

CHAPTER 6  
HARBOR SURGING

Vito A. Vanoni and John H. Carr  
California Institute of Technology  
Pasadena, California

SIGNIFICANCE OF SURGING ON HARBOR USAGE

Surge is the name applied to wave motion with period intermediate between that of ordinary wind waves and that of the tides; say from one to sixty minutes. An additional characteristic of surge is that it is usually of very low height; perhaps 0.3 ft. is typical. This type of wave motion has been observed along the entire Pacific coast of the United States (Coast and Geodetic Survey, 1943), and in some places, notably Los Angeles Harbor, has been of serious concern to harbor authorities (Calif. Inst. of Tech., 1945).

Although the height of surge may be so small that, coupled with the very great wave length, the motion cannot be visually observed as a wave train, the horizontal water motion may be large, and it is this factor which accounts for the importance of surge in harbor operations. Since the height of the surge wave is very small compared to either the wave length or water depth, the classical Airy wave theory (Beach Erosion Board, 1942) may be applied to the problem with small error. Thus, the horizontal amplitude of water motion is substantially constant from surface to bottom, and is equal to  $\frac{HT}{2\pi} \sqrt{\frac{g}{d}}$ , where H is the wave height (vertical distance from crest to trough), T is the wave period, d the water depth, and g the acceleration of gravity. The average water particle velocity is therefore  $\frac{H}{\pi} \sqrt{\frac{g}{d}}$ .

This result may be easily verified in the case of a standing wave by reference to a diagram such as Fig. 1. If at some initial time the wave profile is in one extreme position as shown by the solid line, then a quarter wave period later the

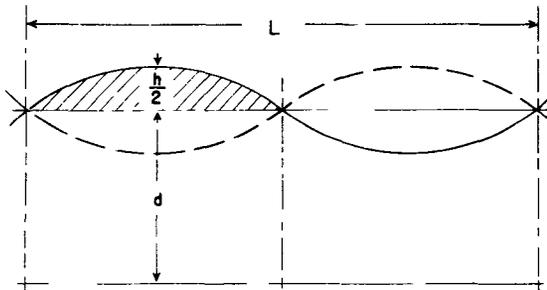


Fig. 1

Diagram for water motion in a standing wave.

entire surface is horizontal, the water above the mean level in each crest flowing to the right and to the left to fill in half of each adjoining trough, and another quarter period later the surface is in the other extreme, as shown by the dashed line. Therefore, in one-half a wave period, a volume of water proportional to the area shown cross-hatched flows through each nodal section of depth d. The average flow rate, Q, is therefore:

$$Q = \frac{2 \int_0^{\frac{L}{4}} \frac{H}{2} \cos 2\pi \frac{x}{L} d x}{\frac{T}{2}}$$

or  $Q = \frac{HL}{\pi T}$

since  $L = CT = \sqrt{gd} T$

$$Q = \frac{H \sqrt{gd}}{\pi}$$

and the average velocity through the nodal section becomes:

$$v = \frac{Q}{A} = \frac{H \sqrt{gd}}{\pi d} = \frac{H}{\pi} \sqrt{\frac{g}{d}}$$

# HARBOR SURGING

As a numerical example, a 3-minute period surge, 0.3 ft. in height, would cause oscillatory horizontal water displacements of 9 ft. in a harbor depth of 30 ft., with an average velocity of 0.1 ft. per sec. or 0.06 knot.

Since a ship is small compared to the wave length of a surge (5600 ft. in the foregoing example) it may be expected to move in space with the water motion unless rigidly restrained. Serious damage has occurred where such surge-excited ship motion has been resisted by dock and pier structures. Fig. 2 is a record of typical surge motion and resulting damage at the Terminal Island, California, Navy Base prior to the construction of the mole.

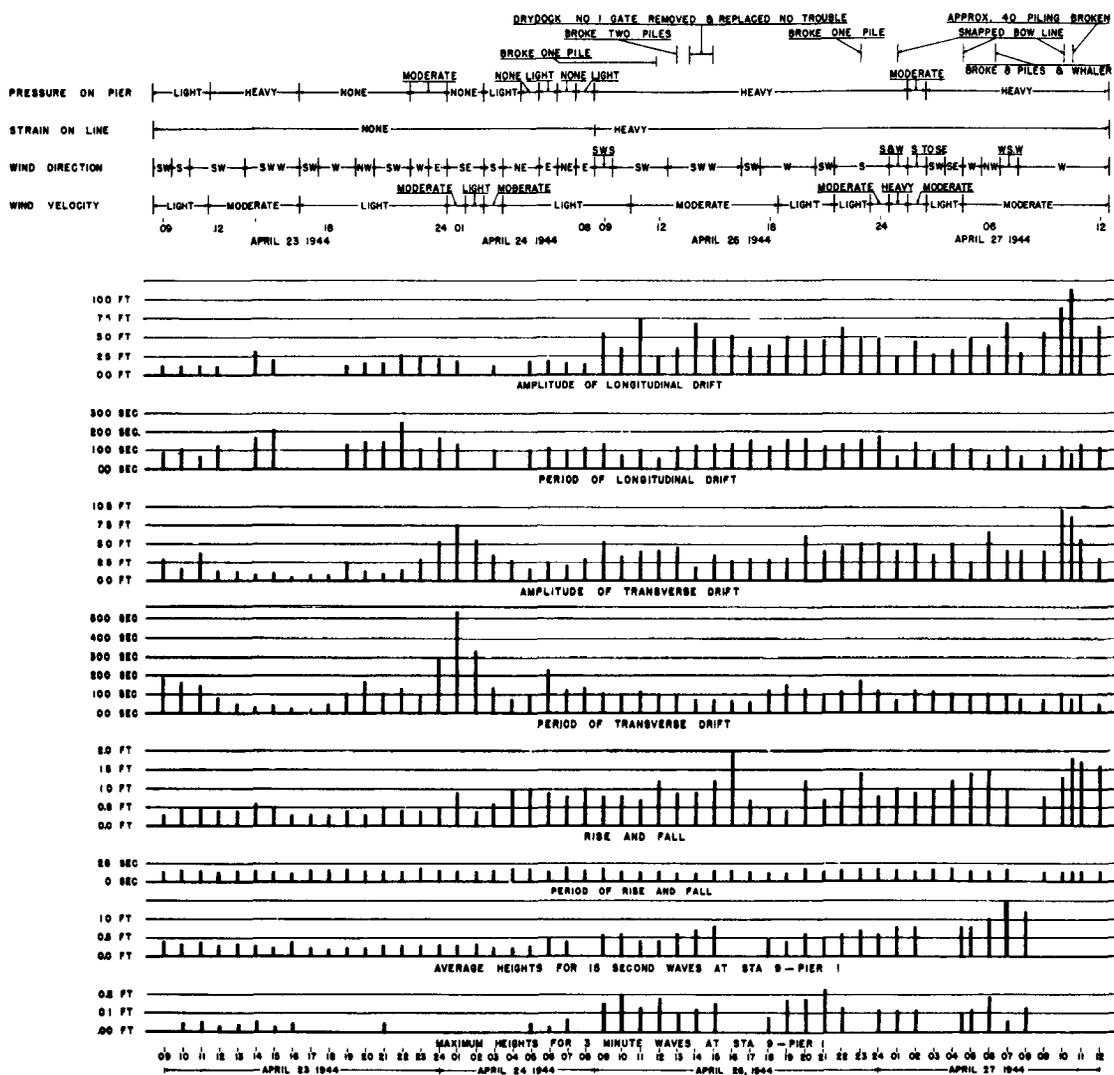


Fig. 2. Record of surge and damage, U.S. Naval Drydock, Long Beach, California.

# COASTAL ENGINEERING

## CHARACTERISTICS OF LONG PERIOD WAVES

Wave Behavior. Like other surface waves, long period waves may be of either progressive or standing type. Because of their large wave length, standing surge waves account for special problems and effects in harbors. A standing wave results from the superposition of two identical progressive wave trains traveling in opposite directions. Where the water particle motions due to each of the wave

trains coincide, they mutually reinforce and the motion is doubled; conversely, where the motions are opposed the resultant is zero. The result is that at fixed positions a half-wave length apart the vertical amplitude of the water motion is a maximum, and half way between these antinodal points the vertical motion is zero. In a progressive wave train, the horizontal velocity of partial motion is greatest at points beneath the moving troughs and crests, but in a standing wave the horizontal velocity is zero at antinodes and a maximum at the position of no vertical motion, or nodal points. Fig. 3 illustrates these characteristics of a standing wave.

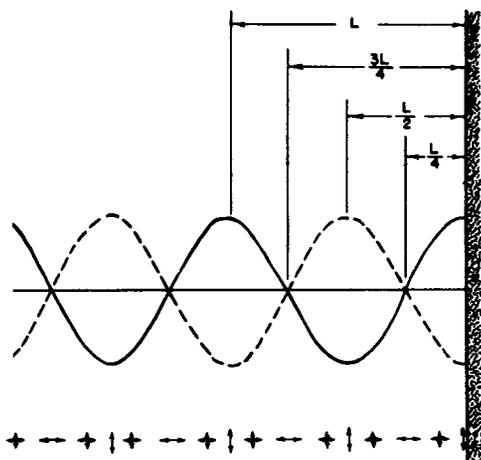


Fig. 3. Profile and water motion of a standing wave.

The important distinction between the two wave types as far as harbor surge is concerned is, therefore, that if the surge is due to a progressive wave train, all areas in the harbor experience the same maximum horizontal motion, whereas if the surge is of the standing wave type, there will be distinct areas of active and quiet water.

It is apparent that a standing wave always exists seaward of a reflecting barrier, the reflected and incident waves combining to produce this result. In this connection, it should be noted that the reflective properties of a shoreline are determined by the scale of the irregularities of the shoreline with respect to the length of the waves. Thus, a given stretch of irregular shoreline will appear "straight" to long period waves, and the incident wave energy will be concentrated in a well-defined reflection, whereas the same shoreline will scatter reflected short period waves in all directions with resulting diffusion of energy.

If two parallel reflecting shorelines are oppositely disposed in a basin, a wave train will travel between them, each wave being successively reflected from one to the other, until damped out by frictional forces. If the distance between the reflecting shorelines is such that the time required for a wave to travel from one boundary to the other is an integer multiple of half the wave period, the standing wave patterns produced by reflection from each boundary will coincide, and a condition of free oscillation of the basin will result. In the case of a basin open at one end to the sea or other large body of water, and closed by a reflecting boundary at the other, it can be shown that the condition for free oscillation will be realized if the length of the basin is such that the wave travel time is an odd-integer multiple of one-quarter of the wave period (Sverdrup, Johnson, and Fleming, 1942). It may be noted that the term seiche is applied to such free basin oscillation.

Basin oscillation, or seiching, is analogous to the motion of a spring-mass system, pendulum, or other mechanical or electrical oscillating system; once started, the motion persists unless brought to rest by outside forces. Fig. 4 illustrates the fundamental and first two harmonic modes of oscillation of basins.

In any type of oscillatory system, if a periodic excitation is applied at one of the free or natural periods of the system, the motion will increase to an amplitude determined by the damping of the system; this phenomena is termed resonance. Thus in the present case, if a long period wave train whose period corresponds to the fundamental or an harmonic period of the basin enters the harbor

## HARBOR SURGING

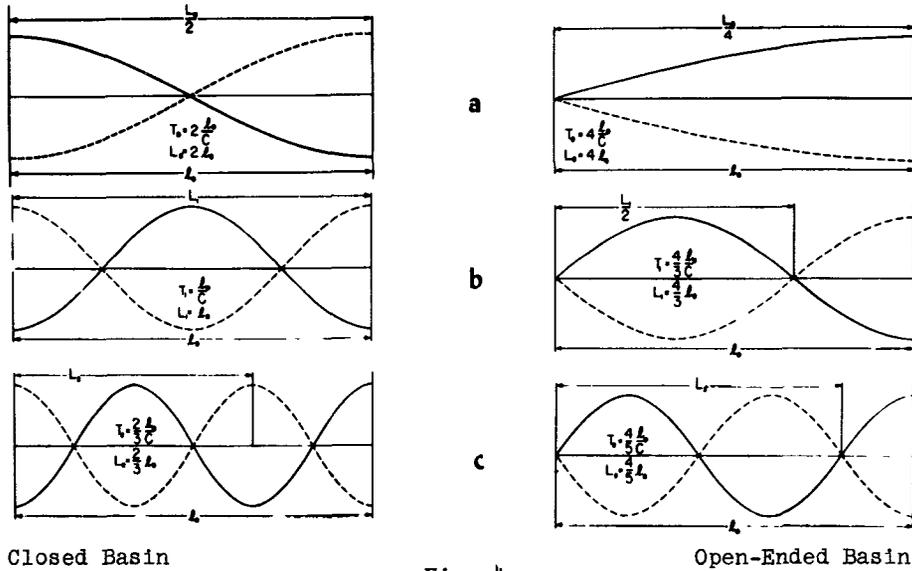


Fig. 4  
Modes of basin oscillation  
(a) Fundamental, (b) First Harmonic, (c) Second Harmonic

from the open sea, a condition of resonant basin oscillation will result. The significance of resonant basin oscillation is that all of the wave energy coming into the area is concentrated in one standing wave system, with resulting build-up of large amplitude vertical and horizontal water motion at the positions of nodes and antinodes. This amplification may result in a serious surge condition in a harbor basin even though the exciting long period wave train is nearly totally excluded from the harbor by a breakwater or mole. Thus, model studies of the Terminal Island Mole Basin (Calif. Inst. of Tech., 1945) have shown wave heights within the mole 50% greater than those in the outer harbor for critical surge periods.

Where the water depth in a basin is substantially constant, the velocity of shallow water, long period, waves may be taken as  $\sqrt{gd}$ , and the previously mentioned conditions for resonant periods become:

For closed basins:

$$T = \frac{2l}{(k+1)\sqrt{gd}} \quad \text{where } l \text{ is the basin length} \\ k = 0, 1, 2, 3, \text{ etc.}$$

For open-ended basins:

$$T = \frac{4}{(2k+1)} \frac{l}{\sqrt{gd}}$$

Where the water depth is not uniform, the critical periods may be computed by numerical integration of the equations in the following form:

For closed basins:

$$T = \frac{2}{k+1} \int_0^l \frac{dx}{\sqrt{gd_x}}$$

For open-ended basins:

$$T = \frac{4}{2k+1} \int_0^l \frac{dx}{\sqrt{gd_x}}$$

where  $d_x$  is the depth at distance  $x$  from the end of the basins.

## COASTAL ENGINEERING

These relations have been verified by model experiments for the cases of uniform water depth, and parabolic variation of water depth, at the University of California (Johnson, 1949). These experiments also investigated the damping effect of sills located at nodal points in the standing wave pattern, with the result that a sill of height approximately one-third the water depth was found to reduce the wave amplitude by approximately 50%.

Sources of Long Period Disturbances. The question of the sources of the long period wave disturbances which cause surge problems in harbors is one which can not be answered completely at the present time. Early thinking on this subject was confined to the assumption that surge was a phenomenon always related directly to the basin in which it occurred, hence was a free oscillation of the basin following some initial disturbance such as a piling up of water due to winds, atmospheric pressure anomalies, or local seismic activity. This explanation is indeed the only one admissible for the case of seiching of completely land locked basins such as lakes, but recent observations of surge activity in coastal regions have demonstrated the inadequacy of this theory as a general condition. The existence of surge conditions in harbors at intervals completely uncorrelated with local atmospheric or seismic disturbances has focused attention on the proposition that long period, low amplitude wave trains exist in the open sea, and where these wave trains enter a harbor they constitute a surge. If the wave period coincides with the natural period of the harbor basin, the waves will excite resonant oscillation, with resulting increase in the severity of the surge.

One obvious source of such long period wave trains in the sea are seismic sea waves or "tsunamis" generated by distant submarine earthquakes, Fig. 5. This source is quite limited in frequency of occurrence, but the recently developed theory of "surf beat" due to Munk (1949), offers a source of long period sea waves that is quite general in occurrence and so satisfies the observations of frequent periods of surge in coastal regions.

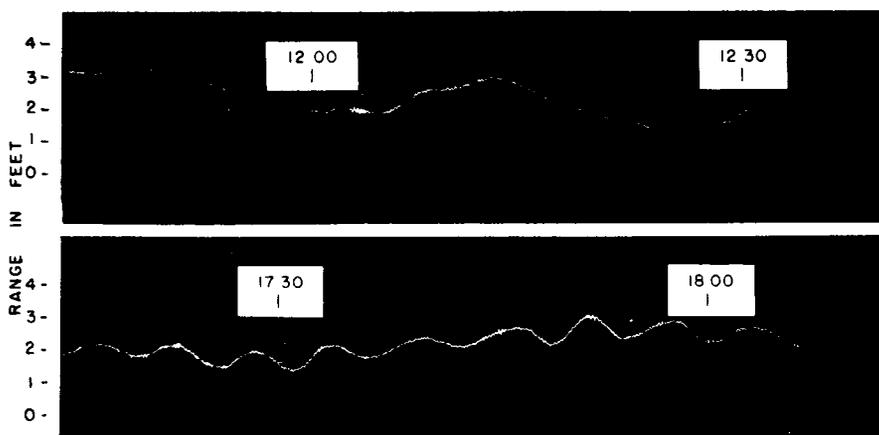


Fig. 5  
Marigram record of 20- and 6-minute  
surges at Terminal Island due to the  
Alaskan Earthquake of April 1, 1946

The theory of surf beat indicates that in the process of wave breaking, a small fraction (approximately 1%) of the wave energy which enters the breaker zone is reflected back to sea as a long period wave. This behavior is due to the non-linearity of the wave breaking process; the phenomenon of frequency demultiplication being a characteristic of non-linear systems (Den Hartog, 1940). Thus, a storm in some remote region of an ocean basin may produce a period of high surf along some distant shoreline, and the long period waves radiated from this shore may then travel across vast ocean distances in the same manner as tsunamis to produce a surge condition in harbors thousands of miles from the generating area. The theory of surf beat has been verified by experiments at the Scripps Institution

## HARBOR SURGING

of Oceanography (Munk, 1949); it remains to determine its importance as a source of harbor surge. The techniques for such an investigation are available and should be put in operation, since if it is as important as the foregoing discussion assumes, it should be possible to forecast periods of surge by a combination of present-day techniques for wave forecasting, to determine generating areas, and for tsunami warning, to determine the path of the long period waves.

### REMEDIAL MEASURES

Since the principal problem associated with harbor surging is unwanted ship motion, especially where ships are moored in close proximity to fixed structures such as docks or piers, alleviation of the problem will be obtained only by the reduction of ship motion to a tolerable minimum. Two approaches to this requirement are apparent; (1) the reduction in amplitude of the surge waves in the harbor, and (2) the development of mooring systems which will limit the amplitude of ship motion.

In connection with the first named approach, the reduction of breakwater gate width, or harbor opening, to the minimum required for navigational purposes will reduce the amount of long period wave energy which can enter the harbor from the sea, with resulting reduction in surge activity in the harbor. By way of illustration, model studies of the Navy Mole Basin at Terminal Island, California, indicated that a reduction in gate opening from 2000 feet to 600 feet resulted in approximately 50% reduction in surge amplitude in the basin (Fig. 7). The location of the harbor entrance is not so important in reducing entering surge excitation, since the entrance width is usually small compared to the wave length of the long period surge waves. As a result, the diffraction phenomena at the entrance are relatively independent of the direction of wave approach, and on the harbor side the transmitted wave energy is directed nearly uniformly in all directions.

Model studies are also useful in surge problems since they enable the mapping of water motions in all parts of a harbor for any assumed surge condition, and thus permit the rational choice of "quiet" areas for dock and pier location. Since the degree of water motion may vary by a factor of 10 to 1 in various parts of a harbor due to the characteristic standing wave patterns which are produced, model studies may make significant contributions to a harbor design project. Figs. 6, 7, and 8, which are the results of model studies made for the U.S. Navy, Bureau of Yards and Docks, illustrate this behavior for the cases of Terminal Island and Apra Harbor, Guam (Calif. Inst. of Tech., 1949). In Fig. 6 the results of a disturbance survey of the entire Terminal Island mole basin are presented in the form of contours of equal vertical amplitude. It is apparent that for surge periods of 3 and 6 minutes the harbor is divided into sharply delineated areas of minimum and maximum activity, whereas the disturbance level is nearly uniform throughout the harbor for ordinary sea waves of 15-sec period. In Fig. 7, the vertical amplitude in a particular area near the Navy piers is plotted as a function of wave period. The peaks of activity correspond to the several resonant periods of the basin. Fig. 8 summarizes the results of a horizontal water motion survey of Apra Harbor for surge periods of 1.9 and 3.8 minutes, corresponding to two resonant periods of the harbor. Again, a wide variation in degree of water motion within a short distance is exhibited.

The second approach to the solution of harbor surge problems, that of improvements in ship mooring practice, has received very little attention as yet. To be successful, a system must be developed that is virtually rigid, since if the ship moves at all, it acquires kinetic energy, and can then only be brought to rest by the conversion of this energy into strain energy of deflection of the mooring system. The catenary suspensions of cable mooring systems, even extraordinary ones such as shown in Fig. 9, which were used at Terminal Island prior to construction of the mole, may permit deflections as large as six or eight feet, hence some entirely new type of mooring will have to be devised.

It is also important that the elastic constants of the mooring system be proportioned to the mass of the ship so that the natural period of the ship-and-mooring system is not close to the expected period of harbor surge, since if these

# COASTAL ENGINEERING

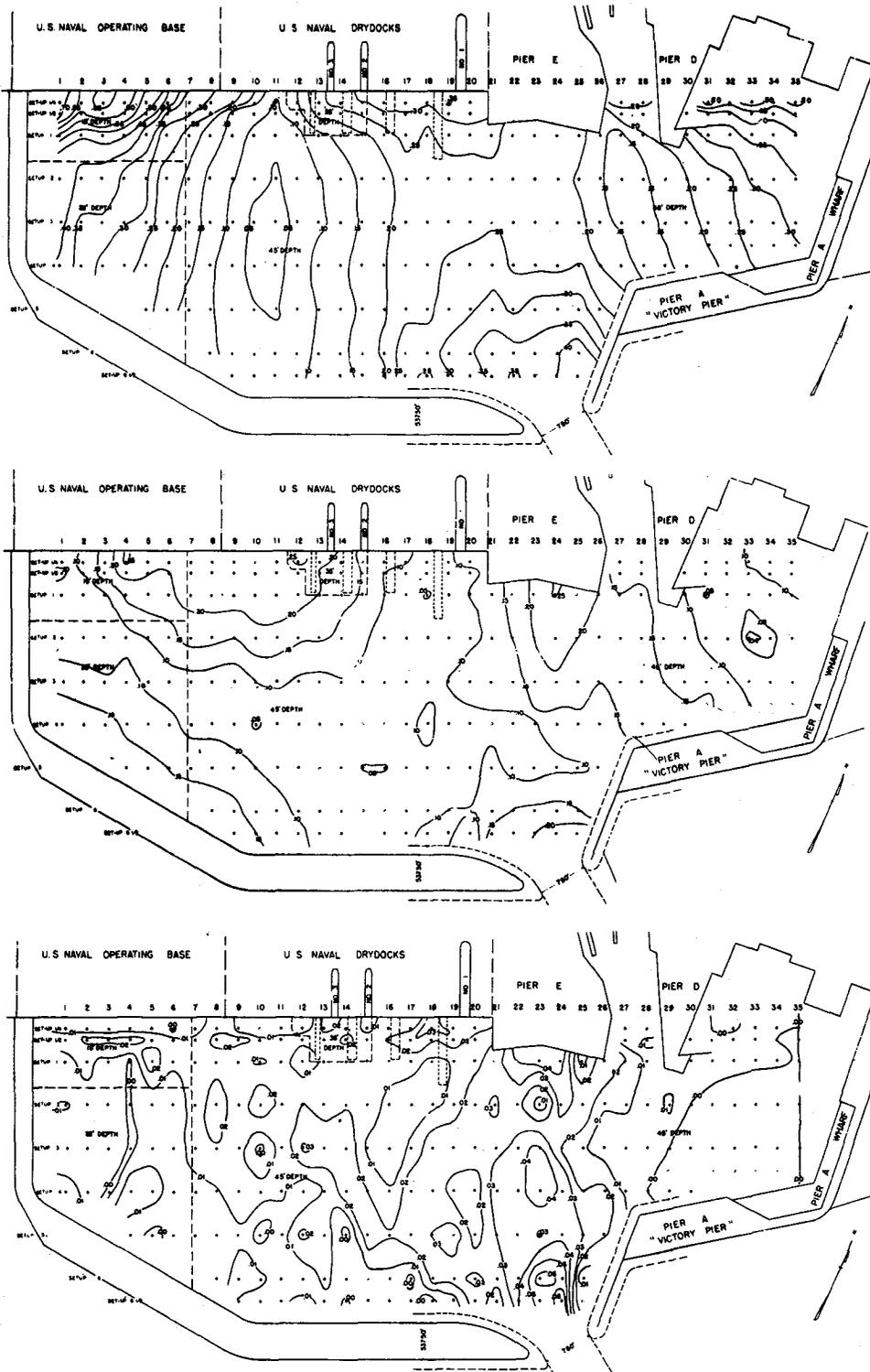


Fig. 6  
Contours of vertical amplitude, Terminal Island Mole Basin for three  
wave and surge periods  
(a) 6-minute                      (b) 3-minute                      (c) 15-second

## HARBOR SURGING

periods are nearly equal the ship will be driven at resonance by even small surge waves with resulting large amplitude ship motion and high stress in the mooring system. The effect of the elastic properties of the mooring system on ship motion and mooring stress recently has been analyzed in great detail by Wilson (1950).

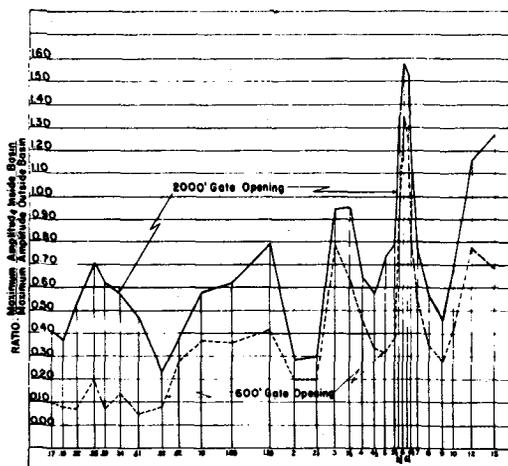
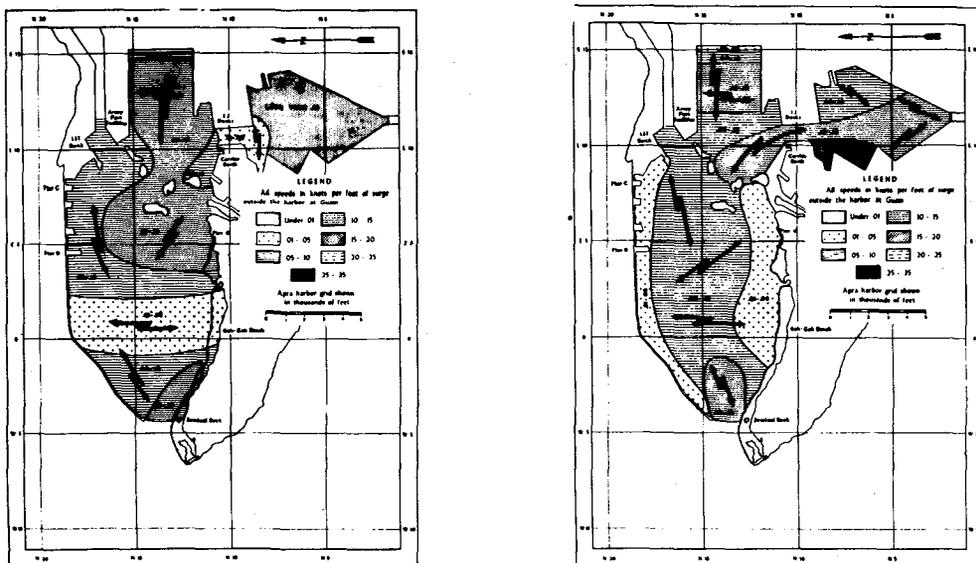


Fig. 7. Vertical amplitude as a function of wave period in vicinity of Navy Piers, Terminal Island, California



1.9-minute period 3.8-minute period  
 Fig. 8. Horizontal water motion due to surge, Apra Harbor, Guam, M.I.

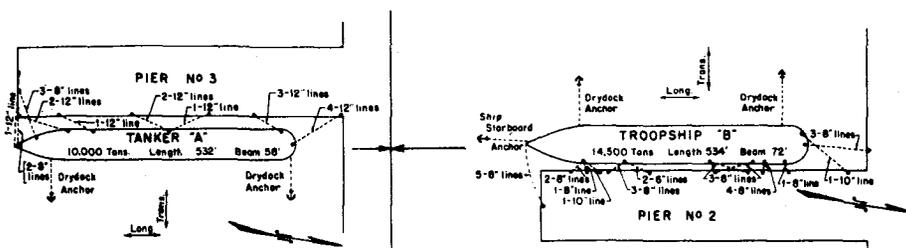


Fig. 9. Typical mooring systems

# COASTAL ENGINEERING

## REFERENCES

- Beach Erosion Board (1942). A summary of the theory of oscillatory waves: Tech. Report No. 2, Corps of Engineers, Washington, D.C.
- California Institute of Technology (1945). Wave and surge study for the Naval Operating Base, Terminal Island, California: Hydrodynamics Laboratory Publ. No. 55.
- California Institute of Technology (1949). Model studies of Apra Harbor, Guam, M.I.: Hydrodynamics Laboratory Publ. No. N-63.
- Coast and Geodetic Survey, U.S. Department of Commerce (1943). United States Coast Pilot, Pacific Coast: Serial No. 649, Government Printing Office, Washington, D.C.
- Den Hartog, J.P. (1940) Mechanical vibrations: 2nd Edition, McGraw-Hill Book Co., New York.
- Johnson, J.W. (1949). Scale effects in hydraulic models involving wave motion: Trans., Amer. Geophys. Union, vol. 30, pp. 517-529.
- Munk, W.H. (1949). Surf beats: Trans., Amer. Geophys. Union, vol. 30, pp. 849-854.
- Sverdrup, H.U , Johnson, M.W., and Fleming, R.H. (1942) The oceans: their physics, chemistry and general biology: Prentice-Hall, Inc , New York.
- Wilson, B.W. (1950). Ship response to range action in harbor basins: Proc. Amer. Soc. of Civil Engrs., vol. 76, Separate No. 41, pp. 1-29.