CHAPTER 4

THE MECHANISM OF SEICHES IN TABLE BAY HARBOR, CAPE TOWN

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ABSTRACT

Surging in Table Bay Harbor is shown to be favored by the peculiar location of the harbor within Table Bay and of Table Bay within the South Atlantic Ocean, and by the fortuitous fact that both the external and internal dimensions of the harbor accentuate the development of seiches. The roadstead comprising a three-sided quasi-basin permits resonant augmentation of several bay-seiches, notably those of about 11 and $5\frac{1}{2}$ minutes period, and certain harmonics among these are stimulated sufficiently to communicate themselves into the docks and achieve resonance there also. The periodicities of oscillations found by observation are explained theoretically and confirmed in model experiments. The largest basin of the harbor, during its construction period, exhibited different oscillating properties from those in evidence today. The differences are explained on the basis of the changing dimensions in shape and depth of the enclosed body of water. Model experiments again confirm the general mechanism of behavior.

INTRODUCTION

The occurrence of troublesome Range-action or surging in Table Bay Harbor, Cape Town, South Africa, during critical shipping years of World War II, at a time when this phenomenon was still improperly understood, led to an intensive model study (1943-46) conducted under the auspices of the South African Railways and Harbours Administration. Some results of these researches which have general applicability to harbors or bear more particularly upon Table Bay Harbor itself, have recently been published (Wilson, 1950, 1952, 1953); the present paper may be said to contain another phase of the general findings.

The same problem, as affecting harbors in this country and elsewhere in the world, has received considerable attention in the last decade and the essential principles of the action taking place during surging are now well understood (Neumann, 1948; Irribarren, 1949; Vanoni, 1951; Knapp, 1952; Carr, 1952; McNown, 1952; and Wilson, 1953 (ii)).

Briefly, the phenomenon may be attributed to the development of coastal seiches in bays, inlets or semi-enclosed bodies of water as a result of the ingress and reflection of long waves or ground swells whose energy cannot normally be dissipated in surf and by attrition along the coast.

Every enclosed or semi-enclosed body of water has natural periods of oscillation which depend entirely upon its dimensional characteristics such as the surface configuration and the topographical features of the bed, as affecting the depth. A measure of agreement between the impressed frequency of the pressure or ground-swell excitation and the natural frequency of the water-body may be all that is required to stimulate the development of a seiche. In general seiches tend to occur in families of related frequencies, which, in the special cases of basins with simple geometrical shapes, such as the rectangular forms of uniform depth, constitute a pure harmonic series; ordinarily, however, the relationship is more complex. (Chrystal, 1904-5).

A condition for oscillation of closed bodies of water is that antinodes or loops shall exist always at the extremities of the basins. In the case of basins which open upon larger bodies of water the modes of oscillation generally require nodal conditions at the mouth. However, if the opening to a basin is comparatively small in terms of the basin dimensions, response will be to modes of oscillation which are a combination of the modes for basins fully closed and fully open. The problem is somewhat complicated when the mouth itself attains to appreciable dimensions in length between the connected bodies (Neumann, 1950).

SEICHES OF TABLE BAY

Evidence secured from marigram records at Cape Town suggests that the submerged oceanic basins to the west of the South African coast (Fig 1) permit independent oscillations of the water masses within the pseudo-rectangular trench and triangular canyon (Wilson, 1953 (iii)). The inference is that these oceanic basins are responsive to fluctuating pressure changes arising within the east bound frontal depressions which traverse them in wave-like sequence and contribute a component of motion along the long axes of the basins.

Topographically, Table Bay itself is similar to a semi-ellipsoidal bowl with two openings in its side wall, parallel to its major and minor axes (Fig 1, inset). As the bay lies on the boundary of both the oceanic basins mentioned it would be subject to the forced seiches imposed by some of the higher modes of the oceanic oscillations. Several of these forced seiches seem capable of securing near resonant response from Table Bay, but of its own accord the Bay can beget its own system of free seiches, activated by wave or pressure disturbances whose frequencies are too high to make any sensible impression upon the larger water bodies in the oceanic basins.

Analysis of the oscillating properties of Table Bay from three standpoints, - theoretical, observational and experimental - seems to indicate that the important critical periods conform to the series (Wilson, 1953 (iii)): -

T = 71-66-57; 55-51; 43-36; 33-26; 23-17; 14-12; 11-10;
9.8-9.4; 8.3-7.8; 7.5-7.0; 6.8-6.5; 6.3-5.9; 5.7-5.4;
4.8-4.4; 4.3-4.1; 4.0-3.7; 3.6-3.4; 3.2-3.1; 2.9-2.7;
..... minutes ________ (1)

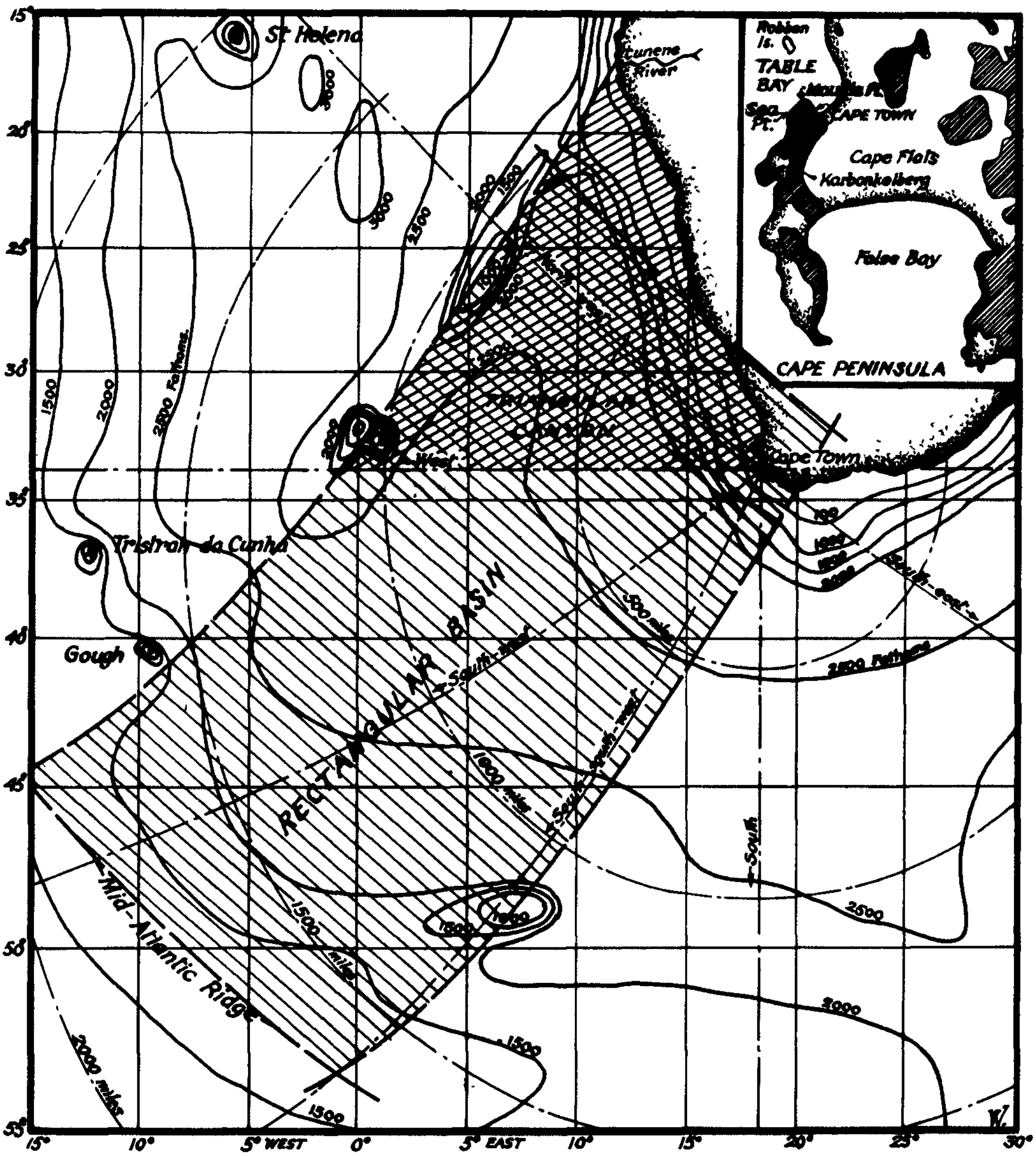


Fig. 1. Configuration of South Atlantic Ocean

These figures give the approximate ranges within which particular periodicities of oscillation tend to occur.

THE BREAKWATER - SHORE OSCILLATING SYSTEM

Just as the majority of the above frequencies cannot much influence the water-mass in the oceanic basins, so the highest frequencies of ground-swells (periods smaller than shown in the above sequence) cannot excite much response in the water-body of Table Bay. It requires a still smaller oscillating basin to encourage the development of such seiches, and this, as it happens, has been provided by the handiwork of man, in the form of an open sided basin between the harbor breakwater and the opposite shore (Fig. 2).

The depth of water and distance between the breakwater and the shoreline, the latter's parallelism with the breakwater, the rectangularity and axial disposition of the quasi-basin, all fortuitously favor the imposition of particular forced seiches of the bay and the reproduction of their families of dependent frequencies. Thus, in the sequence (1) of periodicities given above, the 11-10 minute seiche of the bay, its 22-20 minute overtone, and $5\frac{1}{2}$ minute harmonic, resonate almost perfectly in the breakwater-shore basin, greatly stimulating themselves in that corner of the bay and ensuring the promotion of yet higher-frequency seiches. This fact has now been fairly convincingly demonstrated by model experiments, refraction-diagram analysis of seiches, and by harmonic analysis of seichograms (Wilson 1953 (iii)) with results for the latter such as shown in Table I:

The regular shape and very gradually changing depth of water in the breakwater-shore basin ensure that the natural periods of longitudinal oscillation between the breakwater and shore boundaries will not be far removed from an harmonic series. In the knowledge, then, that the most important fundamental oscillation for the quasi-basin is about 11 mins., we could expect harmonics in the series 1, 1/2, 1/3, 1/4, . . . to be 11, 5.5, 3.7, 2.8, 2.2, 1.8, 1.57, 1.38, 1.22, 1.10, 1.00, 0.92 . . . minutes. A typical harmonic such as the quadrinodal one of 2.8 minutes would accommodate itself in the quasi-basin after the fashion of Fig. 3.

Forced seiches such as the predominant 13/6.5 minute and 9.5/4.7 combinations, falling within the periodic sequence, Equation (1), would find in the breakwater-shore system a receptacle for achieving near-resonance, and could be expected to yield their own harmonic trains to add to or reinforce the possible modes of oscillation of the water-mass in the harbor area.

A seiche of the order of 22 minutes period has been shown to have a node in line with the breakwater, and parallel to the coast (Wilson, 1953 (iii)), and may be likened in its effect on the breakwater-shore system to the fundamental seiche for an open basin with node at the mouth. As a forced seiche, it could thus be expected to impress itself upon the quasi-

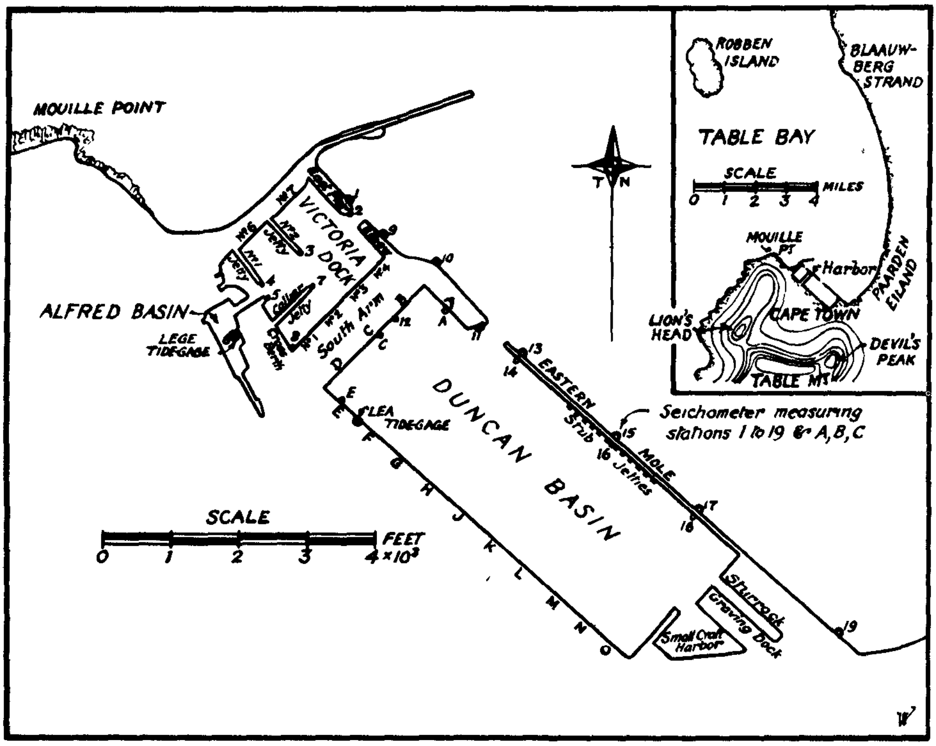


Fig. 2. Table Bay and harbor, Cape Town

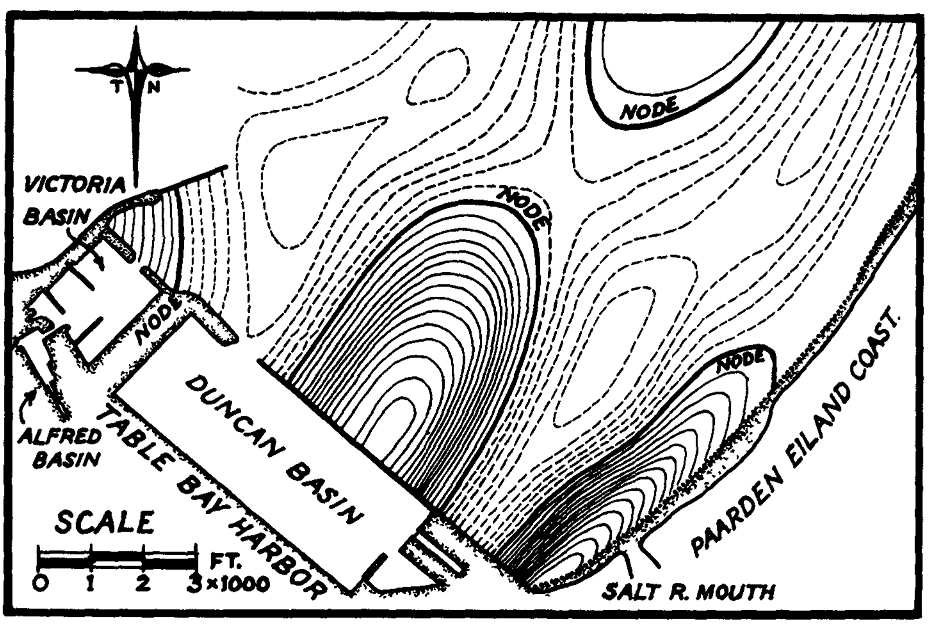


Fig. 3. Approx. instantaneous form of 2 3/4 min. sieche off Table Bay Harbor. (Graphical synthesis)

Table I

Apparent Periodicities of Component Oscillations in Seichograms Obtained by Method of Residuation (cf Chrystal, 1906).

General Location	Recorder Station	Date of Record	Apparent Periodicities (Minutes)																						Analyst
Outside Eastern Mole near Shore.	15	Oct. 4/43	—	—	—	25.7	—	—	11.4	—	—	5.7	4.5	3.8	2.8	2.2	—	—	—	—	—	—	—	—	Wilson
	19	" "	—	—	—	25.7	—	—	11.4	8.6	—	5.7	4.5	3.8	2.8	2.2	—	—	—	—	—	—	—	—	Wilson
	19	Nov. 6/44	—	51	—	25.7	—	—	11.5	—	6.9	—	4.9	4.3	2.8	2.0	—	—	—	—	0.75	—	—	0.25	Joosting
	19	" "	58	—	—	29.0	—	—	11.1	—	—	5.6	4.3	—	—	2.2	—	—	1.06	—	0.71	0.62	0.49	—	Wilson
	19	" "	—	—	—	—	—	—	10.2	—	—	5.7	4.2	—	—	2.3	—	1.52	1.10	—	—	—	—	—	de Boer
	19	Nov. 8/44	—	—	—	—	18.6	—	10.9	—	7.4	5.5	—	3.5	—	2.1	—	—	1.06	—	—	—	—	—	Wilson
	19	Aug. 6/46	62	—	—	23.4	—	14.0	—	8.8	—	5.4	—	3.4	2.8	—	1.74	1.54	1.09	—	0.70	—	0.41	0.33	Joosting
	19	" "	—	—	—	—	—	14.5	11.0	—	—	5.5	—	3.8	2.5	—	—	—	1.10	—	—	—	—	0.36	Cowan
	19	Aug.23/46	62	—	—	22.7	—	13.6	—	9.2	—	5.6	—	—	3.0	2.5	1.50	1.33	1.07	—	0.76	—	0.41	—	Joosting
	19	" "	—	—	—	26.0	—	14.0	—	9.1	—	5.6	—	—	2.5	—	—	1.40	—	0.90	—	—	0.45	—	Cowan
Entrance of Duncan Basin	11	Aug. 1/44	—	—	—	—	—	16.0	—	—	—	5.6	4.2	—	2.7	2.0	1.90	—	1.00	—	—	—	0.51	—	de Boer
	11	" "	—	—	—	—	21.0	—	—	—	—	5.4	4.3	3.9	—	2.1	1.97	—	1.02	0.96	—	—	0.53	—	Joosting
	11	Aug. 3/44	—	—	38	—	19.0	—	—	9.5	—	5.3	4.9	—	2.5	2.3	—	1.25	1.00	—	—	0.60	0.50	—	de Boer
	11	" "	—	—	38	—	19.0	—	—	9.5	—	5.5	4.8	—	2.5	2.3	—	1.25	1.02	—	—	0.56	0.50	—	Joosting
	11	Oct. 1/44	—	—	43	29.0	21.3	17.0	—	—	6.8	—	4.3	—	—	2.0	—	1.35	—	—	0.68	—	—	0.25	Joosting
	11	June21/45	—	—	—	—	19.0	—	—	—	—	5.6	—	—	—	2.3	1.87	—	—	0.94	0.67	—	0.49	—	Joosting
	11	July 7/45	—	—	—	—	—	14.0	—	—	7.0	5.6	—	—	2.6	—	1.76	—	1.00	—	0.69	0.54	—	—	Joosting
	11	July31/45	—	—	—	—	21.0	—	—	—	—	5.9	—	3.5	—	—	1.87	—	1.05	—	0.71	—	0.50	—	Joosting
Breakwater Bight outside Victoria Basin	1	Oct. 1/44	62	—	—	31.0	19.2	12.1	10.1	—	—	—	4.1	—	—	2.2	—	—	—	—	—	—	—	—	Joosting
	1	Nov. 6/44	—	51	—	—	20.3	—	—	9.8	—	5.5	—	—	2.8	—	1.60	—	—	—	—	—	—	—	Joosting
	1	Nov. 8/44	—	—	—	—	21.0	—	11.0	—	—	5.8	—	3.5	2.9	—	1.68	—	—	—	—	—	—	—	Wilson
Inside Victoria Basin	4	Oct. 1/44	62	—	—	31.0	18.6	—	11.5	8.7	7.8	—	4.2	—	2.8	—	—	—	—	—	—	—	—	—	Joosting
	4	Nov. 6/44	—	51	—	22.5	—	—	11.2	9.5	—	5.5	4.1	—	2.8	—	—	1.39	—	—	—	—	—	—	Joosting
	8	June20/45	—	—	—	—	—	—	10.8	—	—	5.4	—	3.1	2.3	2.3	1.91	—	1.10	0.87	—	—	—	—	Joosting
Inside Duncan Basin	12	Aug.30/44	—	—	—	28.0	—	14.0	—	—	—	5.6	4.7	3.8	—	2.2	1.90	1.30	1.00	—	—	—	0.50	—	de Boer
	12	" "	—	—	—	28.0	—	14.0	—	—	—	5.5	4.8	3.4	—	2.2	1.89	1.42	1.00	0.91	—	—	0.50	—	Joosting
	12	Nov. 6/44	—	52	—	26.0	18.0	—	11.2	—	6.3	—	4.3	—	—	2.0	—	1.53	—	0.90	—	—	0.45	0.25	Joosting
	12	Nov. 8/44	—	—	—	27.5	—	13.7	—	—	—	5.5	4.1	—	—	2.1	1.68	1.22	—	—	0.71	—	—	—	Wilson
	12	" "	57	—	—	28.3	—	14.1	—	—	6.5	—	4.3	—	—	2.1	—	1.41	1.15	—	0.66	—	—	0.25	Joosting
	12/C	Aug. 6/48	—	—	—	—	—	14.0	—	—	—	5.9	4.0	—	—	—	—	—	—	0.95	—	—	—	—	Cowan
	12/C	Aug.23/48	—	—	—	—	—	—	—	—	—	—	4.0	—	—	—	—	—	1.05	0.80	—	—	—	—	Cowan
	A	Aug. 6/48	—	—	—	—	17.0	—	—	—	—	5.4	—	—	—	2.1	—	1.57	—	—	—	—	—	—	Cowan
	A	Aug.23/48	—	—	—	—	—	13.0	—	—	—	5.5	—	—	—	—	—	1.44	1.00	—	—	—	—	—	Cowan
	E/F	Aug.18/45	—	—	—	—	—	16.0	—	—	—	5.5	—	3.8	2.6	—	—	1.50	—	0.90	—	—	—	—	Cowan
	E/F	Nov.17/45	—	—	—	—	—	—	11.0	—	—	5.6	—	—	2.6	—	1.91	1.50	—	—	0.76	—	—	—	Cowan
	E/F	Dec. 7/45	—	—	—	—	—	—	11.0	—	—	5.6	—	3.5	—	—	1.75	1.55	—	0.93	—	—	—	—	Cowan
	14	Oct. 1/44	—	—	—	29.0	18.6	17.0	—	9.8	6.6	—	—	—	—	—	1.77	—	—	—	—	—	—	—	Joosting
	16	Oct. 1/44	—	—	—	29.0	19.1	12.7	—	—	—	5.0	—	—	—	—	1.66	—	—	0.89	—	—	0.43	—	Joosting
	16	Nov. 6/44	—	51	—	20.4	17.4	12.2	—	—	—	—	4.6	3.8	—	—	1.86	1.29	—	—	0.68	—	—	0.25	Joosting
	18	Oct. 1/44	—	—	—	29.0	19.1	12.2	—	—	—	—	4.7	—	—	—	1.66	—	—	—	—	—	0.43	—	Joosting

basin by begetting higher harmonics in the odd modes only so as to comply always with the requirement of a node lying in line with the breakwater. In this way harmonics would conform to the series 1, 1/3, 1/5, 1/7, . . . yielding periodicities approximating to 22, 7.3, 4.5, 3.1, 2.4, 2.0, 1.69, 1.47, 1.30, 1.16, 1.04, 0.96, ...

The co-existence of these several seiches for Table Bay with their developed families should then produce upon coalescence, in the immediate vicinity of the harbor, seiches of the average periodicities shown at the foot of Table II. The values have been derived from the figures tabulated by weighting twice in favor of the 11-minute seiche to make some arbitrary allowance for its more perfect resonance in the breakwater-shore quasi-basin.

Table II

Natural and Forced Periods of Oscillation for the Breakwater-Shore Quasi-Basin.

Funda-mental Forcd. Oscil.	Higher Harmonics (Minutes).													
22	7.3			4.5	3.1	2.4	2.0		1.69	1.47	1.30	1.16	1.04	0.96
13		6.5		4.3	3.2	2.6	2.2	1.86	1.63	1.44	1.30	1.18	1.08	1.00 0.93
11			5.5		3.7	2.7	2.2	1.83	1.57		1.38	1.22	1.10	1.00 0.92
9.5				4.7	3.2		2.3	1.90	1.58		1.36	1.19	1.05	0.95
All	7.3	6.5	5.5	4.5	3.4	2.6	2.2	1.86	1.61	1.45	1.35	1.19	1.07	0.96

The final row of figures, which, of course, are capable of some fluctuation up or down, bears favorable comparison with the apparent periodicities identified by residuation analysis in the seichograms for the area outside the harbor (Table I) and leads to the inference that this mechanism, in part at least, explains the existence of the multi-period sea movements outside the harbor basins.

PERIODOGRAMS FOR THE HARBOR AREA FROM MODEL TESTS.

The Range-action model of Table Bay Harbor, constructed to a coefficient of distortion (vertical exaggeration) of 8 (horizontal scale 1/1200, vertical scale 1/144), reproduced the whole of Table Bay from Mouille Point to Robben Island and Blaauwberg Strand (Fig 1). Two wave paddles across the west and north channel entrances to the bay were used to simulate the ingress of swells from the outer ocean. In the process of determining the appropriate adjustments for these paddles it was found that the amplitudes of the oscillations in the harbor area varied with periodicity in a manner which could not be attributed wholly to the changes introduced in the settings of the paddle machinery. The model was in fact functioning as an harmonic analyser in revealing the resonant frequencies of the harbor system.

An early experiment, aimed at determining some of the natural frequencies of the harbor, gave the periodograms of amplitude measurements shown in Fig 4 for three stations, one of which was in the Victoria Basin and the others in the Duncan Dock (see Fig 2). At the time that the test was made the best adjustments for the paddles had not been finally determined and the amplitudes of oscillations are not really comparable, quantitatively, over a wide span of periodicities, though comparisons are valid enough over short period-ranges. The remarkable increase in amplitude of the oscillations at certain periods is at once evident from Fig 4. The following critical periods reveal themselves:

$$T = 13.2,\ 11.5,\ 9.5\text{-}9.0,\ 8.5\text{-}7.6,\ 6.8\text{-}6.4,\ 5.7\text{-}5.4,\ 4.8\text{-}4.5,\ 3.6\text{-}3.4,\ 3.0\text{-}2.8,\ 2.4,\ (2.2),\ 2.0,\ 1.9\text{-}1.8,\ 1.6,\ \ldots \text{ minutes} \qquad (2)$$

These experimental results, insofar as they extend, provide good confirmation of the observed periods (Table I) and the theoretical interpretations placed upon them (Equation (1) and Table II). But later experiments, having reference more particularly to a periodic range from 1.0 to 8.0 minutes, afford more material for defining the critical frequencies.

Once the appropriate paddle-settings for the model had been worked out, the search to discover critical periodicities for the model harbor-basins involved recording the water oscillations at four different points in the model harbor for some 80 different wave-periods taken in succession. Each set of observations was repeated four times to simulate the effects of waves from four directions in the outer ocean, south-west, west-southwest, west and west-northwest, the paddles being appropriately slewed or altered to cover these cases. The results, embodied in the composite periodograms, Figs 5 (a) and (b), have been corrected for the distortional effects of the model (time scale) and converted to natural proportions. The range or double-amplitude of oscillations are far in excess of movements measured in the real harbor, but the exaggeration of wave effects in the model does not detract from the usefulness of the results which should be interpreted on a comparative basis only.

Two things are immediately noticeable about Fig 5: the first is that there are relatively isolated frequency bands of response in all the basins; the second, that there is not a great deal of difference in the response to waves from different directions in the external ocean. The critical periods in all cases are much the same, only the overall magnitude of the disturbances being appreciably affected by wave direction.

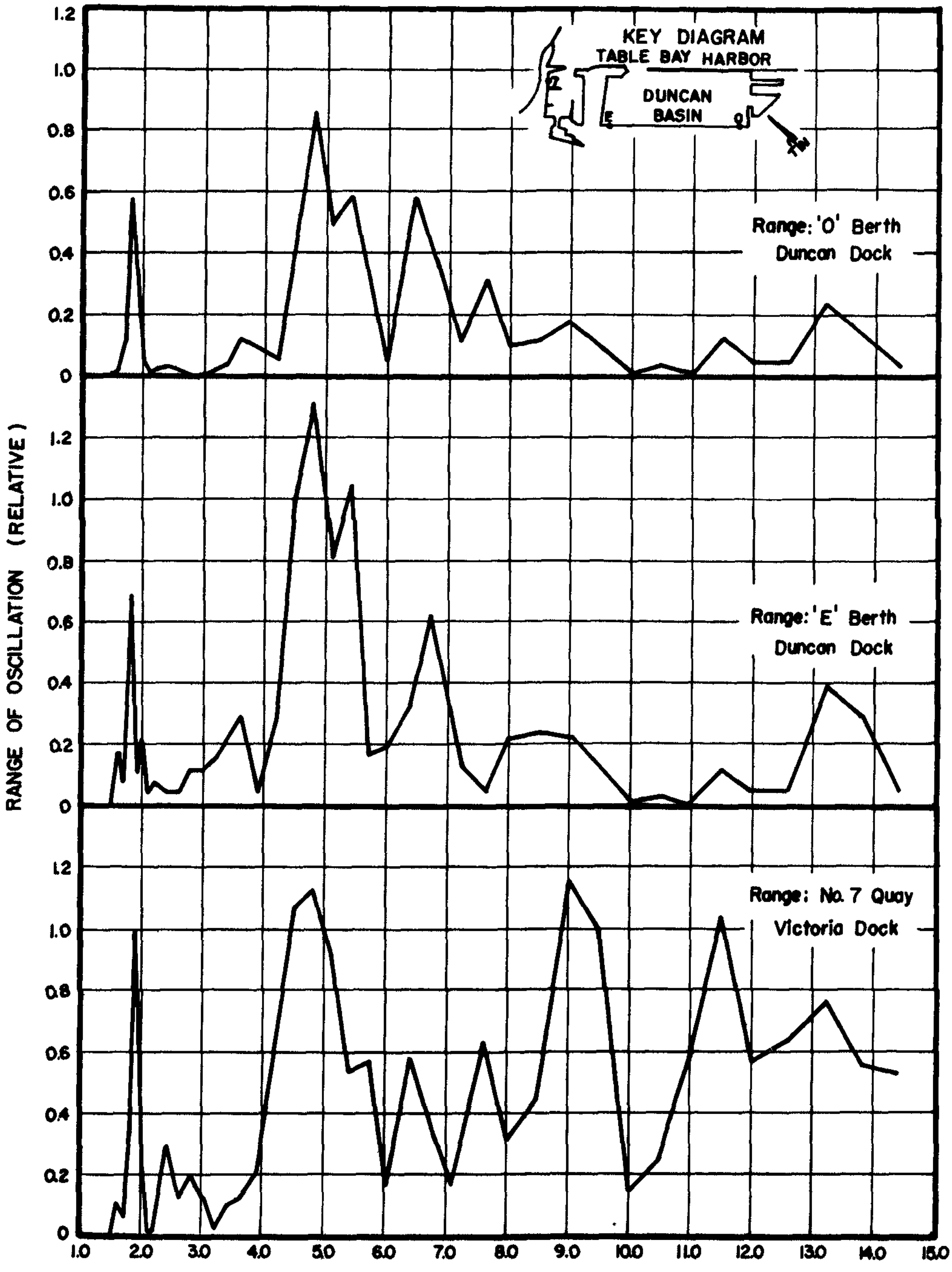
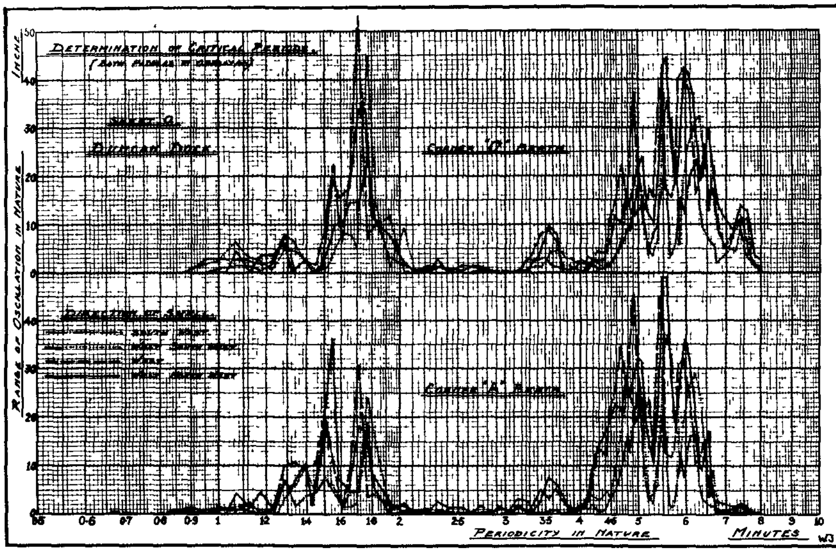
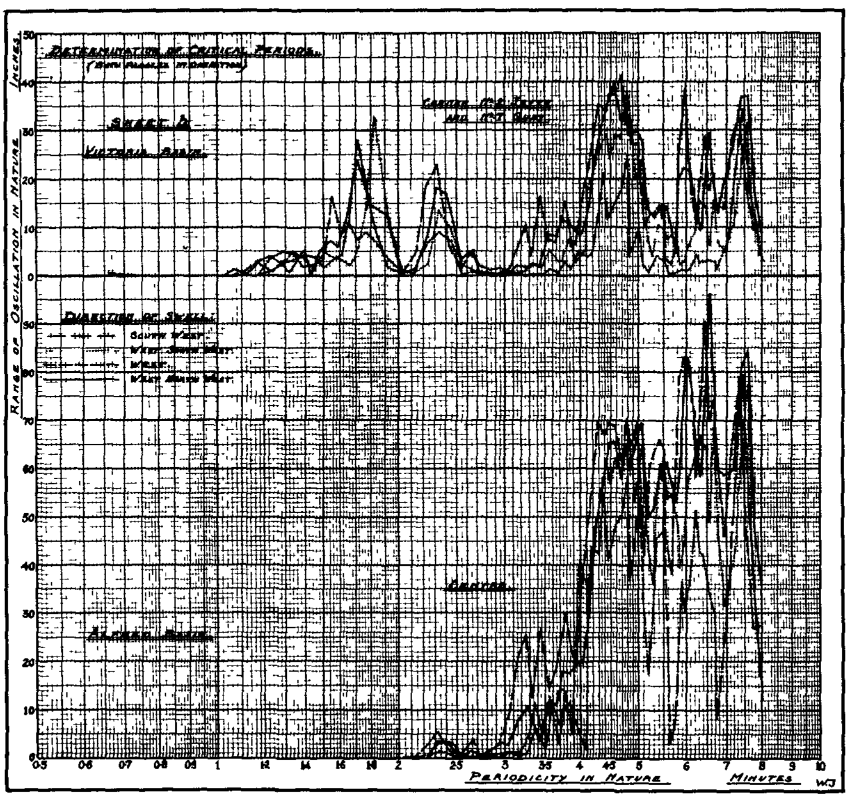


Fig. 4. Periodograms of response of model harbor to different wave frequencies. (Early model experiments)



(a) Duncan Dock



(b) Victoria and Alfred Basins

Fig. 5. Periodograms of response of model harbor to waves of different frequencies.

The explanation for these features is not difficult to descry. The harbor basins, clearly, only respond to those forced seiches of the external breakwater-shore system as agree reasonably closely with their natural frequencies. Further, the relative unimportance of wave direction derives from the refractive influence of Table Bay in causing swells that penetrate to the harbor to have only a small directional variation (Wilson, 1953 (iii)).

Taking the periodograms of Fig 5 collectively and grouping peak periodicities for the different wave directions whenever they are closely knit, we may identify what are obviously the forcing seiches of the breakwater-shore oscillating system. In this process, certain minor peaks justify inclusion since their apparent unimportance can be attributed to the unresponsiveness of the basins to those modes of the external oscillation. Certain other peaks, particularly the three occuring between 3 and 4 minutes in the Victoria and Alfred Basins (Fig 5 (b)), have been unified, since it is known from the model studies that these are resonance peaks for individual compartments of the Victoria Basin (cf Fig 2) and are thus peculiar to the inside of the harbor rather than to the outside. The resulting sequence of critical periods fluctuates round the following most significant values.

$$T = 7.5,\ 6.6,\ 6.0,\ 5.5,\ 4.7,\ 3.6,\ 2.6,\ 2.3,\ 1.81,\ 1.72,\ 1.55,\ 1.40,\ 1.30,\ 1.17,\ 1.07,\ 0.95,\ \ldots \text{ minutes} \qquad (3)$$

This series, compared now with Table I, Equation (1) and Table II, but especially the latter, shows good correspondence and confirms the picture of the essential underlying structure of the phenomenon. However, there are one or two notable omissions in Table II, such as those of the 6.0 and 1.72 minute periodicities, which demand an explanation. The existence of the former, as proved by the model, could be attributed to the 6.3-5.9 minute forced seiche of the bay (Equation (1)) and would seem to indicate that a 12/6.0 minute near-resonant combination should have been included in the assembly of Table II. The seventh harmonic of a 12 minute fundamental oscillation would be 1.71 minutes and its comparative isolation from neighboring harmonics of the other fundamentals (22, 13, 11, and 9.5 minutes, Table II) could perhaps explain its independent occurrence. However, it will be shown later that the development in strength of this oscillation in the harbor basins can be aided from another source.

If Table II is amended to include a 12-minute fundamental oscillation and harmonics, as well as the independent higher harmonic seiches of the bay from Equation (1), with the arrangement and weighting shown in Table III, which makes some arbitrary allowance for the degree of 'resonance-fit' of the fundamentals within the breakwater-shore basin, the resulting sequence of arithmetic means gives the probable central values of the critical periods:

These are now the periodicities likely to be most active in producing sympathetic oscillations within the harbor and the bracketed figures or cumulative weights should give some idea (admittedly artificial) of their relative importance and likelihood of occurrence, though not necessarily of their relative amplitudes.

Table III

Periods of Natural and Forced Oscillation for the Breakwater-Shore Quasi-Basin (Revised)

Fundamental Forced Oscillation (Mins)					Assigned Weight	Harmonics (Minutes)																	
22					(3)		7.3				4.5		3.1	2.4	2.0		1.69		1.47	1.30	1.16	1.04	0.96
	13				(2)			6.5				4.3	3.2	2.6	2.2	1.86		1.63	1.44	1.30	1.18	1.08	1.00 0.93
		12			(3)				6.0			4.0	3.0	2.4	2.0	.	1.71	.	1.50	1.33	1.20	1.09	1.00
			11		(4)					5.5		3.7		2.7	2.2	1.83	.	1.57	.	1.37	1.22	1.10	1.00 0.92
				9.5	(2)						4.7		3.2	.	2.3	1.90	.	1.58	.	1.36	1.19	1.05	0.95
						8.0 (1)	7.3 (3)	6.6 (2)	6.1 (3)	5.6 (4)	4.6 (2)	4.2 3.9 (2)	3.5 3.2 (2)	2.8 (4)									
22 (3)	13 (2)	12 (3)	11 (4)	9.5 (2)		8.0 (1)	7.3 (6)	6.5 (4)	6.0 (6)	5.5 (8)	4.6 (7)	4.0 (13)	3.2 (14)	2.6 (16)	2.1 (14)	1.86 (8)	1.70 (6)	1.59 (8)	1.47 (8)	1.33 (14)	1.19 (14)	1.08 (14)	0.96 (20)

THE NATURAL MODES OF OSCILLATION FOR THE DUNCAN BASIN

The extent to which the forcing seiches just considered will communicate themselves into the harbor will depend very largely upon the oscillating properties of the harbor basins and the location of the latter in relation to the external seiches. The Duncan Dock which is vertical walled, of very regular shape (Fig 2), and of almost uniform depth provides a good case for the application of the hydrodynamical theory of seiches to the determination of the modes of free oscillation. Thus the periods, T_m , of the several modes of oscillation along the axes of a rectangular basin of length, L , breadth, B , and uniform depth, d , are given by the equation (Sverdrup, 1942): -

$$T_m = \frac{1}{m} \cdot \frac{2L \text{ (or B)}}{gd} \qquad (4)$$

in which g is the gravitational acceleration, and m an integer of successive values 1, 2, 3, . . . , defining the mode. The numerical evaluation of T_m for the Duncan Basin according to (4) is given in Table IV:

Table IV

Natural Periods of Duncan Basin from Hydrodynamical Theory

Direction	Dimensions		Computed Periods (for values of m)-Minutes						
	L or B	d	1	2	3	4	5	6	7
Length	6000	40	5.57	2.78	1.85	1.37	1.11	0.93	0.79
		45	5.26	2.63	1.75	1.31	1.05	0.88	0.75
Breadth (northend)	2100	40	1.95	0.97	0.65	0.49	0.39	0.33	0.28
		45	1.84	0.92	0.61	0.46	0.37	0.31	0.26
Breadth (southend)	2200	40	2.04	1.02	0.68	0.51	0.41	0.34	0.29
		45	1.93	0.96	0.64	0.48	0.39	0.32	0.28

Equation (4) however, is really a special case of a more general relationship for the two dimensional oscillations in a rectangular basin of uniform depth (Lamb, 1932), namely: -

$$\left.\begin{aligned} &\text{(i)} \quad \frac{4L^2}{T_{mn}{}^2 gd} = m^2 + \frac{n^2}{\beta} \\ &\text{(ii)} \quad \beta = (B/L)^2 \end{aligned}\right\} \qquad (5)$$

Here m and n are integers of possible values 0, 1, 2, 3, . . . defining the nodality along the longitudinal and transverse axes respectively. The natural periods already given in Table IV correspond to the cases, taken separately, of $n = 0$ and $m = 0$. As the length-breadth ratio, L/B , for the Duncan Basin is very closely 3, we find, on taking $\beta = 1/9$ in equation (5), the period-values shown in Table V for some of the remaining cases when m and n are both finite: -

Table V

Natural Periods of Duncan Basin: Two-Dimensional Oscillation

Depth d	Computed Periods (for different values of m and n)-Mins.									
	m = 1	2	3	4	5	6	1	1	1	2
	n = 1	1	1	1	1	1	2	3	4	2
40	1.76	1.55	1.31	1.11	0.96	0.83	0.92	0.62	0.46	0.87
45	1.67	1.46	1.24	1.05	0.90	0.78	0.86	0.58	0.44	0.83

Only the first few important periods are incorporated in the above table, because other values of m and n tend to give overlapping periods which are either indistinguishable from those given or approximate to the values already listed in Table IV.

Besides the natural periods shown in Tables IV and V, which are those for a closed basin, there will exist modes of oscillation for the Duncan Dock as an open basin, the applicable equation in this case being (Lamb, 1932):

$$T_s = \frac{1}{s} \cdot \frac{4L \text{ (or B)}}{gd} \qquad (6)$$

where s is an integer having only odd values 1, 3, 5, ... Equation (6) is strictly applicable to an open-ended rectangular canal of uniform depth, but since the entrance of the Duncan Basin is on the long side towards the north end and the diagonal distance from the mouth to the far corner approximately equals the length of the basin, L , the application of (6) may be considered admissable as an approximation. This is favored too by the fact that the basin mouth has negligible length of its own, and any "mouth correction" (Neumann, 1950) can be disregarded.

For s = 1 , the period of the fundamental oscillation of this type will be double of that for the fundamental seiche in the longitudinal direction given by Table IV, namely from 11.1 to 10.5 minutes, according to the height of the tide. The third harmonic, s = 3 , by the same token will have a period of from 3.71 to 3.51 minutes and will be reinforced by the close congruency of the fundamental oscillation (s = 1) in the direction of the breadth, B , (equation (4)), whose periodicity can vary from 4.08 to 3.68 (double the primary values in Table IV).

For a basin of such a narrow entrance as the Duncan Dock (400 feet in relation to a length of 6000 feet) it may be assumed that the open-mouth type of oscillation cannot develop with ready facility and that higher harmonics than the third will not be of importance. The third harmonic in the direction of the breadth with a period 1.36-1.30 would be perhaps the highest frequency deriving from this stimulant.

Based on equations (4), (5) and (6), then, the critical periods for the Duncan Basin, taken collectively, could be expected on the average to center round the values forming the series: -

$$T = 10.8,\ \underline{5.4},\ \underline{3.8},\ 2.7,\ \underline{2.0},\ \underline{1.85},\ \underline{1.72},\ \underline{1.51},\ 1.34,\ 1.28,\ \underline{1.08},\ \underline{0.98\text{-}0.90},\ 0.80,\ 0.66\text{-}0.60,\ 0.54\text{-}0.45,\ 0.33\text{-}0.30,\ \text{minutes} \qquad (7)$$

Underlined are the periodicities that are likely to be of greatest importance because of the special shape and dimensions of the basin, these being, in general, the lowest modes of the several kinds, longitudinal, transverse and two-dimensional.

THE EXCITATION OF SEICHES IN THE DUNCAN BASIN.

As to whether these natural frequencies will ever be excited depends essentially on the nature of the disturbances infiltrating from outside the basin. Reference to Tables I and II shows that many of the periodicities of the seiches which have been shown to exist in the external oscillating basin between breakwater and shore are very close in value to the natural periods of Equation (7). The 11, 5.5 and 1.86 minute seiches outside the Duncan Basin are almost exactly tuned, and if the antinodal positions are favorably situated to cause a flux through the basin entrance, they will induce completely resonant oscillations inside. The external seiches of periods nearest to these critical values can also be expected to beget forced seiches of near-resonance.

The model tests reflected in Fig 5 (a) prove that the 6.0 and 4.7-4.5 minute external seiches can obtain a fair measure of response from the Duncan Basin. Their co-existence, in fact would be likely to produce a beat oscillation with an apparent periodicity of about 5.3 minutes, which would strongly reinforce the main 5.5 minute forced seiche. The longest periodicity recorded in the Duncan Dock in any given case would depend on how many of these three forced seiches were present outside. If the 6.0 minute seiche were absent, for instance, the 5.5 and 4.6 minute seiches would tend to promote a beat oscillation of about 5.0 minutes period inside the basin, whereas if the 4.6 minute one were missing, the apparent periodicity would run to about 5.8 minutes or possibly higher. On rare occasions, no doubt, one or other of these forcing seiches might operate alone and impress its own periodicity upon the basin. Conformation of this would seem to lie in the fact that actual periodicities secured at random from marigrams for the Duncan Basin show values fluctuating from about 5.0 to 6.0 minutes with the average round 5.6 minutes. Fig 6 (a) gives a frequency diagram of these periodicities as recorded over the year 1945.

Direct and convincing evidence of the combining of the forced seiches in beats is provided by the seichograms of Fig 7 for stations A, C and E at the north end of the Duncan Basin. Attention is drawn in particular in these reproductions to the very obvious beats occurring simultaneously in the oscillations at A and E berths. The oscillations at stations A and E are seen to be directly opposite in phase while the trace for the intermediate station, C, shows a complete absence of the periodicity producing the

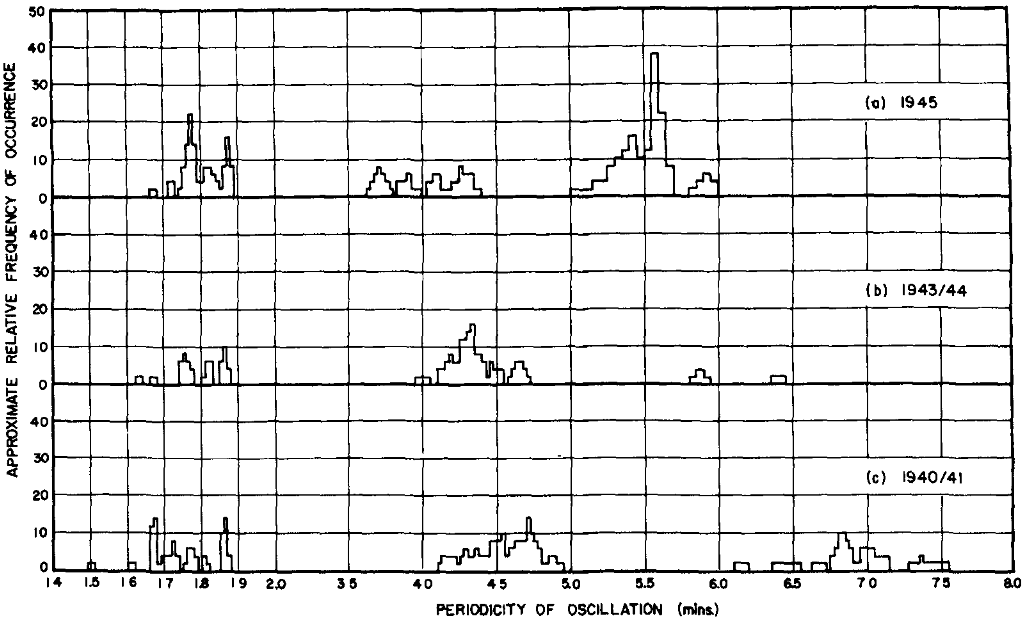


Fig. 6. Periodograms of prominent oscillations in the Duncan Basin at various stages of construction (see also Fig. 9.) as obtained from lea tide gauge at E/F berth location.

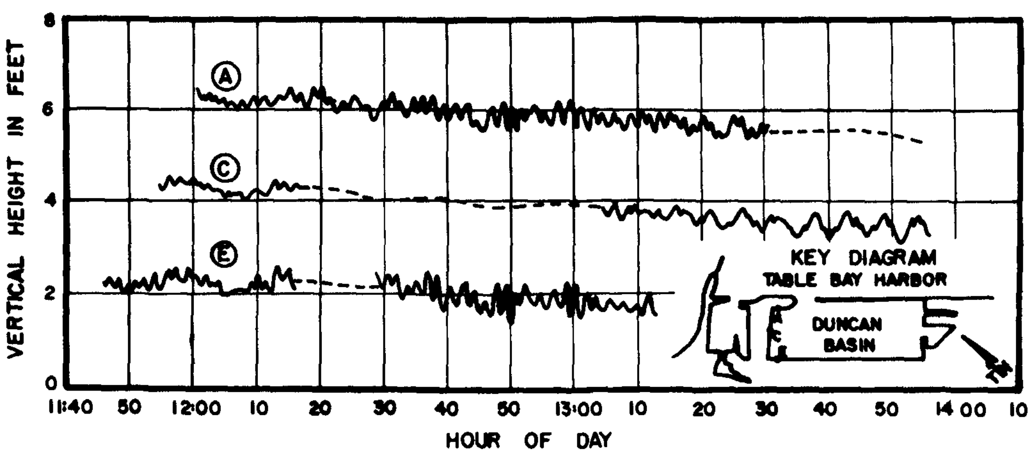


Fig. 7. Synchronised seichograms for North west end of Duncan Basin - July 22, 1946.

beats, though revealing what is clearly the second harmonic of it. All this is consistent with a fundamental transverse seiche across the northern end of the dock, whose apparent periodicity on the average is 1.765 minutes. The average length of the beats in which it occurs is 11 minutes.

Now if the beats are assumed to result from the interaction of two constituent seiches of frequencies p_1 and p_2, thereby producing a resultant of apparent frequency p which decays and grows with a beat frequency ω, it can be shown, if p_1 and p_2 are not markedly different in value, that

$$\left.\begin{array}{ll}\text{(i)} & p_1 = p + \omega \\ \text{(ii)} & p_2 = p - \omega\end{array}\right\} \qquad (8)$$

For the case in point $\omega = 1/22$ and $p = 1/1.765$, whence from (8) the component periods T_1 ($= 1/p_1$) and T_2 ($= 1/p_2$) are found to be respectively 1.63 and 1.92 minutes. These values suggest strongly that the 1.86 (±) and 1.59 (±) minute forced seiches of the breakwater-shore system (Table III) were co-existent (with or without an additional constituent of intermediate period) and impressed themselves as a resultant upon the Duncan Dock, in view of their close congruency with the free periods of transverse oscillation 1.85, 1.72, 1.51 minutes as suggested by equation (7).

Tide-gage marigrams for the Duncan Basin show that periodicities of transverse oscillations at the northern end of the dock vary mainly between 1.7 and 1.9 minutes with the relative frequencies of occurrence shown in Fig 6 (a). The greatest tendency is for the oscillations to have a period of either 1.875 or 1.775 minutes. These are the most important transverse periodicities for the two-dimensional modes of oscillation ($m = 0$, $n = 1$) and ($m = 1$, $n = 1$), respectively (Tables IV and V) and are easily brought into vibration by the outside disturbances; but it must be supposed from the evidence of the more accurate seichograms, such as Fig 7, in which beat oscillations were of common occurrence, that the 1.775 minute oscillation is more often the result of the combining of the ($m = 0$, $n = 1$) and ($m = 1$, $n = 2$) modes of free oscillation of the basin under the stimulus of the 1.86 and 1.59 minute external seiches. The latter frequency is not often found on its own and this, no doubt, is because it becomes merged with its stronger partner, whenever it builds up in amplitude, and completely loses its identity to the latter when it weakens.

Intermediate between the fundamental longitudinal and transverse seiches in equation (7) are natural periods of 3.8, 2.7 and 2.0 (±) minutes. The first is in evidence in Table I and is found also in the model periodograms (Fig 5 (a)), being obviously activated by the 4.0 or 3.2-minute external seiche of Table III. The 2.7-minute oscillation, on the other hand, is rather conspicuously absent. The reason for this must be conjectured but is not difficult to explain.

In the first place the 2.7-minute frequency is the second harmonic or binodal oscillation for the basin in the longitudinal direction, and, as such, has nodes at the quarter-points. The location of the basin entrance, however, is also situated at the eighth-to-quarter point in the long side of the dock, and therefore coincides with a nodal area of the second harmonic. No amount of stimulation from outside can then excite this mode of oscillation even though, as we have seen, a 2.8-minute seiche is prominent outside the harbor. In much the same way, a periodic force applied at a nodal point of a stretched string, cannot animate the particular mode of oscillation for which the string is nodal at that point, despite the period of the force being resonant with it.

In terms of Table IV, the 2.0-minute natural frequency of equation (7) is really the fundamental transverse oscillation for the southern end of the dock. Figs 5 (and also 8, which represents the results of later experiments) however, show that, although it is excited at that end of the dock, it is in rather subdued form. This is no doubt because the 2.1 minute forcing seiche outside the basin is somewhat out of step and is only able to impose upon this mode of oscillation by forming a beat frequency of the right order with the 1.86-minute seiche.

Below the 1.51-minute natural frequency in the periodic scale of equation (7) there are natural periods of 1.34, 1.28, 1.08 and the important group between 0.98 and 0.90 minutes. All of these are to be found in Table I and Figs 5 and 8, and as they correspond with the external forcing seiches of Table III, their generation is satisfactorily explained. All oscillations approaching 1 minute in period may be considered to be binodal transverse seiches.

There is not much corroborative material to confirm the natural periods below about 0.9 minutes, other than is contained in Table I, but this on the whole is favorable. The interpretation of most of the periodicities detected in the records for the Duncan Basin, given above, thus appears to approximate to the truth.

THE CHANGING NATURAL FREQUENCIES OF THE DUNCAN DOCK

The explications for the observed commotion in and round the harbor thus far fit the facts reasonably well. A further test of their reliability however, is posed by data pertaining to the construction period of the Duncan Dock.

Particular stages in the development of the Duncan Basin are recorded in Fig 9. By 1940-41 its configuration was something intermediate between stages (3) and (4) of Fig 9 and in plan appearance it was not altogether dissimilar from a three-petal clover-leaf pattern.

The Lea-tidegage marigrams at the E/F berth location (Fig 2) showed at this time, besides the now familiar transverse oscillations, two principal longitudinal oscillations with periods ranging from about 7.5 to 6.5 minutes and from 4.9 to 4.2 minutes, Fig 6 (c).

For the shape of the basin as it then was there is no really dependable simple formula for computing the fundamental mode of oscillation but a guess may be hazarded by applying the equation which Chrystal (1904-5)

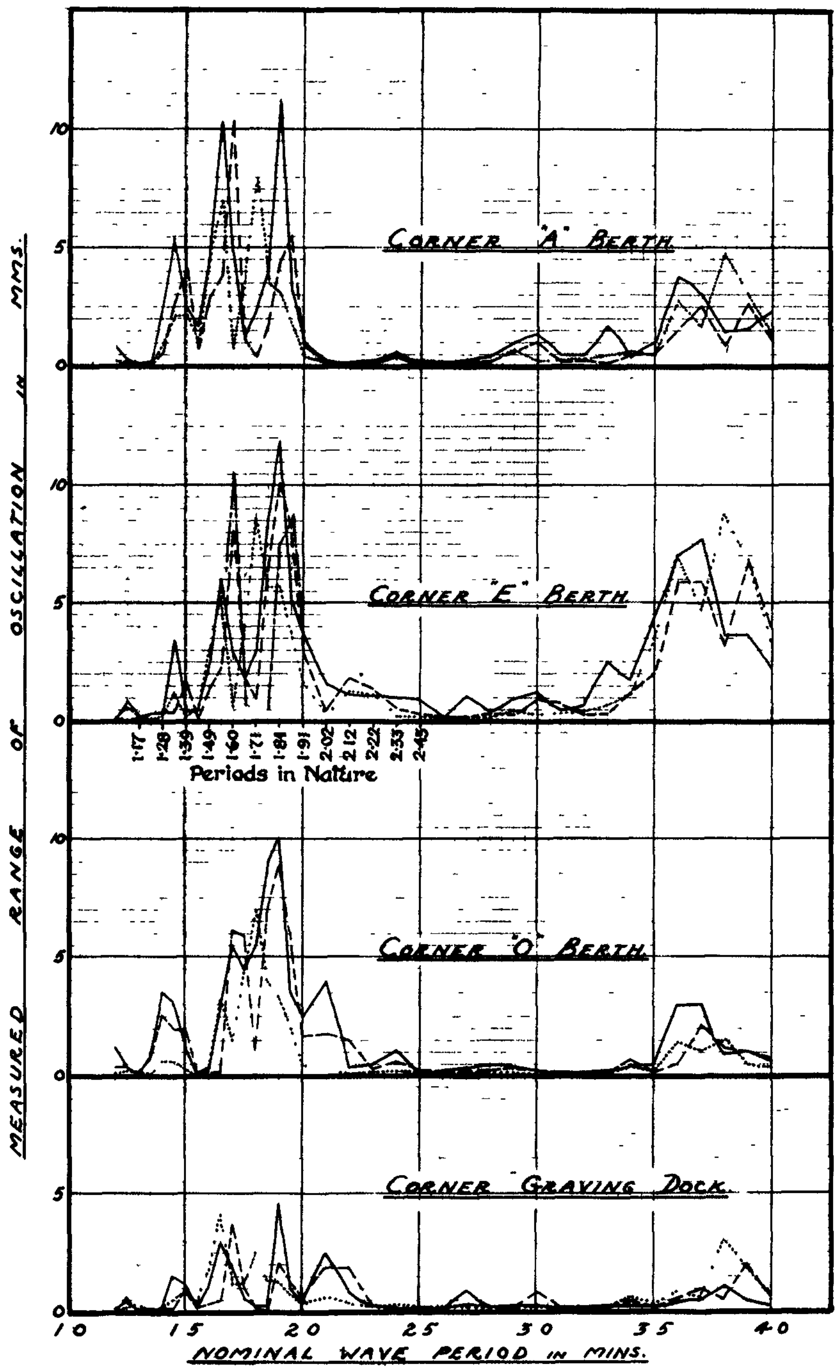


Fig. 8. Periodograms of response of model harbor to waves of different frequencies. (Variations with repeat tests largely unaccounted for - supposed due to slightly different conditions in sand bed of model)

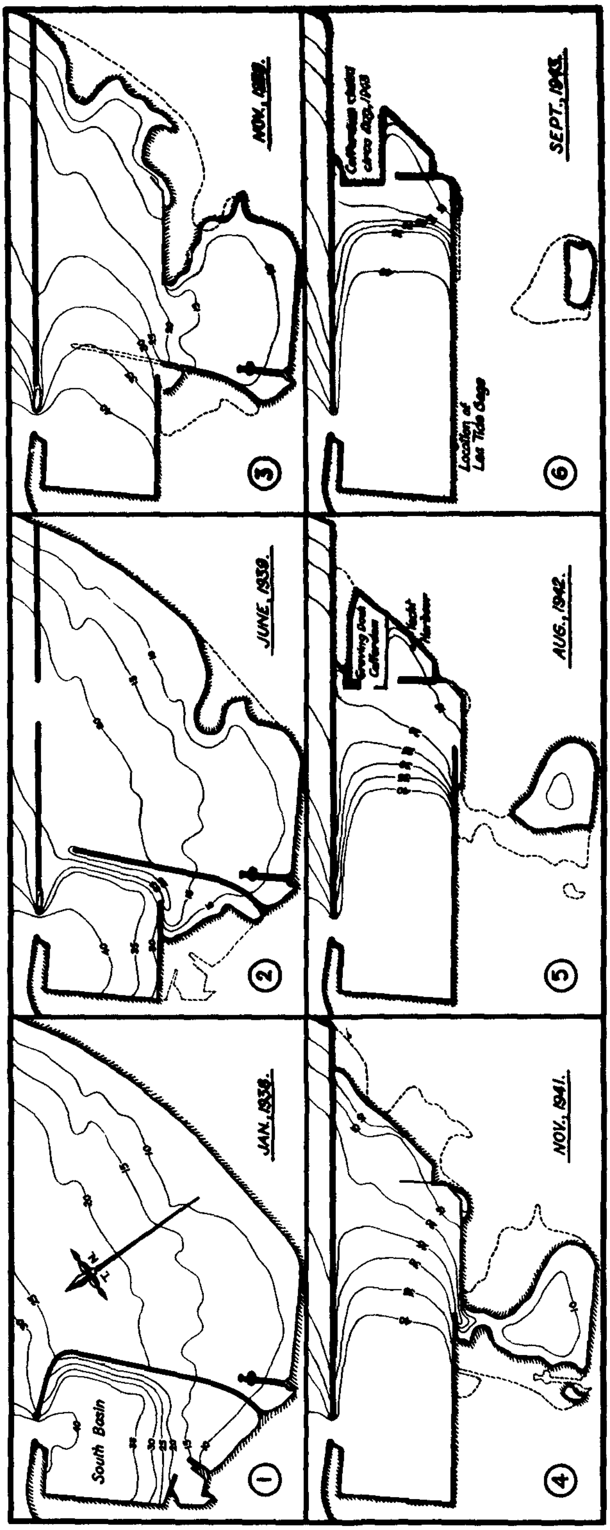


Fig. 9. Growth of the Duncan Basin, 1938-1943.
(Contours in feet approximate only)

found to be so useful in estimating the natural periods of lakes of all shapes of outline and depth, namely:

$$\frac{\pi^2 L^2}{T_m^2 g d_o} = m(m+1) \qquad (9)$$

Ignoring for the moment the lagoon portion of the basin, and taking the mean length of the remainder along its axis as $L = 7200$ feet, with a maximum depth $d_o = 40$ feet, equation (9) gives $T_1 = 7.5$ minutes for $m = 1$, and $T_2 = 4.3$ minutes for $m = 2$. These values tally very well with the observed periods of Fig 6 (c), considering the poor approximation of the assumed parabolic bed of the formula to the true sectional profile of the basin along its long axis.

Another estimate for the fundamental mode of oscillation is possible using the graphical method of wave refraction (Wilson, 1953 (iii)). According to this, the fundamental period of the basin (neglecting the lagoon) will be twice the time taken for a long wave to travel from one extremity to the other, found to be 2 x 3.6, or 7.2 minutes at low tide. At high tide, this figure would be reduced to about 6.9 minutes giving a range in fairly good agreement with Fig 6 (c). These considerations thus leave no doubt but that the longest observed periodicities in 1940-41 correspond with the lowest mode of oscillation for the basin as it then was. The development in strength of this seiche could also logically be ascribed to the 7.3 minute external forced seiche of Table III.

By the end of 1941, the marigrams revealed a definite tendency for the periodicities of the lowest mode of oscillation to incline towards lower values between about 6.8 and 6.0 minutes. Fig 9 shows that the overall length of the basin could not have changed much in this time, but as the dredging and deepening of the basin had been proceeding apace, it is reasonable to attribute the diminution of periods to this cause.

The secondary oscillations of periods from about 5.0 to 4.2 minutes persisted apparently unchanged throughout 1940 and 1941. While the approximation based on equation (9) clearly establishes these vibrations as the second harmonics of the longitudinal oscillation, it is also clear from Fig 9 that the lagoon of water to the south, remaining to be reclaimed from the sea, must have had its due influence upon this mode.

As one means of proving the model the conditions of November 1941 (Fig 9) were reproduced, the lagoon of water on the southern side being included. The critical periods in the range 4 to 8 minutes as measured at three points in the basin are shown in Fig 10.

Two broad bands of critical periods show up in these periodograms, the larger of which incorporates several peaks. These may be identified as frequencies of 7.1, 6.6 and 6.2 minutes period together with minor ones at 6.0 and 5.5 minutes, all of which, significantly, are found in the periodic sequence of external forcing seiches (Table III). It is interesting to note that the 5.5 minute external seiche, which from previous considerations is known to be strong and persistent, was barely able to influence the Duncan Basin because of the latter's non-resonant response at that time.

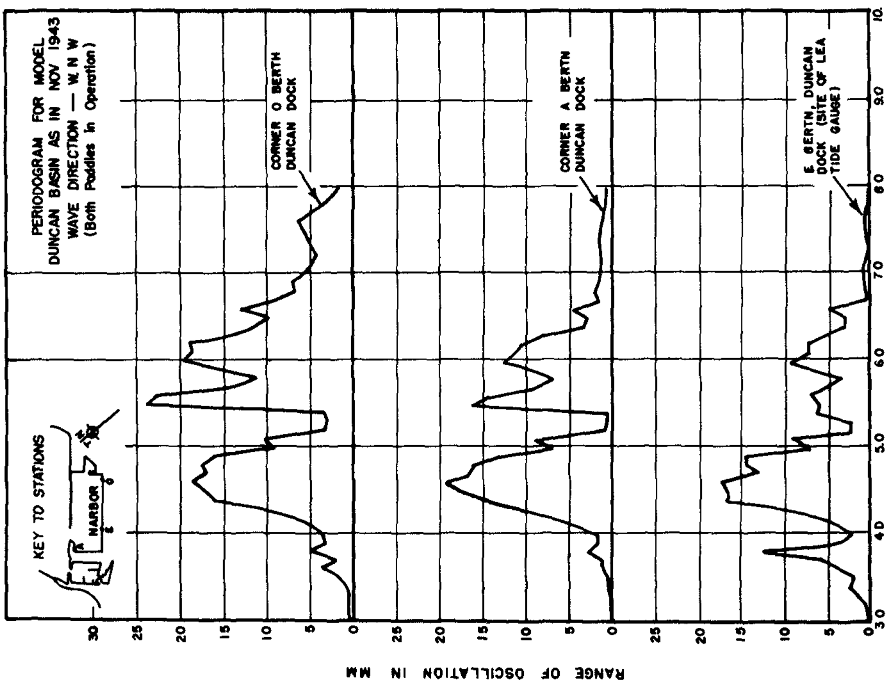


Fig. 11. Periodogram of response of Duncan Basin to different wave frequencies, (1943 conditions).

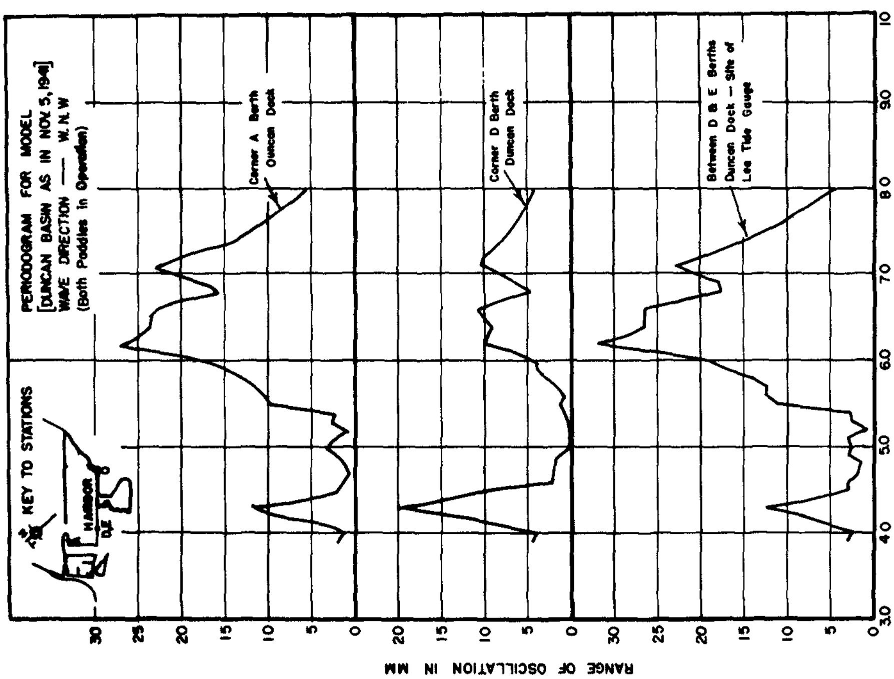


Fig. 10. Periodograms of respones of Duncan Basin to different wave frequencies, (1941 conditions).

The smaller band in the periodograms of Fig 10, giving a peak at 4.3 minutes, corresponds well with the equivalent band of Fig 6 (c). In the model this mode of oscillation was observed to involve the lagoon as well as the basin in a common three-cornered 'flapping' of the whole cloverleaf-like body of water contained by the Eastern Mole. An antinode at the 'stem' or common junction of the three 'petals' of the clover-leaf formation was clearly in evidence. There were thus three nodes, one to each petal, two of which, of course, were roughly transverse to the basin and thus accorded with the binodal longitudinal oscillation of that body of water on its own. The motivating seiches in the external breakwater-shore system would presumably be the 4.0 and 4.6 minute periodicities in the sequence of Table III.

In 1942 the quay-wall construction and reclamation works met and sealed off the lagoon of water to the south of the Duncan Basin (Fig 9). The works for the construction of the graving dock at the south-eastern end of the basin meanwhile gradually pushed out and finally cut off the triangular-shaped end. The closing of this area by cofferdam occurred towards the end of July 1943 and caused the sudden disappearance of the mode of oscillation of 7.1 - 6.2 minutes period in the marigrams of the Lea tide-gage. The 4.3-minute seiche, however, persisted in the face of this shortening of the basin and detachment of the lagoon (Fig 6 (b)) and throughout most of 1944 showed itself to be the only prominent longitudinal periodicity in the marigram records.

It is necessary to record in explanation of this that by 1943, the dredging and rock breaking in the basin had extended the 40 depth limit of the bed at low tide to about two-thirds of the finished length of the basin. Of the remaining one-third length about half had been dredged to between 38 and 35 feet, while the remaining length at the southern end formed a shelf only 20 feet deep (Fig 9-(6)). In effect then the dock comprised a submerged basin of length $L = 5000$ feet and depth $d = 40$ to 45 feet, whose fundamental period according to equation (4) would be from 4.6 to 4.4 minutes according to the state of the tide.

The conditions of November 1943 (Fig 9) were examined in the model and yielded the periodograms of Fig 11 for three observing stations. These periodograms, while showing a strong band of critical periodicities near 4.6 minutes in support of a submerged basin oscillation, also show that there must have been considerable response at that time to the forcing seiches of periods 5.5, 6.1 and 6.6 minutes. However, for the particular location of the Lea tide-gage (Fig 9) the latter periodicities are very subdued (Fig 11) and to this fact, very largely, must be ascribed the absence of any indications of them in the marigrams for 1944.

There was, nevertheless, another factor affecting the issue, which only came to the author's attention long after the experiment. This concerned the deposition of the dredgings from the basin in a wide area outside the Eastern Mole. A considerable shoal formed here, which must have had a profound effect upon the seiches of the breakwater-shore oscillating system. When the extent of the shoal was discovered it was realised by the harbor authorities that it constituted a hazard to ships in the roadstead, and it was by degrees removed. The total disappearance of any

6.0 to 5.3 minute oscillations in 1944 and their reappearance in 1945 in the marigrams of the Lea tide gage was probably intimately bound up with the growth and final removal of this sand bank outside the harbor.

By the end of 1944 the Duncan Basin had been dredged to its designed depths throughout most of its area except that immediately adjoining the cofferdam of the graving dock, but in April, 1945, the removal of this cofferdam was commenced and by June the basin had assumed its completed form. This culminated in the sudden and complete cessation of the 4.3 minute frequency and its replacement on rare occasions by the less stable 3.9 - 3.7 minute oscillation identified in equation (7), and evoked full response to the 5.5 minute forcing seiche as shown in Fig 6 (a).

OSCILLATIONS OF THE VICTORIA AND ALFRED BASINS

Considerations of space preclude detailed discussion of the oscillations peculiar to the Victoria and Alfred Basins, which are complex, but some discursive remarks seem necessary.

The behavior of these basins follows the same general mechanism as the Duncan Basin, their response, of course, depending upon the shapes and sizes of the individual compartments into which these docks are divided. The periodograms contained in Fig 5 (b) are generally indicative of the critical frequencies inspired by the external forcing seiches.

Model experiments showed that at periodicities above 4.0 minutes the oscillation in the Victoria Basin consisted of a pumping action of the entire water-body. In the Alfred Basin this action started at periods above about 3 minutes. In the case of the Victoria Basin it is not difficult to see why this should be so, since this dock is roughly square and of dimensions equal to the width of the Duncan Basin. Any uninodal oscillation for the Victoria Dock must therefore be of the same order as the fundamental transverse oscillation for the Duncan Basin, which was found to be 1.85 minutes (equation (7)). Merely by doubling this figure the approximate periodicity (3.7 minutes) of the open-mouth oscillation is obtained, which is nodal at the entrance and increases in amplitude from the mouth to the head of the dock. Higher periodicities must therefore cause a more-or-less universal scend over the entire area of the basin.

SUMMARY AND CONCLUSIONS

The existence of surging of serious magnitude in the harbor basins at Cape Town can be imputed to the development of seiches in the roadstead immediately outside. These forcing seiches are engendered as features both of Table Bay and the three-sided quasi-basin contained between the harbor breakwater and the coast. The latter is so oriented and shaped as to permit of the development of an extensive series of harmonics whose presence is indicated in seichograms and confirmed by model experiments and theoretical considerations.

The nodal lines of the external seiches tend to be normal to the harbor boundary along the line of the Eastern Mole, so that at any particular point along this boundary, away from a node, the water level will tend to rise and fall in the period of the seiche, creating alternately a head of water outside and then inside the harbor basins at their entrances along this boundary. Of necessity this head of water induces a compensating periodic flux through the basin entrance which provides the pulsation for activating oscillations within the harbor.

The fact that the seiches within the harbor at Cape Town attain to serious proportions is largely due in the first place to the circumstance that the location of the breakwater fortuitously aggravates the development of certain seiches of the bay and in the second place to the circumstance that the basin dimensions and entrance sites permit of fully resonant transmission of some of these enhanced forcing seiches of the roadstead. Both the fundamental longitudinal and transverse oscillations in the rectangular Duncan Basin (respectively 5.6 and 1.85 minutes in period) are favored in this way, and to make matters worse, the dimensions of the long and short sides of this basin are so related (ratio 3:1) as to accentuate the transverse frequencies.

In the Victoria Basin the mechanism of the action follows the same pattern as for the Duncan Dock. Here there are more compartments to sustain particular periodicities of oscillation, but owing to the sheltering effect of the breakwater and wave diffraction the higher-frequency disturbances in the roadstead have less chance of penetrating this basin. The breakwater-bight, however, constitutes an antinode or loop-end for most of the seiches of the external roadstead and the Victoria and Alfred Basins are much imposed upon by the lower frequencies. Seiches of more than 3 minutes period in the Alfred Basin and more than 4 minutes period in the Victoria Basin cause a pumping action of water over the entire dock areas. The equivalent effect is produced in the Duncan Basin by all seiches exceeding 11 minutes in period, very notably the strong seiches of the bay of 17-23, 26-33 minutes periodicity.

The behavior of the Duncan Basin during its construction period affords an excellent example of the influences of shape and depth on the oscillating characteristics of an enclosed body of water. Throughout the time of its construction the external seiches, largely unchanged themselves, have played upon it, often with completely different results. The conslusion is clear that a basin will only respond to those impressed frequencies which accord most nearly with its own. Partial resonance seems to be possible when the forcing seiche is sufficiently close in period to that of the natural frequency, there being in general no precipitate transition from complete unresponsiveness to full resonance.

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