economical way to meet such requirements. The basic scheme of an island built in stages or lifts with each lift consisting of a rock dike containing a core of fine material and protected externally be revetments of heavier armor materials was one of the few elements that remained constant. The partially protected location of the island introduced seemingly endless possible configurations to take advantage of this circumstance. The oil industry prides itself on close economical design, and the Rincon Island Project was no exception. The Owner wanted a safe and adequate island, but not one gold plated with safety factors. On a pioneer type project such a goal is rather difficult to achieve, particularly where rare but possible storms could control the design.

Early studies showed an open causeway or roadway trestle to be the most economical method of supplying the island both during and after construction. However, in order to reduce the initial investment and for other reasons preliminary design had to be based on constructing and supplying the island by water. Various schemes were investigated for utilizing an LCT type of landcraft. The attractive aspect of such a scheme is that conventional oil field equipment could be utilized for the entire oil production operation. The serious drawback, however, was that the island was too small to provide a landing ramp which would have an adequate degree of protection against moderately bad seas. The protection could have been provided, but only at a considerable increase in cost.

Configuration studies led to the concept of a seaward face designed to resist the large waves by energy absorption and reflection. The remainder

Table II

ARMOR WEIGHT REQUIREMENTS
for
VARIOUS SPECIFIC GRAVITIES

CLASS A TETRAPODS

Sp. Gr.	Solid Wt. per cu. ft. lbs.	Min. Wt. of Each Unit Tons	Thickness of 2 layers ft.
2.3	143.5	38	18.3
2.4	149.8	31	16.9
2.5	156.0	26-1/2	15.0
2.6	162.2	22-1/2	14.7
2.7	168.5	19-1/2	13.9

ARMOR ROCK

		Class	Min. Wt. of Each Unit Tons	Min. Avg. Wt. of Unit Tons	Thickness of 2 layers ft.
2.25	140.4	B	29	32	15.4
		C	12	13	11.5
		D	6	6-1/2	9.1
2.35	146.6	B	23	26	14.2
		C	10	11	10.6
		D	5	5-1/2	8.4
2.45	152.9	B	20	22	13.2
		C	8-1/4	9-1/4	9.9
		D	4-1/4	4-1/2	7.3
2.55	159.1	B	17	19	12.4
		C	7	7-3/4	9.2
		D	3-1/2	4	7.3
2.65	165.4	B	14	16	11.6
		C	6	6-3/4	8.7
		D	3	3-1/2	6.8
2.75	171.6	B	13	14	10.9
		C	5-1/4	5-3/4	8.2
		D	2-3/4	3	6.4
2.85	177.8	B	11	12	10.3
		C	4-1/2	5	7.7
		D	2-1/4	2-1/2	6.1
2.95	184.1	B	10	11	9.8
		C	4	4-1/2	7.3
		D	2	2-1/4	5.8
3.05	190.3	B	8-1/2	9-1/2	9.2
		C	3-1/2	4	6.9
		D	1-3/4	2	5.5

of the island would be shadowed by the seaward face and the other revetments could be much lighter than the seaward face. This concept led to an investigation of the possibility of first building the seaward face as a complete breakwater and then constructing the rest of the island in the lee afforded by this first stage of construction. This initial stage was such a large proportion of the total island, however, that the savings in materials by building the seaward face integral with the island definitely outweighed the greater ease of construction. Moreover, the initial breakwater would not have provided complete protection. Another interesting scheme given considerable study and even model tests was the feasibility of sinking ship hulls as the basic core of the seaward face or, alternatively, using them as submerged breakwaters seaward of the island proper. Surplus ship hulls were then available on the west coast at attractive prices.

Island Model Studies

As is typical of many hydraulic design problems, several elements of the design could best be checked by model tests in a laboratory. The model tests for the island involved two series of wave tests. The first of these was a three-dimensional model test in a basin to check the configuration of the island and the second series involved two dimensional models in a wave channel. In order to keep costs within a limited budget and still obtain a maximum amount of information from the test, movie films were made of most tests and time consuming measurements were kept to a minimum.

At one stage of the design the owner wanted a small concrete slip about 40 feet by 150 feet on the leeward side of the island for use as a small boat harbor for servicing the island. One purpose of the three dimensional model was to determine what degree of baffling would be required to maintain quiet water in the slip during stormy weather. As was expected the model showed the slip was highly resonant to wave periods typical of Pacific storms and only a water tight door or lock would provide quiet water by baffling. An alternate solution of providing short stub breakwaters at each of the eastern corners of the island was so effective in maintaining quiet water during most wave conditions that the slip was replaced by a small wharf on the eastern side of the island. In general the other configuration features of the island were found to be satisfactory as was the concept of a high seaward face sheltering the tapering work area of the island which is at a lower elevation.

Using the same model, the feasibility of using two concrete ship hulls as a separate, submerged breakwater seaward of the island was investigated. By comparison of the wave runup on the sides of the island, the effectiveness of different locations and spacing for the hulls was studied. Although cost studies indicated possible appreciable savings in construction cost with use of the hulls, the owner elected not to use them because of the less attractive appearance and possible adverse public relations for the oil industry. Fig. 9 indicates a three dimensional model test.

The second series of laboratory tests involved two dimensional tests of the proposed seaward face revetment section in a wave channel. Fig. 10 illustrates a model section being subjected to a wave seven feet higher than the design wave. The first test runs were of a wave height slightly below the design wave height of 27 feet. These runs verified the stability of the design for the design wave. Following these initial tests, the wave heights were increased in steps to a maximum height of 34 feet.

Fig. 9. Three Dimensional Wave Action Test.

As anticipated, the section showed considerable distress under attack of waves appreciably larger than the design wave. The gratifying feature, however, was that the section showed no tendency towards a catastrophic type failure due to any single wave, but rather a gradually increasing distress. This was consistent with the basic design objective of an economical section which might sustain damage but which would not endanger the whole island when subjected to the rare occurrences of the very large waves.

Island Economic Studies

The first preliminary studies made it clear that it was not economically feasible to design the seaward face revetment so that it would be completely stable against all possible storms. This fact is well illustrated by the history of conventional breakwaters along the Pacific Coast. All deep water breakwaters with a severe exposure are expected to and generally have suffered occasional damage. The dire consequences of a complete failure for the island's revetments made the problem much more critical than for breakwater design. A rational approach to the island problem was developed which essentially consists of six steps: (1) prediction of frequency of occurrences of large storm waves at the site; (2) correlation of predicted storms with laboratory tests of revetment sections; (3) estimates of cost and damage for various trial designs; (4) evaluation of damage to the various designs; (5) economic analysis of various designs; and (6) selection of final revetment sections.

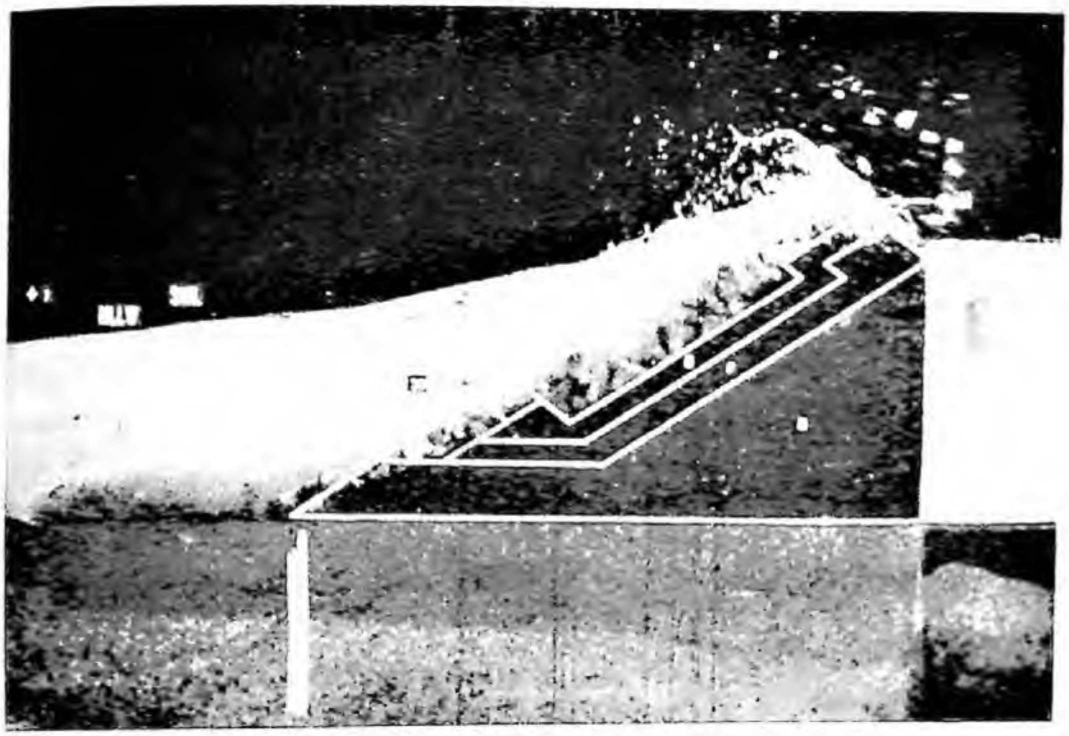


Fig. 10. Seaward Face Test with 34-Foot Wave

Table III summarizes the calculations for estimating the average annual repair cost for a trial design of the island's seaward face revetment. Columns (1) and (2) were developed by the oceanographic study of the island site. For column (3) the maximum wave of a storm is assumed to be 1.9 times the significnat wave of the storm. Column (4) correlates the storm waves and laboratory waves.

It was assumed that the maximum wave of a wave train best describes the

Table III

Estimated Annual Repair Cost for 27 ft. Maximum Wave Design

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Significant Wave height of storm ft.	Frequency Storm recurs once in years shown	Max. Wave height in storm ft.	Equivalent wave ht. for use with armor formula ft.	Ratio max. wave ht. to max. no damage wave	Estimated % damage to armor per storm	Estimated cost of repair for storm $	Incremental avg. annual repair cost for storm $
14	14.4	26.6	23.0	.96	nil	-	-
15	23.8	28.5	24.3	1.01	2	81,500	3,420
16	43.5	30.4	26.2	1.09	7	130,000	3,000
17	74	32.3	27.9	1.16	13	208,000	2,810
18	141	34.2	29.5	1.23	23	286,000	2,030
19 or over	107	36.1+	31.2	1.30	35	400,000	3,740

Average annual repair cost = $15,000.

destructive ability of the wave train and that the maximum wave of a laboratory wave test is 1.16 times the laboratory designated wave height for the test. Based on these assumptions a wave height 1.64 times the significant wave of a predicted storm was used in the required armor weight formula to determine the armor for a no damage design for that storm. Columns (5) and (6) were based on damage estimates obtained in the wave laboratory tests. Considerable refinement of such damage estimates is now possible as a result of recent research in this field.(1) The estimated cost of repair in column (7) was based on two elements: a unit price for armor materials replaced or recovered, and a lump sum cost for mobilization and demobilization. Column (8) is Column (7) divided by Column (2) and gives the incremental portion of the average annual repair cost contributed by each class of storms.

Fig. 11 is a plot illustrating the economic analysis of several trial designs. Curve (a) is the average annual repair cost for various designs computed as illustrated by Table III, and curve (b) is the present worth of the average annual repair cost for a 25 year period at an interest rate of 6%. Curve (c) is the estimated construction cost of each of the various trial designs. The capitalized cost, curve (d), is the sum of curves (b) and (c), and its low point represents the most economical design. Fig. 12 presents another method of analyzing the same information. Starting with a trial design which is definitely less stable than the most economic, curve (a) represents the additional investment required for various more stable designs and curve (c) is the corresponding average annual repair cost. Curve (b) is the incremental reduction in average annual repair cost. Curve (e) is curve (d) divided by curve (b) and represents the effective return on each incremental investment. The economical design is selected as the one beyond which an additional increment of investment fails to offer an attractive return.

It is realized, of course, that such procedures involve low, if not negative safety factors under extremely adverse conditions. However, it is a logical philosophy for severe but infrequent conditions like destructive earthquakes, bomb blast, or severe storm waves to design to high unit stresses and deflections in order to absorb energy and save the construction cost for materials which may never be needed. However, catastrophic-type failures must be considered and avoided in such calculated risk designs.

The Final Island Design

Figs. 3 and 4 show a plan and general sections illustrating the final design of the island. This design evolved from five basic inter-related problems; the island size and shape, the revetments, the filter and core, the general scheme of construction and, of course, the cost. Size requirements were established by the Owner to provide the necessary space for oil drilling and production facilities consistent with the anticipated drilling and production program. The final shape was developed from the oceanographic, model, design, and economic studies. The west, or seaward, face is designed to withstand the heavy seas from the winter Pacific storms, and partially shields the remainder of the island. The north and south faces, or sides, of the island are designed for 12 foot waves, since the maximum size from these directions is limited by the fetch inside Santa Barbara Channel. The east face, or shore side of the island is provided with a small wharf protected against ocean storms by the northeast and southeast stub breakwater or

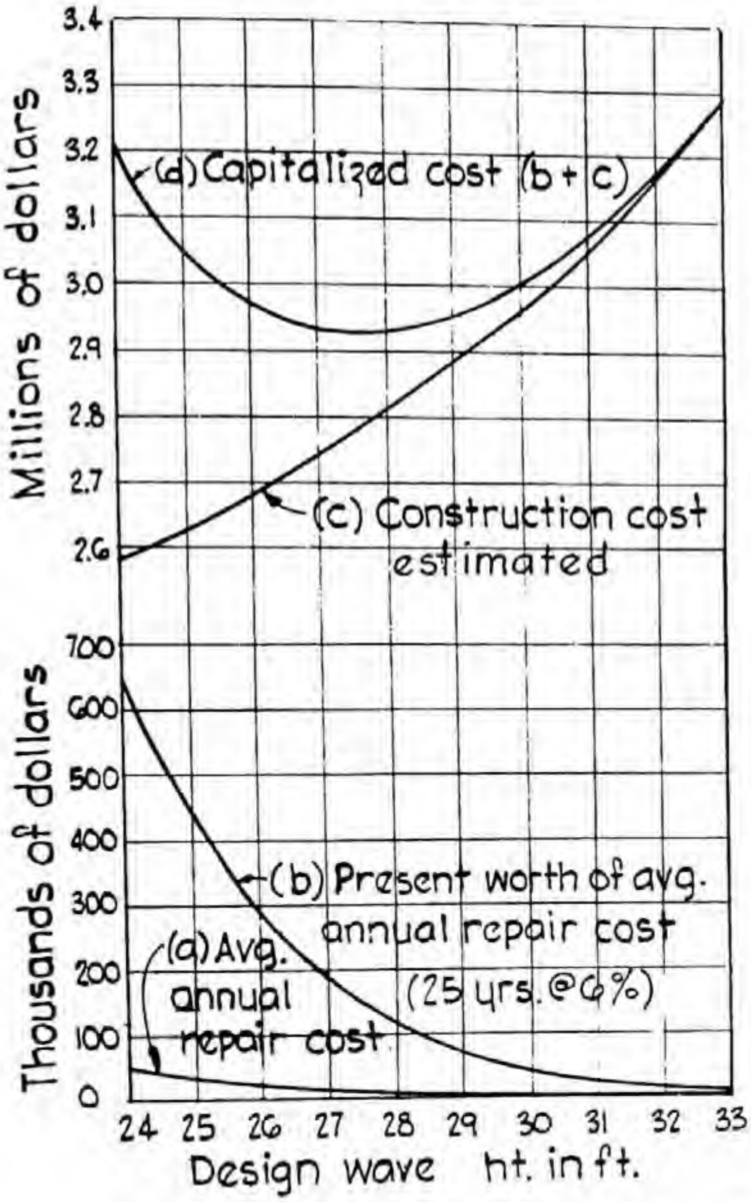


FIG. 11 COMPARATIVE ECONOMY OF DESIGNS

"wings" as they came to be called. The island was originally designed to be served by the wharf only (no causeway) for reasons previously outlined.

The revetment design for the west face also included a cellular wall structure adjacent to the double line of conductor pipes. This structure serves as a support platform for the drill rig which straddles the drill cellar. The rig can be skidded in a north-south direction to center over the desired well. In addition the cellular wall structure serves as a backstop or secondary line of defense for the west face revetment. This revetment can thus sustain considerable damage before the wells themselves could be exposed to direct wave attack. This west face revetment is designed to be stable against 27 foot waves.

The required weight of tetrapods was determined by extrapolation of the U. S. Waterways Experiment Station tests for the Crescent City breakwater

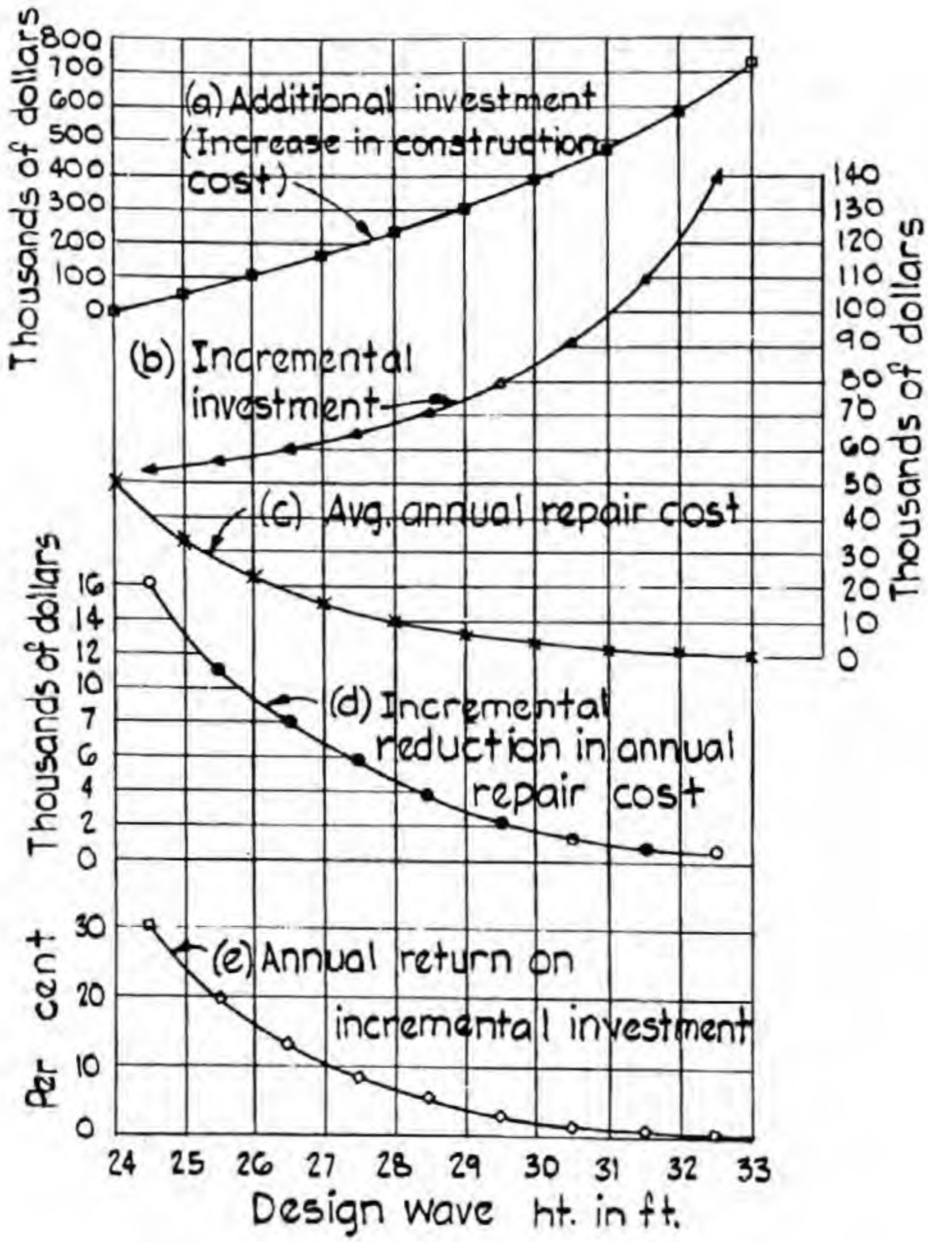


FIG. 12 ECONOMIC ANALYSIS OF INCREMENTAL INVESTMENTS

design.[3] Using the modified Iribarren formula.[4]

$$W = \frac{K' w\, S_f\, S_r\, \mu^3 H^3}{(\mu \cos \alpha - \sin \alpha)^3 (S_r - S_f)^3}$$

where

- W = required weight of individual units of armor material in pounds
- K' = dimensionless coefficient
- w = unit weight of fresh water
- S_r = specific gravity of armor material
- S_f = specific gravity of fluid
- H = wave height for no damage
- μ = coefficient of friction of armor material
- α = angle, measured from horizontal of breakwater slope

values of $K' = .0223$ and $\mu = 1.10$ were used. A prime reason for the wave laboratory tests of the west face revetment was to verify these values.

More recent 1958 tests have given further confirmation. Using the WES formula[1,5] for rubble-mound breakwaters.

$$N_s = \frac{\gamma_r^{1/3} H}{W^{1/3} (S_r - 1)}$$

- N_s = stability number or dimensionless coefficient
- γ_r = specific weight of armor material
- S_r = specific gravity of armor material referred to the water in which the armor is submerged.

The value of $N_s = 2.37$ for no damage on a 1-1/2 to 1 slope gives required unit weights very close to those used for the island design. For the same criteria the required tetrapod weight for the island by use of formula (2) would have been 30 tons in place of the 31 ton weight actually used. Since the design is not for the maximum wave predicted, the slight advantage is quite acceptable.

The seaward face height of + 41-feet above MLLW was selected to limit the overtopping from a 34-foot wave to an approximate height of 3-feet. As shown in Fig. 4, five classes of armor are utilized in the west face revetment. The heaviest is Class A for which the Contractor selected the option of 31 ton concrete tetrapods having a specific gravity of 2.40. The bid documnets actually offered numerous options for each of the five classes or revetment armor because no single developed source of rock material was definitely more advantageous than others. The individual minimum weight requirements for Class A, B, C, and D rock were allowed to vary with the specific gravity of the rock. In addition either tetrahedrons or tetrapods of precast concrete were optional in place of rock for Class A armor. Since variations in size also varied the thickness of armor layers, the quantities of all revetment materials and the core varied with the different options. In all, 59 optional quantity tabulations were included in the bid documents. This allowed bidders to evaluate the advantages of sources of high specific gravity rock which would make considerable reduction in the individual weights of armor.

When all factors except specific gravity are constant the required weight of individual units of armor material, W, reduces to the following:

$$W = \frac{C\,S_r'}{(S_r' - 1)^3}$$

where

c = a constant

Table II illustrates the variation in armor rock with specific gravity for equivalent designs as computed on the basis of the above formula.

An effective filter is essential to avoid the loss of core material through the rock layers from "pumping" caused by wave action. The filter could not conform with the generally accepted "T-V"(2) gradings recommended by Terzaghi and modified by the Waterways Experiment Station at Vicksburg. Since it was considered impractical to place the relatively thin blankets envisaged by the T-V gradings in an exposed ocean location, the size spread in each material was made considerably greater than recommended. It is anticipated that there will be minor losses in the filters, especially the Class G material, as the fines are lost from the outer layers and a stable grading is achieved. Most of this readjustment is believed to have occurred during the construction phase as the Class G material was normally the first material placed in each lift. The Class F material actually served a dual function. In the lower layers it was used as the lightest class of armor and elsewhere as the outer layer of filter. Class F material was a quarry run material with an open gradation ranging from four tons down to a minimum of 15 percent less than 5 pounds. Class G material was an optional quarry run or gravel material with a dense gradation ranging down to not less than 25 percent passing the No. 20 sieve. The core was sand for the reason that this was less costly than even a quarry waste. The bidders were allowed the option of placing the core by dredger from borrow areas on the bottom or to import from shore borrow.

Island Construction

Sealed bids on a unit price basis using the Engineer's quantity estimates for total cost comparison were obtained from selected contractors. In August, 1956 the contract was awarded to the low bidder who elected to open his own on-shore quarry about 6 miles from his loading-out site and to use precast concrete tetrapods for the Class A armor. At the loading-out site, located 4-1/2 miles upcoast from the island site, the contractor built a temporary loading structure in approximately 22 ft. of water which consisted of an L shaped pier of eight forty-foot diameter steel caissons filled with rock and sand with a trestle connection to shore. The pier was sized to provide moderate protection for one flat barge. A 50-ton stiff leg derrick was mounted on the pier to handle materials. Fig. 13 is an aerial photo of the contractor's construction yard and loading out pier.

Tetrapods were cast in the construction yards on shore adjacent to the loading out pier. Since locally available sand and aggregates are mildy re-

Fig. 13. Contractors Construction Yard and Loading-Out Pier

active, the cost of obtaining non-reactive sand was investigated. A type II low alkali cement had been specified. Recent production from the selected cement mill had been averaging approximately 0.3% alkali calculated as equivalent sodium oxide. It was decided to use the locally available sand and aggregates, but to maintain a close check on free alkali content of the cement. The job average was 0.29% with a range from 0.20% to 0.48%. The concrete mix used 5 sacks of cement and 3 in. maximum size of aggregate. A calcium lignin sulphonate additive was used at the contractor's option. A 27 E paving mixer operated on a bulkhead ramp adjacent to the casting pit so that its bucket could discharge directly into the tetrapod forms which were of two piece steel construction. The bottom section formed the bottom half of the three lower legs, and the top section formed the top half of the lower legs and the upstanding leg. End gates for the bottom legs were hinged to the top section. The contractor used 36 bottom sections and 12 top sections, which allowed for a pouring schedule of 12 tetrapods per day. The top forms were stripped after 20 hours and the tetrapods were removed after three days. For this first lift a special compression sling, developed by the contractor, gripped the tetrapod by pressing a bearing plate against the flat end of each bottom leg. By using this sling (Fig. 14) the concrete was in compression and, although the concrete was still green, the tetrapood could be handled without damage or overstressing. A large crawler crane lifted the tetrapods from the casting pit and placed them in the adjacent storage yard to complete their curing.

The first material for the island was placed in February, 1957 after several months of quarry development and the construction of temporary facilities. The majority of the marine work was done on a two shift, six day work week since the marine equipment charges represented a sizable proportion of the contractor's costs. The general procedure was to build the exterior rings of each lift of Class G and F, then place the core material and armor rock. All F, G and core material below elevation-15 were placed by bulldozing the material over the side of carefully spotted barges. Armor materials were placed by cranes. The contractor placed wood pile dolphins on

Fig. 14. Handling Tetrapods

the north and east sides of the island work area. Targets strung between the dolphins were used to provide position lines for placing the below-water materials. The island first broke water in October, 1957. The seaward face was then carried to elevation ± 17 ahead of the other sides in order to provide some protection from the approaching winter weather. Before complete closure of the island above water, sufficient core was placed on the south side to allow the barge mounted crawler crane to be unloaded by beaching the barge against the core and walking the crane off on a temporary ramp of core fill. The top lifts of tetrapods and armor rock were placed by the crawler crane on the island. The final closure of the north face was made in January, 1958.

Core fill for the island was a medium to fine sand obtained from the cliff behind Punta Gorda about three quarters of a mile from the island site. The core material was hauled by truck to the contractor's loading out pier, then hauled by barge to the island site. It was not surprising that the contractor elected not to dredge the core fill, since the final design required a relatively small amount of sand for a dredging operation. The lift type of construction required that core sand be placed on an intermittent schedule, and the open sea is not the ideal place to operate a dredge even on larger projects.

Although two moderately severe storms occurred during January, 1958 when the island was in an incompleted and vulnerable stage, the island received only very light damage. The contractor's loading-out pier was damaged in the second of these storms and required a month for repairs.

The 68 steel conductor pipes were driven when the core elevation was approximately +11. These pipes are the initial casing for the future oil wells to be drilled through the island by the owner and were driven to a penetration of 15 feet into the original ocean floor. Work on the concrete walls on the surface of the island was started after the conductor pipes were all driven. For this work a small batch plant was placed on the island.

Work was substantially completed and the owner took possession in August, 1958.

Quarry Operations and Rock Quality Control

Adequate control of rock quality proved a very difficult assignment, and constant effort by both the Contractor's quarry force and the Engineer's field staff was required in order to insure a supply of rock of adequate quality. The rock specification included two quality tests, the Los Angeles Rattler test and the test for soundness by the use of sodium sulfate which test was considered especially important because of the marine exposure. Rock quality varied widely throughout the quarry site. Much of the rock which was the Cold Water Sandstone Formation, Eocene Age, was of excellent quality, but some deposits were very poor and practically uncemented. There were also many intermediate grades. The quarry site, however, contained a vast amount of good material and was of a type which could be quarried in very large unit sizes where desired.

During the period of initial development the Contractor drove many small tunnels or coyote holes into the canyon sides searching for the most desirable rock. The coyote holes in sound rock were later used for primary blasting. An extensive field testing program was carried out by the Engineer on samples taken from these coyote holes, and an intensive search was made for any quickly identifiable characteristics which would correlate with soundness. Acid reaction, specific gravity, Schmidt hammer reading, color, density, grain size, and microscopic examination were all tried but found unreliable. The final solution was to test each separately identifiable type of rock found in the quarry and to classify each type according to its actual soundness test results. Over 100 samples were required for adequate coverage. In order to speed the test results the Engineer's field office was equipped to perform soundness tests on a continuous basis. Untested portions of each sample were retained and small chips from these were carried in a compartmented box as an aid in quick field identification of the rocks. This method proved effective in the majority of the cases, but a few types of rock, which straddled the acceptance line, remained difficult to classify throughout the job.

Rock quantities were measured for payment by barge displacement. Occasional checks of barge gaging accuracy were made by weighing all loads on truck scales and agreements were normally within 1%. Individual weights of armor stone were normally judged by eye. In cases where doubt existed, weight was checked by truck scales or by measuring the cubage of the rock. As the work progressed considerable skill was developed in estimating rock weights. The importance of rock quantity control and also quality control to the Owner cannot be over emphasized for a unit price contract in 50 feet of water in the open sea.

Field Engineering

One basic problem for the Engineer who provided engineering supervision and inspection throughout the construction was to insure that the filter zones of the revetment construction were adequately placed and that no chinks in this essential element of the island's defense were left for the remorseless attack of the seas. Another responsibility was to see that the various rock layers were placed within acceptable tolerances. The fact that two-thirds of the island's cost was below water points up the difficulty of these problems. Survey and layout work was basically a contractor responsibility and a high percentage of his marine work was directly or indirectly concerned with performing this task. A lead line was almost constantly in use during all underwater material placement operations.

The magnitude of the survey work made it impractical for the Engineer's staff to check all survey operations. Field inspectors observed and spot checked the contractor's marine survey operations, but considerable reliance was placed on independent surveys of the underwater mounds as placed in the early stages of the work by use of a modern ultrasonic depth recorder. An essential feature of this instrument was the narrow (approximately 6 degree) cone of response, which was necessary in order to adequately delineate the sharp breaks in grade typical of the island form. As anticipated, vertical accuracy of the instrument when properly calibrated was no special problem. The never ceasing problem was maintaining adequate horizontal accuracy in a highly congested work area, on the never-quiet ocean surface. Special accessories for the survey boat "Blu-Isle" were helpful in obtaining the desired horizontal accuracy. The echo sounder was a portable instrument so the transducer was mounted outboard toward the stern. The most versatile method of position control was by taking simultaneous sextant angles on three targets from the boat. To help reduce plotting errors a platform was rigged to overhang the transducer, so that both sextants could be positioned over the transducer when taking position shots. As an aid in obtaining a conveniently large horizontal chart scale, a special high speed chart drive motor was installed in the echo sounder. In addition, "spoiler plates" were rigged to be lowered into the water directly behind each of the "Blu-Isle's" twin propellers. The "spoiler plates" were very effective in reducing the boat speed while still maintaining better than normal rudder control. The slow boat speed was desirable to allow close spacing of position shots and as a further aid in maintaining large horizontal scale on the echo sounder charts. These techniques enabled a limited field staff to take accurate and continuous three-dimensional "sweeps" of underwater construction whenever indicated.

A 1 to 120 scale model of the island (Fig. 15) was built by the Engineer's field staff. Progress on the model was maintained currently with progress on the island, so that it served as an easily understood progress report. While the island construction was below water it was especially useful for visualizing the status of the work, and all those connected with construction of the island watched their efforts reflected in the model with gratifying interest.

SCUBA (self-contained underwater breathing apparatus) diving gear was also utilized by the Engineer's field staff (Fig. 16) for inspecting the underwater portion of the work and this also proved very useful. Although there are

Fig. 15. Construction Progress Model

drawbacks to the use of SCUBA gear, its outstanding advantage is that it allows the engineer to see the object in question with his own eyes. Additional advantages of the SCUBA gear are summarized as follows:

(a) Equipment is relatively inexpensive.

(b) For a diver with limited training and experience it is safer than conventional diving gear, although basic training is still an essential.

(c) Equipment is easily portable so that elaborate preparations for a dive are not necessary.

(d) The diver can get around faster and has greater mobility and flexibility of operations.

Against these advantages the following drawbacks must be balanced:

(a) There is no underwater communication system equivalent in convenience to a helmet diver's phone system. Some of the other drawbacks mentioned are a direct result of this lack.

(b) Unless the water is clear, orientation is more difficult to maintain than using

Fig. 16. Resident Engineer Preparing for Underwater Inspection

conventional deep sea gear. A compass is often very helpful, but is useless if ferrous metal is in the vicinity.

(c) Skin divers should work in pairs for safety.

Voids in the rock materials as placed varied from 40% for the armor rock which was essentially of unifrom size to 30% for the Class "G" material which was of reasonably dense gradation. If losses of the core fill material are ignored, the tonnage placed would indicate about 20% voids in this material, the majority of which was placed under water. A more reasonable assumption of 35% voids in place, indicates that approximately 23% was lost due to ocean currents and wave action.

The Open Causeway

The lack of a commercial harbor close to the island site, the savings inherent in running production and utility lines ashore along a causeway rather than on the ocean floor, the convenience of ready access of truck-mounted oil field equipment, and numerous other reasons finally caused the Owner to decide on an open causeway to the island in lieu of marine transportation. Traffic density requirements were very light so the design aim was for maximum economy.

Span lengths of 40 feet with alternate single and double pile bents were selected from economic studies for minimum cost. The deck elevation of 35 feet above MLLW is adequate to keep the structure above wave crests. The selected design wave of 25 feet is not the highest possible wave at the site, but it represents a calculated risk based on providing an economic life for the structure. Figs. 5 and 6 show the causeway.

At the time the borings were made for the site investigation of the island, several additional borings were made from the "La Ciencia" along the probable alignment for a causeway. These borings indicated very little overburden above the shale formation from a water depth of approximately 25 feet shoreward. Fathometer runs over the proposed alignment at a later time established the bottom profile and revealed occasional rock outcrops out to a depth of 30 feet. A SCUBA diving inspection of some of these outdrops indicated they were similar to the rock outcrops on shore at Punta Gorda. Although a solid fill causeway was considered for the area shore section, an open causeway all the way to shore was selected so that there would be no affect on the normal littoral drift in this area.

The design vehicle load, which represented the Owner's forecast of the heaviest conventional oil field equipment they would require in their island operation was a tractor-trailer of approximately 34 tons gross. If heavier loads are required at some future time these loads can be handled by barge to the island wharf. Wave forces created the greatest lateral loads, but seismic forces based on 0.08g and wind loads of 30 pounds per square foot were also investigated with certain other load combinations.

All piles were assumed to be fixed below the ocean bottom. The point of assumed fixity varied from five to ten feet, depending upon the type of material at the bottom and the amount of moment induced at the lower end of the pile by horizontal loads. The top supports of the single-pile bents were treated as elastic supports with their reactions taken by the adjacent frame-bents through the superstructure. For expansion, the causeway is divided into three longitudinal sections. Battered pile frames, set longitudinally, provide the necessary support in that direction.

Most causeway piles are subject to breaking waves. A probability study of storm damage resulted in the selection of a 25-foot, 12-second period wave as maximum for design. Each bent was checked for wave forces at high and low tides, since either could control the design, depending, of course, on the distribution of the load vertically.

Many sources were investigated for proper drag coefficients. What appears to be a very logical approach to the problem of waves breaking on piles with relatively small $\frac{D}{H}$ ratios was given by Reid and Bretschneider.(6)

Using the Brekeley-Monterey field data, which consisted of measurements of moments on piles, due to breaking or near breaking waves, the drag coefficient was obtained from the relation

$$C_D = \frac{M}{\frac{w}{2g} \; DH^2 \, K_{Dm}\left(\frac{S_D}{d}\right)d}$$

where C_D = drag coefficent

M = measured moment at ocean bottom on cantilever pile

w = specific weight of water

D = diameter of pile

H = wave height

K_{Dm} = maximum value of wave force factor for drag effect of pile applicable to nearly breaking waves.

S_D = vertical position of action of total drag force on pile above ocean bottom

d = still water depth

Total forces and their centers of gravity were computed by the same source.(6) The forces were then distributed along the pile in general accordance with Munk. (7,8) Instead of using a smooth curve for this dynamic force distribution, the loading was simplified to an equivalent straight line distribution which gave the same or slightly higher results. For example, a 25 foot 12-second wave breaking in 32 feet of water was found by Reid and Bretschneider's work to have a resultant drag force of 9 kips acting 34.5 feet above the ocean bottom. Munk's smooth curve for velocity distribution gave a resultant of 7.5 kips acting 35 feet above bottom, and the simplified straight line force distribution gave a resultant force of 9.5 kips acting 35 feet above ocean bottom.

The basic uncertainty in the correct value of the drag coefficient and the cumbersome analysis of the pile frames using the more refined smooth curves for dynamic force distribution were deciding factors in selecting the simplified loading diagrams for pile frame analysis.

The net pile diameters were used for determing wave forces. In lieu of using an increased diameter as an allowance for marine growth the Owner intends to include pile cleaning as a routine item in the maintenance program.

Causeway Construction

The bid documents provided for five optional combinations of steel pipe or prestressed concrete piles, with steel or concrete caps, steel stringers and timber deck or 40 foot prestressed concrete slabs. Pile driving provided alternates of driving, driving and jetting, or drilling and grouting in the shale rock. It was presumed that driving might be practical for the steel pipe pile alternate, but that drilling and grouting would be required on the near shore piles if concrete piles were used.

The low bid was submitted for the steel pile, steel caps and stringers, and timber deck option. Before final award of the contract two test piles were driven into rock on shore to determine whether or not it was necessary to drill and grout the steel pipe piles. The two test piles of 1/2" wall 16 inch diameter pipes were successfully driven with a heavy drop hammer. As a result of these tests the option of driving the steel piles was selected, and a lump sum contract was awarded on that basis.

The scheme of construction selected by the contractor was to build a temporary work trestle of his design from which the piles for the causeway were driven by a heavy drop hammer handled by a small crawler crane. Stringer assemblies were shop fabricated and placed by a truck crane operating on the work trestle. The cap connection to the piles consisted of a stiffened connection plate welded to the bottom flange of the cap which fitted into vertical transverse slots in the piles as shown in Fig. 17. The work trestle afforded ready access for alignment of the piles and cutting the slots and thus made the erection work a simple operation. Construction of the work trestle paced the causeway erection work.

Specified pile penetration for the typical single pile and double pile transverse battered bents was 8 feet into the shale formation or a minimum penetration of 20 feet into other materials and a driving resistance giving not less 45 ton safe load by use of the ENR pile driving formula. Required penetration for the four longitudinally battered bents was 50% greater. Pile sizes ranged from 16 inch diameter, 3/8 inch wall at the shore end to 24 inch diameter, 9/16 inch wall for the deep water longitudinally battered bents. All piling was sandblasted and coated with coal tar enamel. The three expansion joints are semi-insulated as a cathodic protection system will be installed by the Owner. Concrete pipe sleeves were installed at the bottom line on the first nine inshore bents as a precaution against sand abrasion.

Work on the causeway was started in November, 1957 and the first vehicles crossed in July, 1958. The January 26, 1958 storm caused approximately one month's delay by knocking over about 750 feet of the contractor's temporary work trestle. Only the abutment of the causeway had been completed at this time.

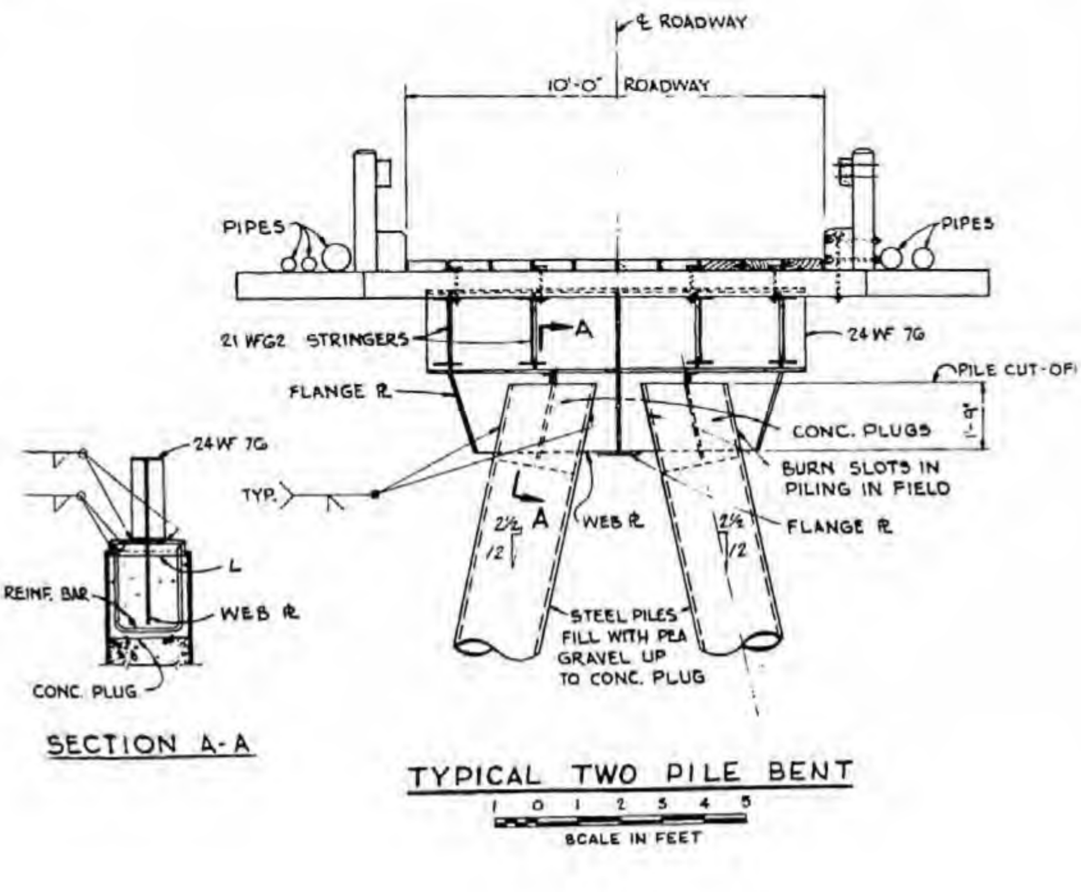


FIG. 17

Controls for Settlement, Erosion, and Damage to Island

A program of controls was prepared for the Owner so that an accurate service record of the island will be maintained. The lack of any precedents of similar structures makes such a program very desirable. Elevation check points are located in several zones, so selected that differential settlements between different zones will isolate the cause of any settlement. If settlements become significant at some future time this knowledge of the cause would be of prime importance in selecting remedial measures. Possible causes of settlement could include in addition to further consolidation of the island and its base due to time and pressure, earthquake or storm wave damage, loss of fine materials because of piping, erosion of rock or tetrapods, subsidence due to drilling or production, or general geological subsidence. None of these are expected to be of major importance in this installation because of the design and construction care and the Owner's pressure oil production techniques.

It is hoped that reasonably accurate wave observations and possibly photographs of large swells can be made by reference to the causeway deck level. Runup or overtopping of the seaward face can also be recorded. This information combined with data on damage, or preferably lack of same, would be an important contribution to marine engineering. To date there has been no damage although the storm swells have probably not yet exceeded those of a ten year frequency.

An additional phase of the program consists of an indexed series of holes in the exposed armor rock which will be periodically measured to determine the rate of erosion.

General: Islands Versus Platforms

Although legal requirements which were then in effect dictated that Rincon Island be a solid man-made island of natural materials, there was still some choice of materials and techniques. It could have been argued for example that concrete contains nothing but natural materials as does steel. Even the adjective "solid" before the word island would still leave the possibility of using concrete or steel to retain solid fill. In fact, such construction was considered in the early design stage and later by some bidders but it was rejected on the basis of cost. A small island and/or deeper water would make prefabricated or precast construction more attractive or compared to the rubble revetment type from the cost standpoint. However, the break-even point varies with a great many other parameters than area and depth including wave size and bottom conditions.

The obvious thing, of course, is to raise a platform above the level of the worst waves to let these pass under. Such was prohibited in this case by the "solid" requirement. However, for the given depth, waves, work area and other factors, the island was and still is considered no more costly than a platform, and perhaps less so when maintenance is considered. Other benefits include complete fire resistance, the space and layout to operate as under normal land production; and an installation that has the appearance and charm of a natural island.

The general conclusion has to be that every problem must be considered on its own and in the light of its particular limitations and requirements. If the conditions are proper and if the design and construction are done in a modern engineering manner and not ruled too much by traditional methods and outmoded equipment (which have often led to failure of less critical marine construction) a rubble mound, sloping-sided island can be effective, long lasting and economical as well as attractive in appearance.

The Complete Project

Immediately upon assuming essential occupancy of the island and the causeway, Richfield Oil Corporation started its drilling program and the installation of oil field equipment and piping. Several wells have been completed at the time of this writing. When the drilling program is entirely completed, there will be no derrick on the island. The palm trees, installed by the Owner, enhance the natural appearance of the project which is visible to the many people traveling north and south along the coast via highway, train and plane. The causeway as well as the island receives considerable attention since the alternate single and double (battered) pile bents provide a clean appearance and constantly changing line patterns as the viewer travels along the shoreline.

CREDITS

It took the combined effort of many persons to bring the concept of a man-made island and causeway into physical existence. Only a few of these can be mentioned. The Owner of the installation and the responsible party for the island location and oil production facilities is Richfield Oil Corporation. The project was under the production department headed by W. J. Travers vice president, with Karl Kreiger manager of operations, and R. O. Pollard manager of the southern division which will operate the facility. The general contractor for the island proper was Guy F. Atkinson Company with D. E. Root, vice president in charge, Edward Raimer and Charles Thompson, field superintendents for the island construction and quarry operations, respectively. The general contractor for the causeway was Healy Tibbitts Construction Company with R. H. Smith in charge and James Lees as field superintendent. Establissements Neyrpic and Sotramer of Grenoble, France are holders of patents on the tetrapods. The design, wave research, general engineering supervision and inspection were conducted by John A. Blume & Associates, Engineers with the consulting aid of Paul Horrer on wave predictions and Robert Y. Hudson on revetment stability and wave action model testing. The latter operation was conducted at the U. S. Army Engineer's Waterways Experiment Station, Vicksburg under special financial arrangements. H. J. Sexton was engineer in charge of design; James M. Keith was design engineer and later resident engineer at the wave laboratory and in the field during all construction operations; John A. Blume was the firm principal in direct charge of the overall project.

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