CHAPTER 133

HARBOR STUDY FOR SAN NICOLAS BAY, PERU

By James M Keith[1] and Emmett J Murphy[2]

ABSTRACT

A pair of ducted impeller current meters, one mounted vertically and the other horizontally, were used to measure wave action at San Nicolas Harbor, Peru The horizontal water velocity records are superior to conventional wave records because they measure directly the wave property which induces adverse horizontal ship motion, and provide directional wave data Spectral analysis methods proved well-suited to detailed interpretation of the particle velocity records, while considerable insight into the wave phenomena was gained by simple, rational inspections and interpretations of the records Time-lapse movies of a moored ship, when correlated with simultaneous water particle velocity records, provided an exceptionally clear picture of ship response to wave action, and led to the rather surprising observation that long-period ship motion is not necessarily caused by long-period waves The foregoing ship response was duplicated in hydraulic model tests

INTRODUCTION

The results of a study program were used to determine the source of difficulties in mooring ore carriers at Marcona Mining Company's iron ore loading facility at San Nicolas Harbor, Peru Observations of wave action were primarily obtained by time-lapse movies of a moored ship and by an orbital velocity meter consisting of two ducted impeller current meters, one mounted vertically and the other horizontally The horizontal water velocity records are superior to conventional wave height records in two important respects (1) They provide direct data regarding the wave property most directly affecting horizontal ship movement, and (2) they provide directional wave data

Analyses were performed in two distinct stages A direct, rational application of the records as a time-history of the horizontal water velocity was used to derive the time-history of horizontal water displacement Using this approach, a mechanism was established whereby a relatively short-period swell of 16 sec induced long-period (50 sec to 150 sec) ship motion transverse to the pier Spectral analyses by digital computer were then employed to derive a clear insight into the various wave trains existing at particular times, and to quantitatively evaluate the relative energy contents of selected wave frequencies Simple hydraulic model tests were utilized to verify that swell generated periodic transverse ship motions having a period many times longer than the period of the swell This occurred when a quartering stern swell acted on a ship moored with slack elastic mooring lines to a pier with elastic fenders

[1] Vice President, John A Blume & Associates, Engineers, San Francisco, California

[2] Project Manager, Marcona Corporation, San Francisco, California

BACKGROUNO

The port at San Nicolas Bay is utilized by Marcona for the annual shipment of approximately 9 million tons of iron ore concentrates and pellets The bay is a typical hooked embayment not fully protected from the ocean At times, serious mooring problems have been experienced at the pier due to adverse water motion which has resulted in the breaking of many mooring lines and damage to the pier by the ship's impact (see Fig 1) Individual ships have broken more than twenty mooring lines and some of the impacts against the pier have been estimated to exceed the pier's design load by a substantial margin

In general, rough water conditions in the bay occur during the winter months when storms in the lower southern latitudes frequently cause heavy swells along the coast Ouring these periods, which vary from a few hours to three or four days, ships are forced to anchor well out from the pier awaiting calmer water, and many ships have been delayed in this manner

The pier deck (see Fig 2) is constructed of prestressed concrete sections supported on prestressed concrete piling The fender system consists of hollow, end-loaded rubber cylinder buffers 18 in OD, 9 in 10, by 21 in long for energy absorption Timber piles bear on the outer ends of rubber cylinders and support 12-in x 12-in rubbing timbers

Fig 3 is a map of San Nicolas Bay showing the pier projecting into the bay from the south shore line The harbor is relatively deep, water depth at the pier when the latter was completed in 1962 was 45 ft at the south end and 59 ft at the north end

The mooring problem at San Nicolas Bay is further complicated by the large vessels currently using the pier facilities Marcona Corporation owns and operates a fleet of the largest dry bulk, ore, and combination ore-oil carriers available These carriers are used to transport Peruvian iron ore mined and concentrated by Marcona to Japan To date, ships of over 100,000 OWT have been loaded at San Nicolas pier, by early 1970, ships of 130,000 OWT will be in service Use of carriers exceeding 150,000 OWT is foreseen in the future, and the west side of the pier, where ships are moored for loading, has been dredged to 57 ft to meet the draft requirements for vessels of this size Table 1 shows typical dimensions of bulk and ore carriers

The economic advantage of larger ships is easily demonstrated by comparison of crew requirements and tonnage capacities A crew of 45 was required to man a 10,000-ton Liberty ship, the highly automated 100,000-ton ships of today require 35-man crews The 10-knot Liberty ship could make about four Peru-Japan voyages per year for a total annual ore lift of about 39,000 tons, or about 850 tons for each crew member, the 16-knot 100,000 OWT ore carrier can average about 6-1/4 voyages per year, lifting about 635,000 tons annually or over 18,000 tons per year for each crew member, 21 times the rate of the Liberty ship

FIG. 1. - FENDER DAMAGED FROM IMPACT OF MOORED SHIP

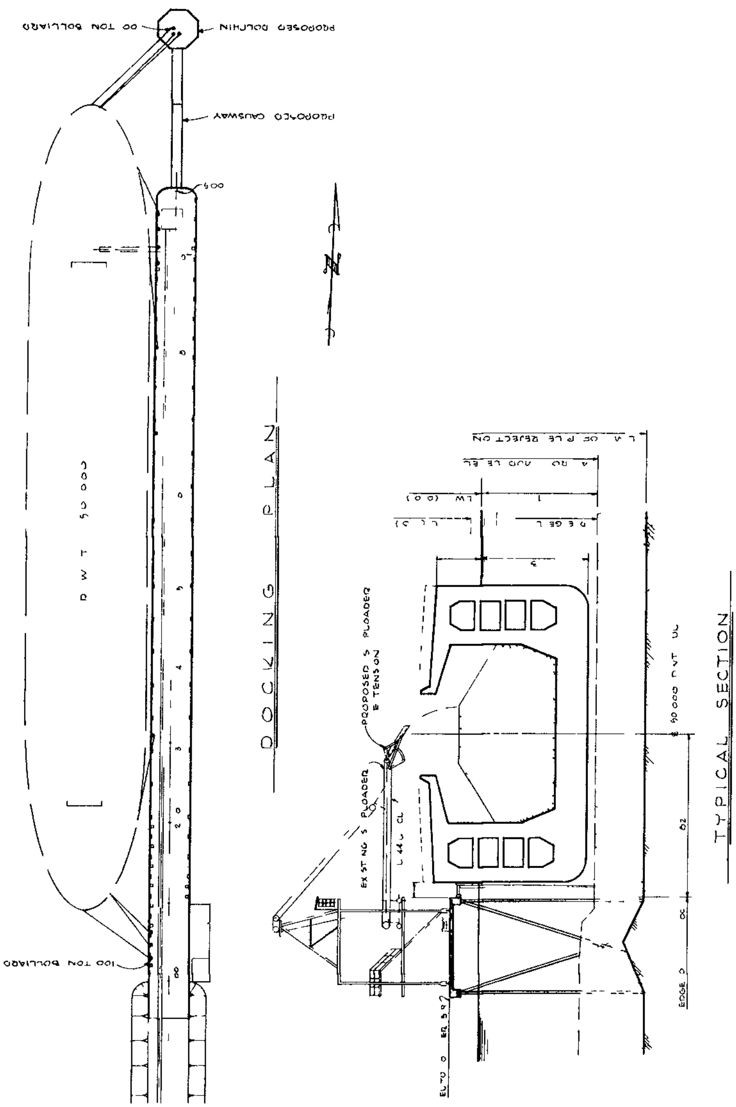

FIG 2 - SAN NICOLAS PIER

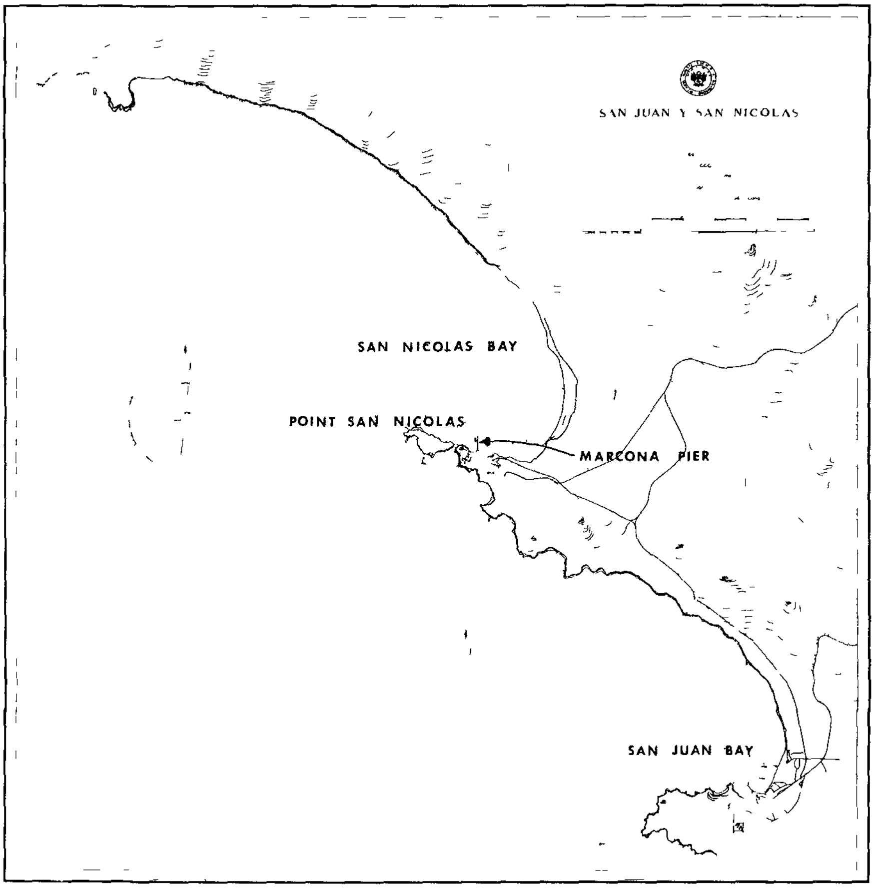

FIG 3 - SAN NICOLAS BAY, PERU

TABLE 1 - TYPICAL DIMENSIONS, BULK AND ORE CARRIERS

Vessel type (1)	Vessel size, DWT (2)	Displacement (3)	Length overall, in feet and inches (4)	Beam, in feet and inches (5)	Depth, in feet and inches (6)	Draft summer, in feet and inches (7)
Liberty	10,800	14,100	441-6	56-11	37-4	27-8
Oread	31,662	41,641	655-0	87-0	46-6	34-2
San Juan Pathfinder	71,205	89,122	835-0	106-0	65-0	44-9
San Juan Exporter	106,000	123,852	865-3	124-8	68-11	50-10
-	130,000[a]	154,400	948-2	138-10	74-2	51-9
-	150,000[b]	180,000	1,014-0	150-0	75-0	53-0

[a] Under construction
[b] Possible design

Considering the trend toward larger ships and the problems encountered in mooring ships currently in service, Marcona Corporation retained John A Blume & Associates, Engineers, to conduct a study to define wave action in the harbor This information was considered essential to an evaluation of various proposals for improvement of the harbor

Initial observations suggested that the ship motion to and from the pier was caused by harbor surge, since the period of motion ranged from 1 min to 3 min, and since the pier tide gage indicated occurrence of long-period waves ranging up to 20 min Some ships at anchor appeared to swing on their anchors at periods approximately 20 min, an additional indication of surge Discussion of the problem with local pilots indicated that swell might be a dominant factor in disturbances to moored vessels The pilots relied upon the height of breakers on the north side of Point San Nicolas and the height of the surf along the beach southeast of the pier to estimate mooring conditions It was therefore evident that if surge was the problem, it occurred only during periods of adverse weather as evidenced by the heavy swell

The offshore swell approaching San Nicolas Bay from the south and southwest is refracted around Point San Nicolas and directed toward the pier from a northwesterly direction It was noted that placement of a breakwater west of the pier would provide an excellent means of shielding the pier from the swell Additional information, however, was needed to determine the effects of the breakwater on ship motion caused by surge, since a breakwater might well have little effect on reducing a long-period surge An observation program was initiated to determine whether swell, surge, or a combination of these forces was causing the adverse motion

OBSERVATION PROGRAM

Most conventional wave instruments record only wave height, and additional observations must be made to determine wave direction Since wave direction at San Nicolas Bay is difficult to observe because of relatively low heights of swell and surge, a method of measurement was required which would eliminate the need to determine horizontal water motion from wave height data and observations of wave direction Horizontal water motion from the swell or surge or both of these was the dominant factor causing ship motion, the most promising approach to the problem, therefore, was to measure this motion directly at the pier location

Several marine instrument manufacturers were contacted for proposals to supply instrumentation which would record horizontal water particle direction and velocity Two ducted impeller current meters arranged orthogonally on vertical and horizontal axes (see Fig 4) were purchased from Marine Advisors, Inc These meters were suspended approximately 10 ft below the low tide water surface and readings from each were simultaneously recorded on strip charts A direction-sensing vane was installed in addition to the meters, and data from the vane was also recorded on a strip chart Fig 5 shows the instruments being placed off the north end of the pier

FIG. 4. - PROTOYPE: ORTHOGONALLY MOUNTED DUCTED IMPELLER CURRENT METERS

FIG. 5. - INSTALLING METER AT SAN NICOLAS PIER

Marine Advisors, Inc indicated that threshold current velocity for operation of the meters would be less than 3 cm per sec (0 06 knots), and that the meters would have a response time of 40 msec to 70 msec and a directional response approaching a cosine function of the angle between the meters' axes and the direction of water motion Development data for these meters is available in another publication (3)

Since conditions causing mooring problems occurred relatively infrequently, readings were only taken during the rough sea periods Recordings were made at 30° increments for six successive headings from 270° to 60°, with a 4-hr recording period for each heading On April 8, April 15, and April 19, 1968, recordings of moderately rough conditions considered typical of problem-type storms were obtained On July 26-27, 1968, recordings of the most severe wave disturbances since construction of the pier were obtained These disturbances were considerably worse than any conditions previously experienced at the pier The storm generating these waves caused damage to many marine installations along the Chilean and Peruvian coasts In addition to the instrument records, a time-lapse motion picture study was filmed on April 19, 1968, of an ore carrier of 74,730 tons displacement moored at the pier The camera mounted on the mole at the south end of the pier and focused on the bow of the ship recorded one frame every two seconds Data from the wave instruments and the camera records were used to analyze water motion conditions within the harbor

INITIAL ANALYSIS

The initial data analysis was a noncomputerized, rational comparison of the time-lapse movie and the horizontal water velocity record as shown in Fig 6 The movement of the ship's bow was obtained by plotting sequential positions of a point on the ship's bow as the film was projected one frame at a time The horizontal movement of a water particle was obtained by integrating the horizontal velocity record Integration was done by measuring the area between the velocity curve and the zero line with a planimeter The ship's bow movement consisted of a clockwise circular motion which showed excellent correlation with the swell period, but which was distorted by a long-period motion toward and away from the pier Although the horizontal water motion also has a long-period component, the correlation between the long-period motions of the ship and the water was very poor

In seeking an explanation of the long-period ship movements, the following hypothesis was proposed the ship, fender system, and mooring lines comprised a vibrating system wherein the fender and the mooring lines were springs having slack or free travel space and the ship represented a mass having circular motion excited by the swell Figs 7 and 8 depict the idealized system A model test was run in a University of California wave tank to confirm this hypothesis The model simulated the conditions depicted by Fig 8 at a linear scale of 1 to 159 Movies of the bow of the model ship indicated that a motion very similar to that shown in the lower portion of Fig 8 could be generated in the

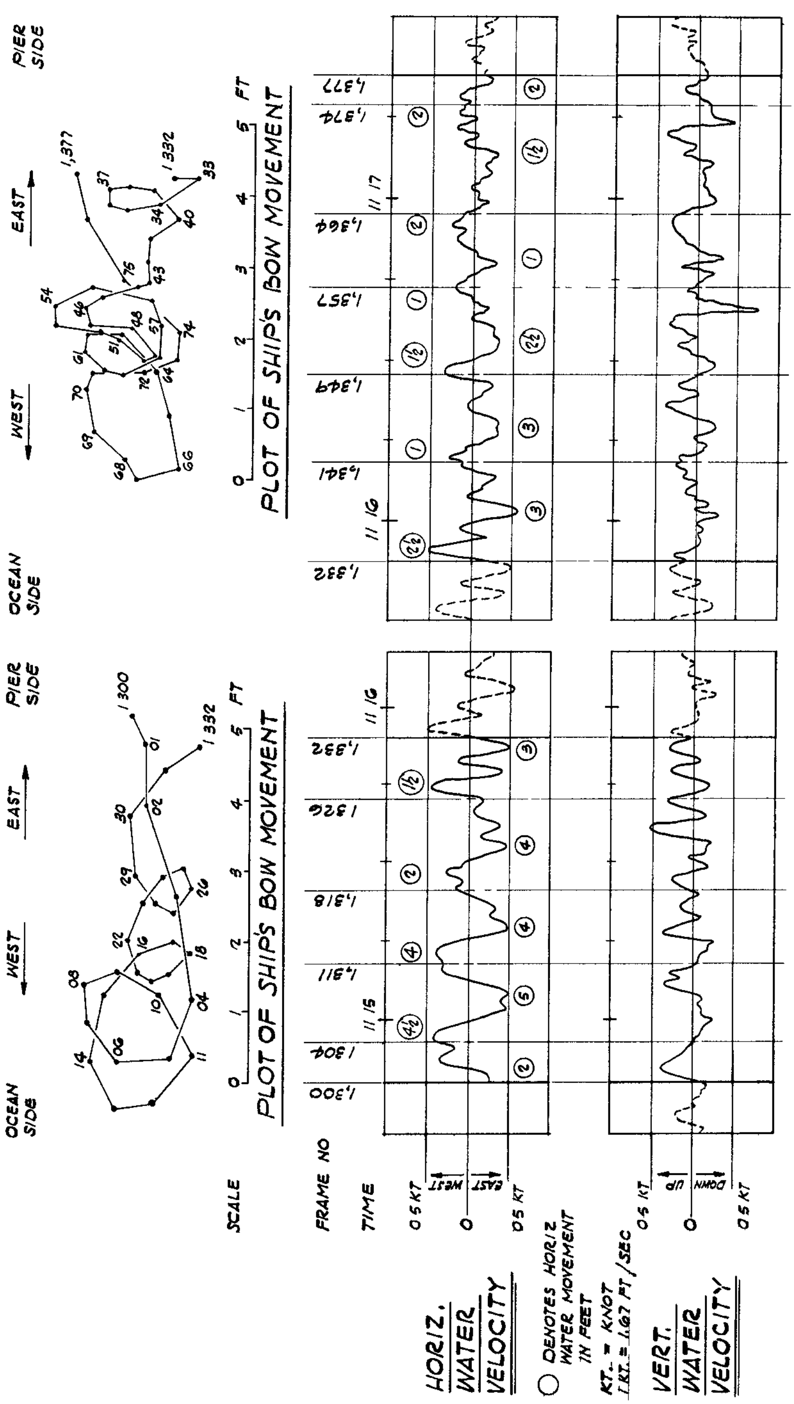

FIG 6 - PLOTS OF SIMULTANEOUS BOW MOVEMENT AND WATER VELOCITIES AT SAN NICOLAS BAY

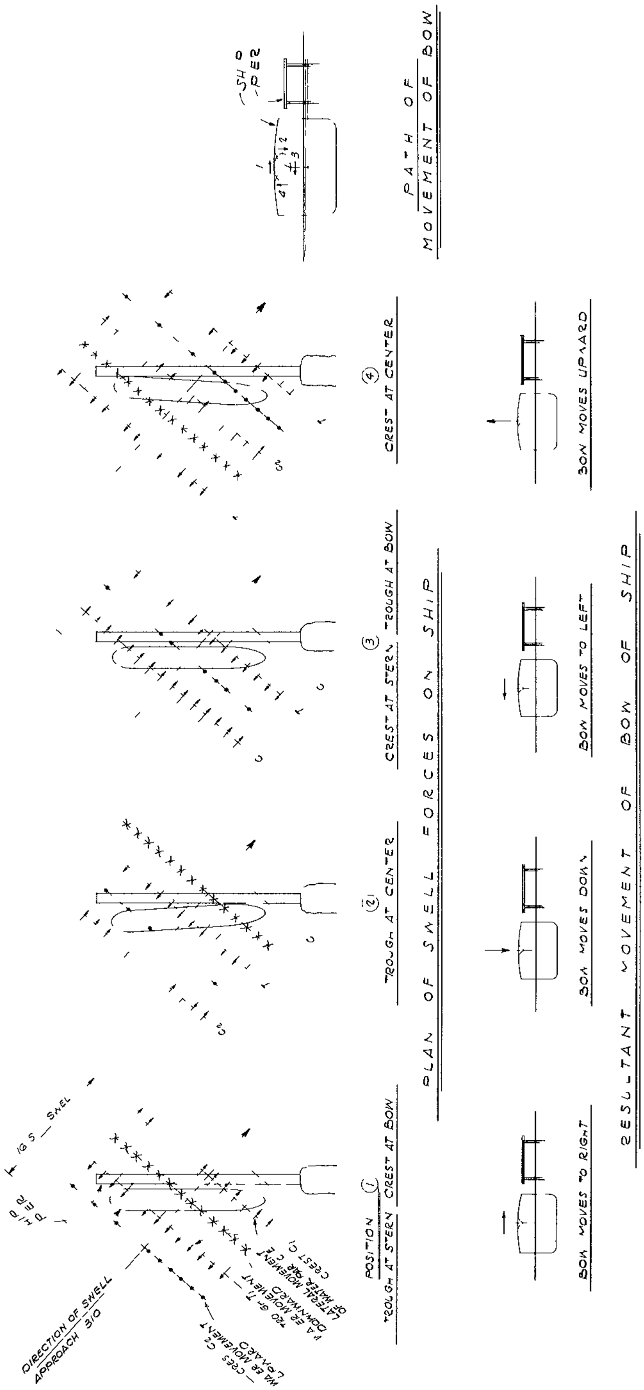

FIG 7 - SHIP MOVEMENT DIAGRAM, SWELL FORCES ONLY

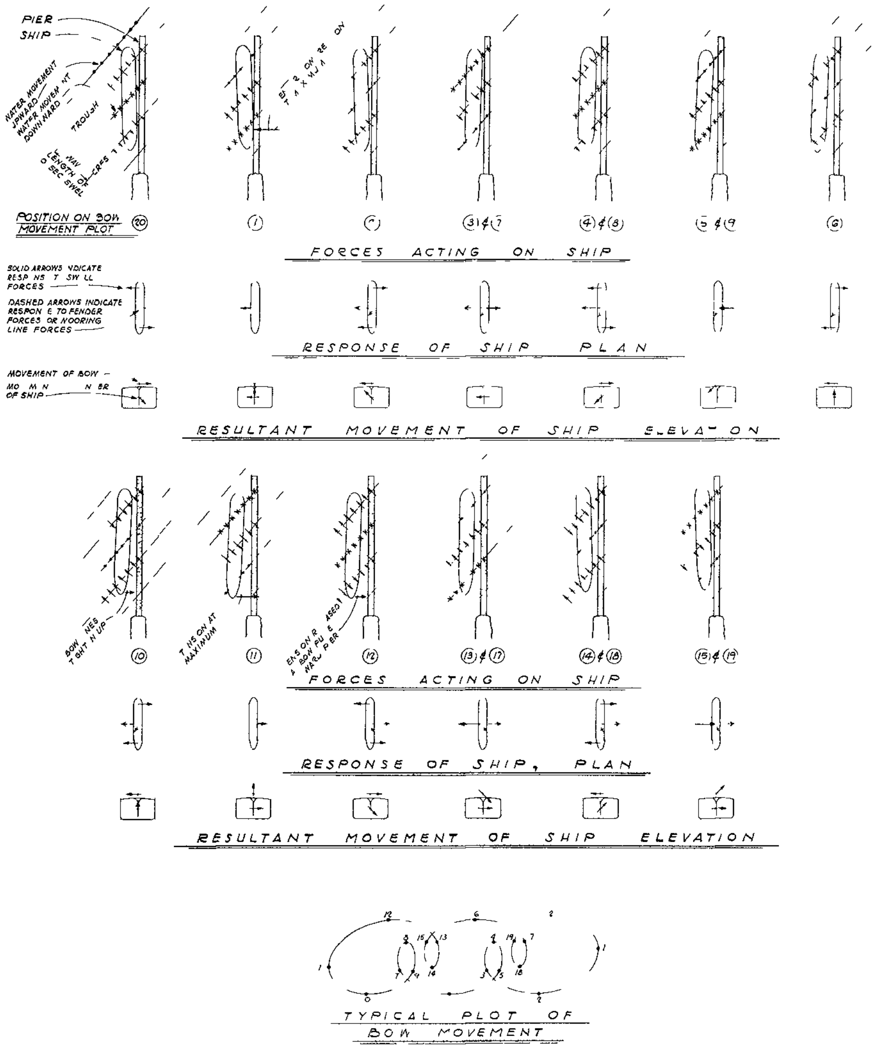

FIG 8 - SHIP MOVEMENT DIAGRAM, COMBINED SWELL AND MOORING FORCES model It was also noted that the amount of slack in the mooring lines directly controlled the period of the transverse excursions of the model ship Another interesting observation was that a nonelastic or energy dissipating fender system attenuated the long-period excursions irrespective of the amount of slack in the mooring lines

The directional response of the ducted impellers of the current meters was essentially flat for a 60° sector centered parallel to the duct's axis, with the duct's axis at right angles to the water movement, however, a good null was obtained Direction was thus shown more clearly by a null position than by a centered position An inspection of the April, 1968, recordings confirmed the assumed swell approach azimuth of ±300°

Upon completion of the water motion analysis and the model test observations, it was concluded that the major cause of the adverse ship motion was swell and not surge While the possibility of a surge problem could not be completely discounted, it was simply evident that swell was the greatest contributor to the ship motion problem The model tests confirmed also that the direction of swell approach to the pier caused the ship to oscillate with a yawing motion, and elastic fenders and mooring lines accentuated the problem

Additionally, it was established by calculation and model testing that this swell could be effectively attenuated by the construction of a breakwater

SPECTRAL ANALYSIS

In comparing the April storms and the July storm, it was noted that the July storm contained significant long-period wave action of high energy content This surge was not evident during the April storms Because the July storm was of such exceptional intensity, a rather complete analysis of the water motion records was warranted

To precisely interpret this July record, a more sophisticated approach based on computer analysis was used The first objective was to obtain a power spectral density analysis for each direction of the horizontal velocity sensor by use of a digital computer Essentially, the computer program splits the total energy in the record into a number of frequency bands, and determines the uniform sinusoidal motion in every frequency band which would have the same power as the original record had in each band When performed on an analog computer, the analysis is more readily understood Here the input signal is an electrical current wherein voltage represents the quantity being measured, and the computer consists of a series of narrow band pass filters which ideally have square cut-offs The signal passing each filter is squared and averaged for the duration of the record to give a measure of the power in the original record which was contained in each frequency band Spectral analyses were computed by FORTRAN program ACAPS (Auto Correlation and Power Spectrum)(1) on a CDC 6600 computer

For the program used, the equivalent uniform sinusoidal motion could be calculated from

$$V_{max} = 2\sqrt{SB_e} = \text{maximum velocity} \quad (1)$$

$$D = 2\frac{V_{max}}{\omega} = \text{displacement} \quad (2)$$

and

$$T = \frac{2\pi}{\omega} = \text{period in seconds} \quad (3)$$

in which S = spectral density, B_e = bandwidth in radians per second, and ω = mid-frequency of the band in radians per second The equivalence can be applied to each bandwidth, individual peaks, or a group of peaks

Record input for the spectral density calculation consists of discrete values of the velocity determined at a constant time interval, Δt, the sampling interval The number of "lags" used in the calculation, m, is predetermined The selection of total record length to be analyzed (which must be continuous), the sampling interval, and the number of lags are influenced by the following factors

1 The maximum period for which the spectral density can be calculated with reasonable accuracy is approximately 1/10 of the total record time

2 The minimum period for which the spectral density can be calculated is 2 times the sampling interval

3 The number of frequency bands is equal to the number of lags

4 The bandwidth is $\pi/(m\Delta t)$ or 1/m times the frequency of the minimum calculated period

5 The maximum calculated period (irrespective of accuracy of computation) is $2m\Delta t$

6 The sampling interval, Δt, should be not more than approximately 1/4 of the minimum period in the record that contains a significant proportion of the total energy in the record

If criterion 6 is not observed, the energy in these shorter periods will show up at spurious frequencies of longer period For the instrument location at San Nicolas Harbor, the prevailing wind is offshore This limits the fetch for local wind waves and gives assurance that the energy content in waves of less than 10-sec period is nominal On this basis, a sampling interval of 3 sec was considered ideal

For all wave records taken to date at San Nicolas Harbor, an attempt was made to obtain 4 hr of continuous record for each orientation of the horizontal velocity sensor This method was based on the assumption that periods up to 24 min would be of interest Subsequent studies have shown that only tsunamis such as from the Alaskan earthquake in 1964 have significant velocities in this period range, and that an upper period limit of 6 min is reasonable for all wave action except tsunamis On this basis, one hour of record was considered ideal for each spectral analysis

Analyses were run with 720 lags and 360 lags for comparison The 720-lag solution gave better definition of the component peaks, showed essentially the same total energy content, and was used for most of the data analysis

Fig 9 is a typical spectral density plot for the horizontal water motion of the seven successive headings for the July 26-27 wave conditions

CROSS SPECTRAL ANALYSIS

A further development of spectral analysis is the cross-spectral analysis, in which two separate records are analyzed Output of this analysis includes the spectral densities of each record, the cross-spectra consisting of two parts, real and imaginary, the coherence, and the phase coherence

The cross-spectral analyses were computed for the study by FORTRAN program CROSPEC on a CDC 6600 computer CROSPEC computes cross-correlation and cross-power spectral density functions for two or more time-series, and was developed from subroutines published by Robinson (2)

Cross-spectral analyses were run on the simultaneous vertical and horizontal velocity records for the 270° heading of July 26, and for the simultaneous ship's horizontal bow velocity and the horizontal water velocity of April 19 For the latter analysis, the displacement plots from the time-lapse movie sequence were converted to horizontal velocity rates by determining the horizontal distance moved every 2 sec

The results of this analysis are shown in Figs 10, 11, and 12 Fig 10 shows the power spectrum of each motion plotted on the same graph The excellent correlation in the range of periods for swell is readily apparent, while in the long-period range, especially from 90 sec to 110 sec, the ship motion has considerably more energy than the water motion These results are also shown in Fig 11, which presents a tabulation of the equivalent uniform sinusoidal motions corresponding to the energy peaks of the two spectra

Fig 12 shows the coherence and phase coherence from this analysis For the coherence between the two records, a value of 1 0 shows excellent correlation and a value of 0 0 represents a completely random relationship Here again, good coherence is shown in the swell range, some coherence in the 90-sec to 110-sec range, and an essentially random relationship in all other frequencies

The phase coherence shows consistent values only in the swell range where the phase-angle values are clustered close to 0° There is actually a 90° phase lag in the ship's response to the swell, but this phase difference was compensated by a time shift in the input data for the ship's

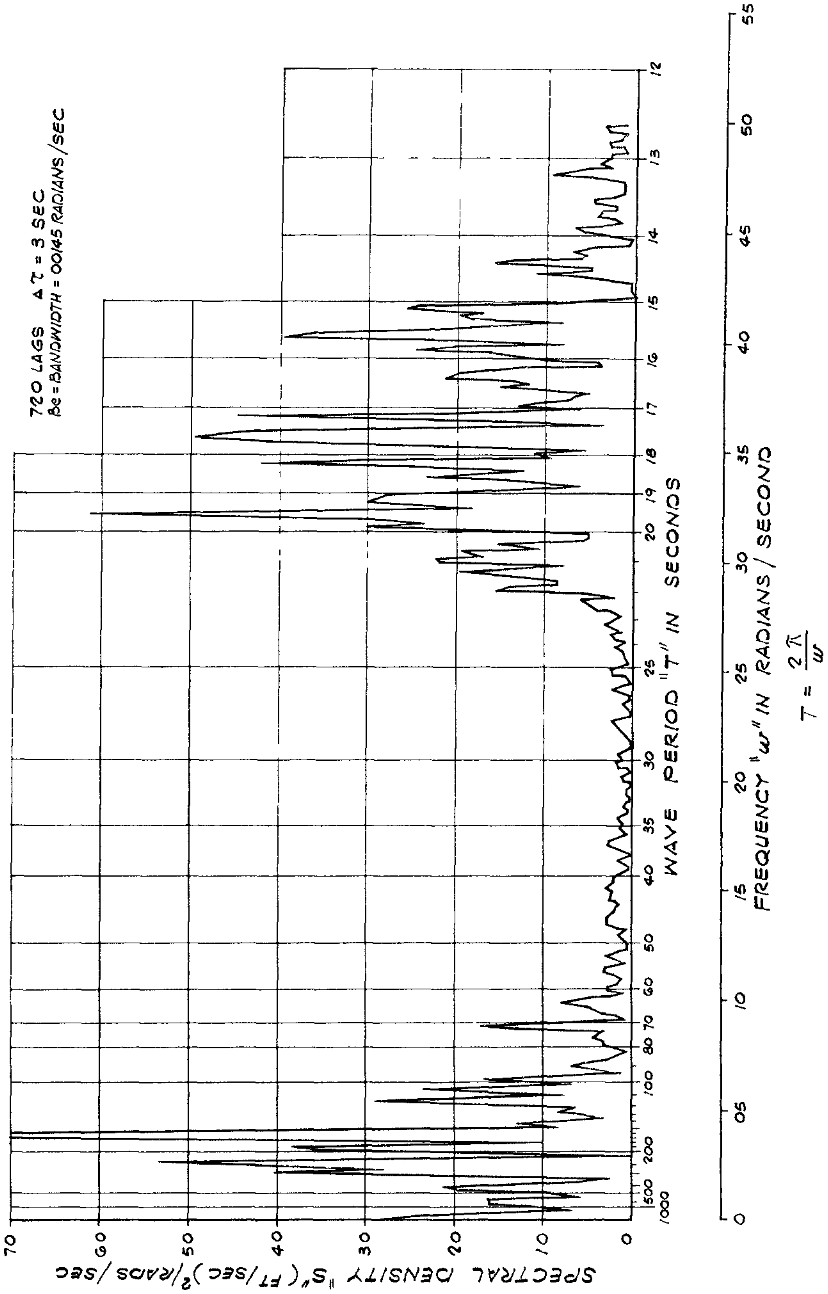

FIG 9 - HORIZONTAL WATER VELOCITY SPECTRUM 270° AZIMUTH, 10 30-11 30, JULY 26, 1968

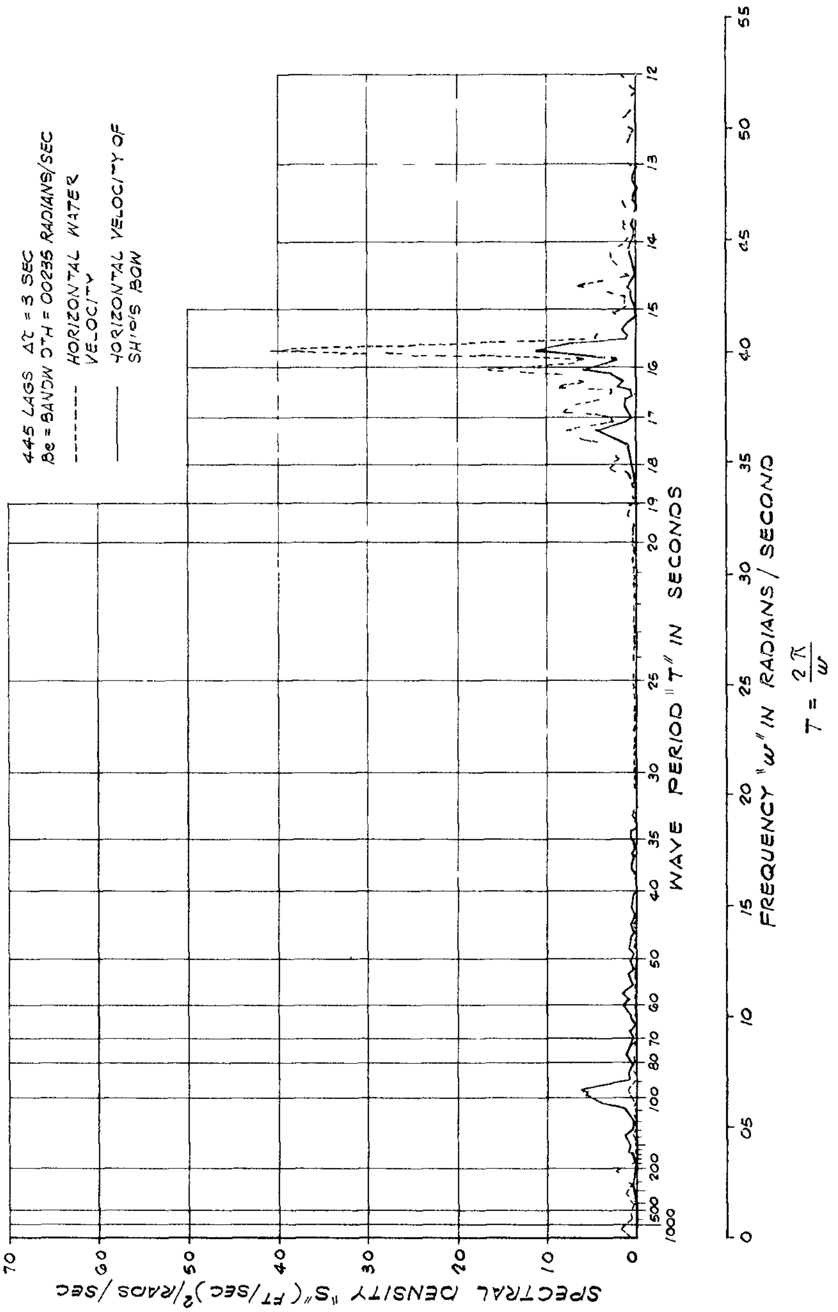

FIG 10 - SPECTRA OF HORIZONTAL WATER VELOCITY AND HORIZONTAL VELOCITY OF SHIP'S BOW 270° AZIMUTH, 11 12-11 53, APRIL 19, 1968

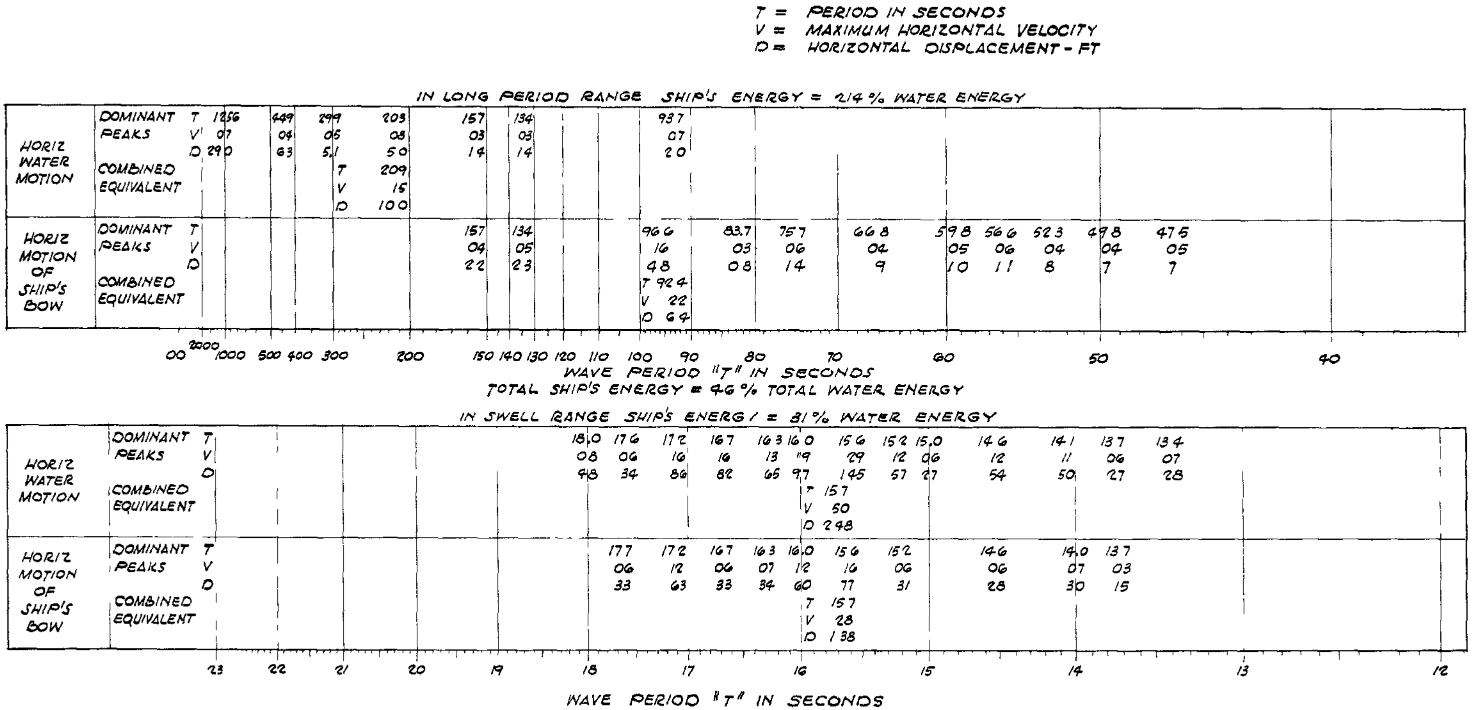

FIG 11 - TABULATION OF EQUIVALENT SINUSOIDAL MOTION EAST-WEST HORIZONTAL WATER MOTION AND MOTION OF SHIP'S BOW, 11 15-11 53, APRIL 19, 1968

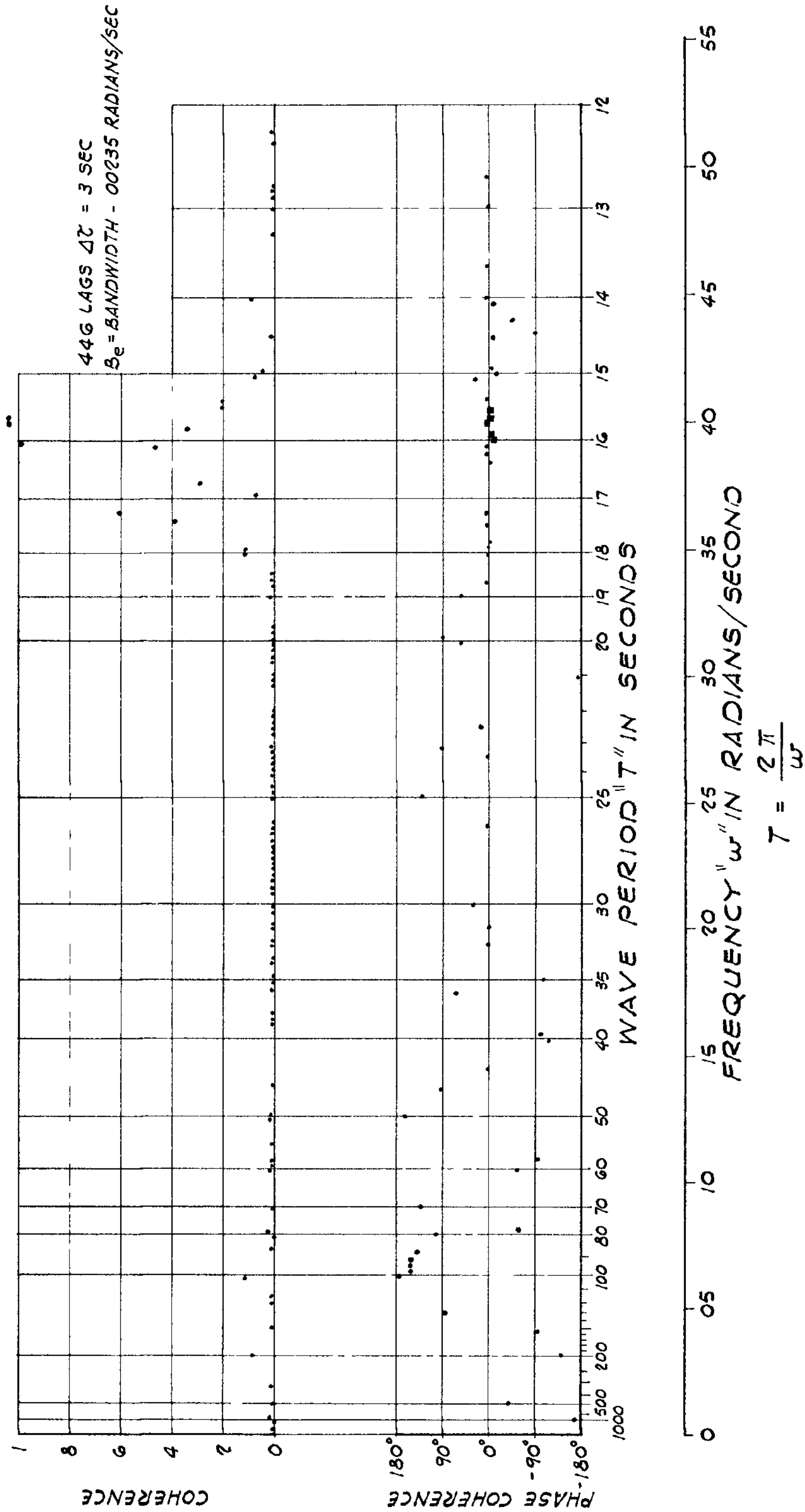

FIG 12 - CROSS-SPECTRA ANALYSIS OF EAST-WEST HORIZONTAL VELOCITY OF WATER AND MOTION OF SHIP'S BOW, 11 15-11 53, APRIL 19, 1968 motion Elsewhere, the phase-angle relationship is essentially random except for a tendency of values to cluster around 180° at 90 sec to 110 sec No firm explanation is offered for this last trend, but it might be that the time shift from 90° to 0° in the input data for the periods for swell may have shifted the long-period coherence in a direction opposite to the anticipated value of 90° No clear physical significance of the real and imaginary cross-spectral functions could be determined, hence, plots of these values are not shown

The results for the vertical and horizontal water velocity cross-spectral analyses were not as consistent as analysis results for the ship motion and horizontal water motion Fig 13 shows a dual plot of the spectral densities for both the horizontal and the vertical water velocities, and Fig 14 shows a plot of the equivalent sinusoidal wave components corresponding to the peaks in each power spectrum In Fig 13, the spectral density scale for the vertical velocity is expanded to better illustrate the correlation between the two It can be noted that the period range for swell again has good correlation, but the long-period correlation is rather inconsistent Especially significant are a few frequencies, such as those near 36 sec, where the vertical spectral density function value is proportionally higher than elsewhere This relationship could be interpreted in three possible ways

1 The instrument was near an anti-node of a standing wave For such a wave the water particle motion would be vertical only and a corresponding horizontal peak would not exist

2 An incident wave of that period passed at right angles to the horizontal sensor In this null direction, the horizontal velocity component would not register

3 The relatively high horizontal velocities, combined with floating seaweed caught on the instrument supporting pipe, deflected the vertical duct out of plumb and thereby caused the vertical sensor to register some of the horizontal velocity as a false downward component For a heavy swell, the false velocity component would not reverse since the false downward component would not be affected by the direction in which the instrument was out of plumb Such behavior would show up as an unduly high peak in the power spectrum of the vertical velocity, indicating a false downward displacement

This last interpretation was believed to be correct, since the displacement plot derived from the vertical velocity record also showed a false downward movement of the water surface considerably greater than that normally expected Fig 15 shows the displacement plot and the horizontal velocity record to the same time scale Correlation between the rate of downward displacement and the magnitude of horizontal velocity is insufficient for this condition to be interpreted as the sole cause of the anomalous peaks in the power spectrum of the vertical velocity record The vertical velocity readings, however, were deemed unreliable due to the false downward reading and no further analysis was done using the vertical velocity records In further applications, this problem could probably be eliminated by modification of the instrument mounting arrangement

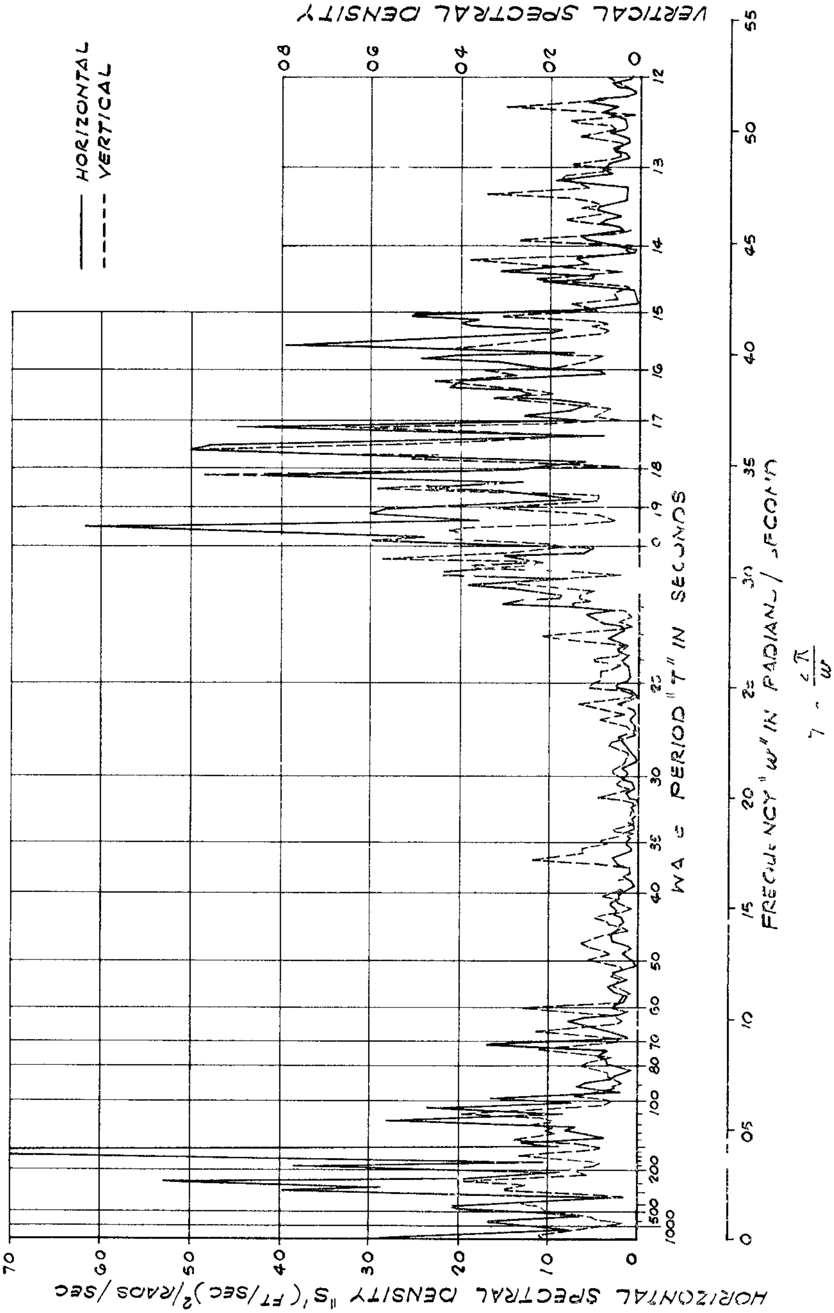

FIG 13 - SPECTRA OF HORIZONTAL AND VERTICAL WATER VELOCITIES, 270° AZIMUTH, 10 30-11 30 JULY 26, 1968

T = PERIOD IN SECONDS
V = MAXIMUM VELOCITY - FT/SEC
D = DISPLACEMENT IN FEET

HORIZ WATER MOTION

Dominant peaks	T	V	D
	796	168	42
	450	204	292
	252	342	274
	190	250	152
	161	408	210
	143	120	55
	151	108	45
	116	200	74
	107	182	62
	98	126	39
	90	122	35
	76	103	25
	71	145	38
	64	137	28
	59	.076	14
	55	083	15
	46	123	18
	41	110	15
	36	098	11
Combined equivalent	165	800	421

VERTICAL WATER MOTION

Dominant peaks	T	V	D
	392	084	102
	250	098	78
	196	.054	34
	165	072	38
	140	074	33
	123	070	27
	110	091	32
	97	056	17
	80	062	16
	73	065	15
	66	062	13
	60	065	12
	50	047	75
	47	062	92
	43	051	70
	364	079	92
Combined equivalent	110	290	102

00 2000 1000 500 400 300 200 150 140 130 120 110 100 90 80 70 60 50 40

WAVE PERIOD "T" IN SECONDS

HORIZ WATER MOTION

Dominant peaks	T	V	D
	218	165	115
	212	210	142
	208	250	165
	203	150	97
	196	400	250
	190	239	145
	185	222	131
	182	260	150
	176	384	215
	171	270	147
	168	150	80
	162	236	122
	158	230	116
	155	300	148
	151	256	123
	145	125	58
	143	152	70
	142	096	43
	139	118	52
	135	096	41
	131	118	49
	130	100	41
Combined equivalent	176	107	597

VERTICAL WATER MOTION

Dominant peaks	T	V	D
	23	067	49
	217	070	48
	212	076	51
	206	070	46
	203	101	65
	196	119	74
	190	.080	40
	18.6	098	58
	181	125	72
	176	165	93
	171	100	54
	165	079	42
	162	109	56
	160	079	40
	156	103	51
	150	.072	34
	149	052	24
	145	056	26
	142	080	36
	139	065	29
	136	056	24
	13.3	082	35
	131	067	28
	123	070	27
Combined equivalent	174	432	240

23 22 21 20 19 18 17 16 15 14 13 12

WAVE PERIOD "T" IN SECONDS

FIG 14 - TABULATION OF EQUIVALENT SINUSOIDAL MOTION HORIZONTAL AND VERTICAL WATER MOTION, 270° AZIMUTH, 10 30-11 30, JULY 26, 1968

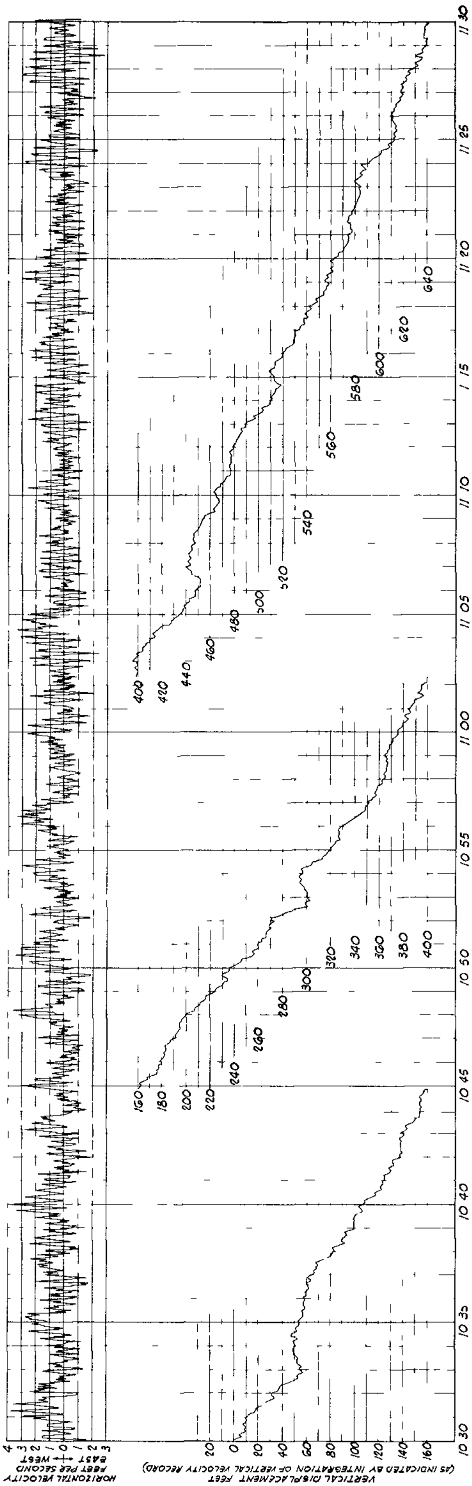

FIG 15 - HORIZONTAL WATER VELOCITY, 270° AZIMUTH DISPLACEMENT DERIVED FROM VERTICAL VELOCITY RECORD, 10 30-11 30, JULY 26, 1968

A primary purpose of the analysis of the July 26-27 data was to determine the magnitude and type of long-period waves The magnitude as shown by the power spectra of the horizontal velocity records left no doubt as to the importance of the long-period waves Energy content was nearly as high as that of the swell, and the energy content recorded for both long-period waves and swell depicted conditions much too rough for mooring a large ship alongside the pier The cross-spectral analysis of the vertical and horizontal velocity records was expected to provide a major contribution in determining whether long-period waves were incident waves similar to the swell, resonant or standing waves, or a combination of incident and reflected waves Since the questionable validity of the vertical velocity readings eliminated this possibility, the power spectra of the horizontal velocities were used instead

Fig 16 shows a tabulation of the equivalent uniform sinusoidal wave components corresponding to each energy peak of the horizontal spectra in the swell range, Fig 17 shows a similar tabulation for the energy peaks of the horizontal spectra in the long-period range For each heading a combined equivalent wave for each period range is also included

If the long-period waves were a resonance phenomenon, nearly identical peaks would be expected, especially for waves approaching from azimuths of 295° and 300°, and long-period waves caused by a beat generated by the swell periods would be expected to change in period in accordance with shifts in the swell periods

A study of Fig 16 indicates that during the recorded interval

1 The periods of swell shifted towards the shorter range

2 The total swell energy decreased in magnitude by a little more than 40%

3 Most of the swell approached the north end of the pier from an azimuth of approximately 300°

4 Several of the peak periods were present throughout the entire recording period

A similar study of Fig 17 indicates that during this interval

1 The energy content of the long-period waves decreased in magnitude by approximately 80%

2 The null direction of the long-period waves was not as clearly defined as for the swell, the dominant direction, however, was similar to the direction of swell

3 Shifts in period were apparently rather random and did not correspond to the shift to shorter periods of the swell

4 Very few of the peaks were apparent throughout the recording period

V - MAXIMUM HORIZONTAL VELOCITY FT SEC
D HORIZONTAL DISPLACEMENT - FT
T - PERIOD SECONDS

270 10 30 11 30 26 JUL 68	DOMINANT PEAKS	T	218 212 208 203 196 190 185 182 176 171 168 162 158 155 151 145 143 142 139 135 131 130
		V	165 210 250 150 400 239 222 260 384 270 150 236 230 300 256 125 152 096 118 096 118 100
		D	115 142 165 97 250 145 131 150 215 147 80 122 116 148 123 58 70 43 52 41 49 41
	COMBINED EQUIVALENT	T	176
		V	07
		D	597
300 14 30 15 30 26 JUL 68	DOMINANT PEAKS	T	223 217 209 203 197 192 189 183 177 172 165 161 157 152 144 141 137 130
		V	112 117 183 227 239 327 255 163 401 279 388 163 290 194 251 136 199 158
		D	79 81 122 147 150 120 153 95 226 152 204 84 145 94 115 61 87 65
	COMBINED EQUIVALENT	T	177
		V	104
		D	589
330 18 00 19 00 26 JUL '68	DOMINANT PEAKS	T	217 211 208 203 194 190 186 180 177 173 170 164 162 158 153 148 145 143 138 135 133 129 122 120 119
		V	103 098 075 177 372 214 233 286 187 310 316 306 294 282 265 165 144 120 182 138 152 132 115 081 096
		D	71 63 50 114 230 129 138 164 105 171 171 160 152 142 129 78 67 55 80 60 64 54 45 33 36
	COMBINED EQUIVALENT	T	170
		V	107
		D	578
360° 22 30 23 30 26 JUL 68	DOMINANT PEAKS	T	194 190 183 179 173 170 164 159 155 149 146 143 138 137 129 125 124
		V	119 098 125 187 153 239 107 229 131 142 107 100 124 119 111 100 121
		D	74 59 73 107 84 129 56 116 65 67 50 46 55 52 46 40 47
	COMBINED EQUIVALENT	T	159
		V	577
		D	293
30° 01 30 02 30 27 JUL '68	DOMINANT PEAKS	T	183 180 175 171 167 163
		V	097 074 099 079 067 079
		D	57 43 55 43 36 41
	COMBINED EQUIVALENT	T	175
		V	204
		D	114
60 05 30 06 30 27 JUL '68	DOMINANT PEAKS	T	192 186 179 173 169 165 164 158 155 152 148 145 136 133 127
		V	074 073 137 111 110 095 102 074 110 066 091 083 087 061 060
		D	45 43 78 61 59 50 53 37 67 32 43 38 38 26 24
	COMBINED EQUIVALENT	T	165
		V	359
		D	189
295° 09 20 10 20 27 JUL '68	DOMINANT PEAKS	T	190 183 176 170 166 161 158 154 148 145 142 139 135 132 128 126 124 119
		V	120 079 132 271 319 223 271 232 118 134 192 113 162 140 154 068 102 130
		D	73 46 74 147 168 114 137 114 56 62 87 50 69 59 63 27 40 49
	COMBINED EQUIVALENT	T	158
		V	761
		D	382

23 22 21 20 19 18 17 16 15 14 13 12

WAVE PERIOD T IN SECONDS

FIG 16 - TABULATION OF EQUIVALENT SINUSOIDAL WAVE COMPONENTS FOR SWELL

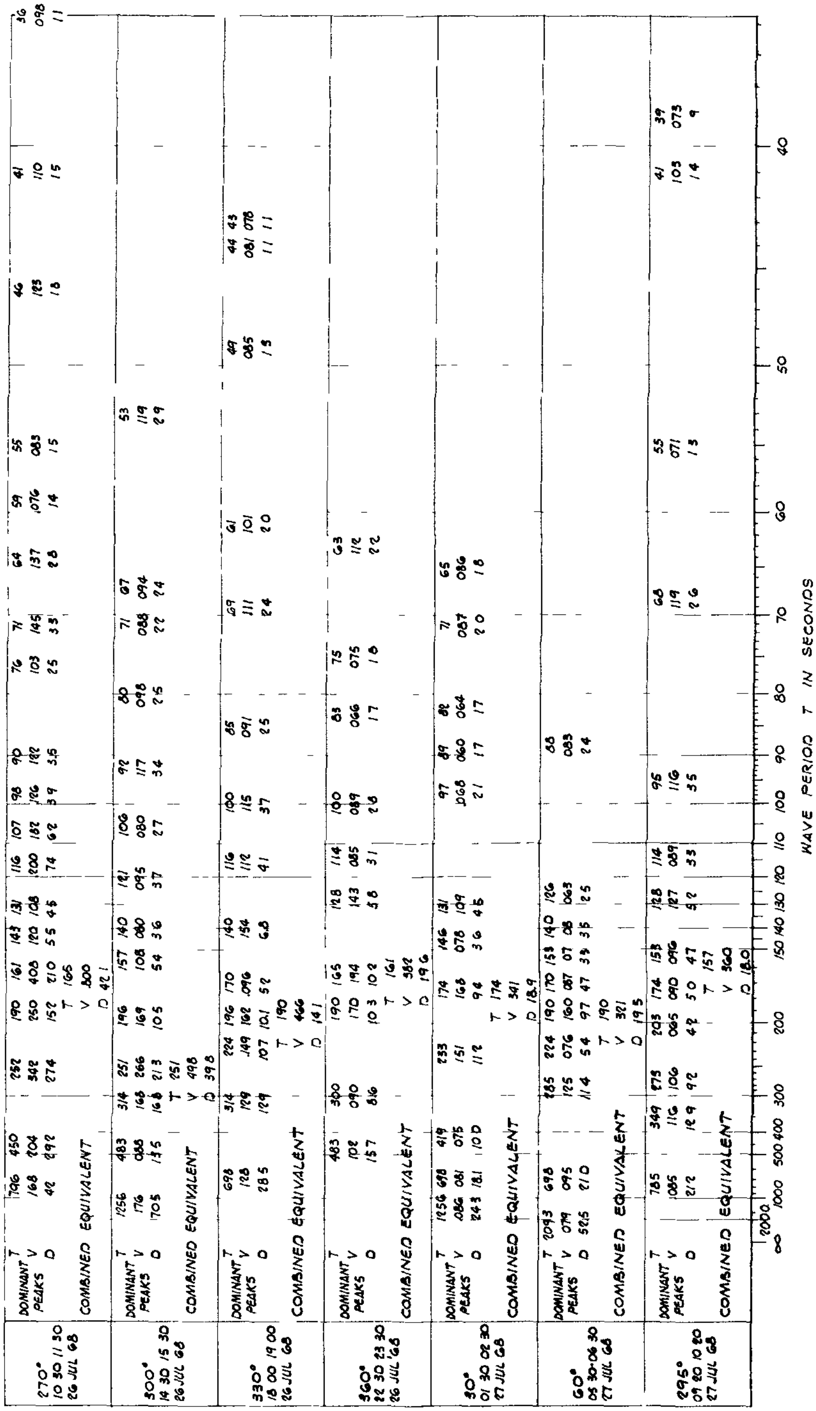

FIG 17 - TABULATION OF EQUIVALENT SINUSOIDAL WAVE COMPONENTS FOR LONG-PERIOD WAVES

These observations implied that the long-period waves are progressive waves originating from the same storm center as the swell, and that resonance of the bay is probably not an important factor Unlike the energy of the swell, very little of the long-period wave energy is dissipated in breakers on the shore and most of the waves are reflected back to the ocean

Some of the long-period waves are probably reflected more than once before returning to the ocean, which would explain their lack of a clear null direction

APPLICATION TO HARBOR PROGRAM

Based on the preceding analysis, it was concluded that ocean swells refracted around Point San Nicolas and approaching the pier from the ±300° azimuth were the primary source of adverse mooring conditions at the pier A breakwater similar to that shown in Fig 18 is currently under construction at San Nicolas The breakwater is expected to attenuate ocean swell so that wave action in the swell range will no longer cause interpretations to ore loading operations Attenuation of long-period waves of high energy content will be nominal, but for these unusual occurrences, the breakwater will have some beneficial effect by reorienting these long-period waves so that their horizontal water motion will be primarily north-south or parallel to moored ships rather than east-west as at present

CONCLUSIONS

The age-old problems of harbor design are becoming increasingly complex due to phenomenal increases in the sizes of modern ships Fortunately, our burgeoning technology is developing many new and powerful tools which can be applied in solving these problems The harbor study at San Nicolas adequately defined wave movement so that an economical solution could be obtained The full potential of the techniques used was not applied, but experience gained during the study indicates the capability for improved results in similar applications

Ducted impeller meters provided an extremely valuable means for studying harbor wave action These instruments were especially useful in measuring long-period swells and surges which were difficult to identify by sight

Spectral analysis methods proved well-suited to detailed interpretation of the particle velocity records, considerable insight into the wave phenomena was gained by simple, rational inspections and interpretations of the records

Time-lapse movies of a moored ship in motion, when correlated with simultaneous water particle velocity records, provided an exceptionally clear picture of ship response to wave action, and led to the rather surprising observation that long-period ship motion is not necessarily caused by long-period waves

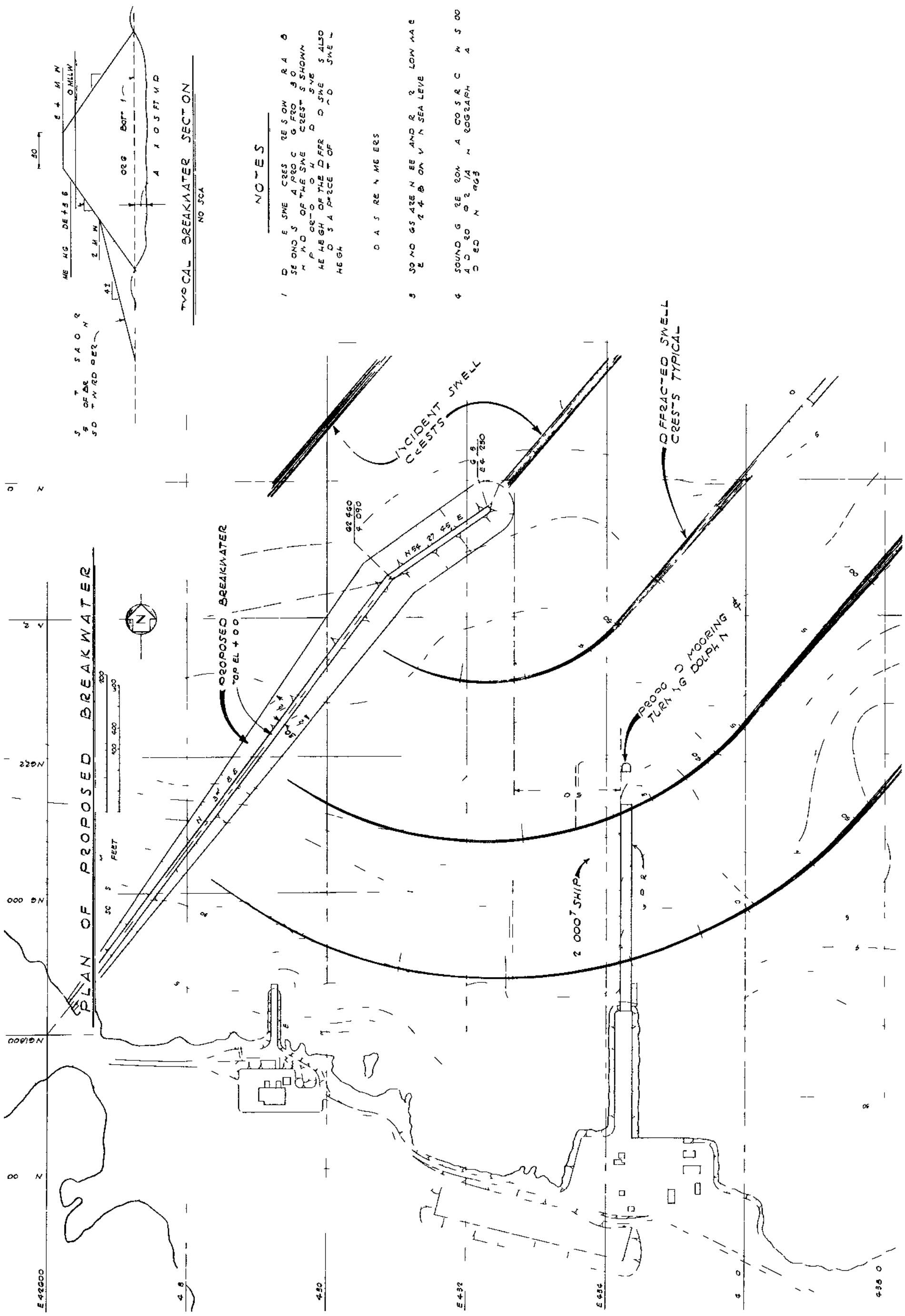

FIG 18 - PRELIMINARY STUDY OF BREAKWATER FOR SAN NICOLAS BAY, PERU

The usefulness of hydraulic model tests was again demonstrated, and it should be noted that very useful results can be obtained from model tests at modest expense if the test goals are clearly defined and the test work performed simply and judiciously

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APPENDIX-REFERENCES

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