JOURNAL OF THE
BOSTON SOCIETY OF CIVIL ENGINEERS SECTION
AMERICAN SOCIETY OF CIVIL ENGINEERS

Volume 65 **October 1978** **Number 3**

STRUCTURAL DESIGN CONSIDERATIONS IN THE MARINE ENVIRONMENT

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Introduction

The ocean is a restless continuum of rising and falling tides, circulating currents, and sporadic wind driven waves. It is teeming with both delicate and resilient life forms. It is subjected and exposed to the full fury of natural events such as winds, sea motions, meteorological extremes, and seismic and astronomical disturbances. Life in the ocean remains in delicate balance with life on land.

The time has come when man has returned to the oceans from which his ancestors evolved to construct more permanent structures both fixed and floating, some built below the surface on the very sea bed itself. Time has come, then, when man becomes aware of the life and physical processes going on in the sea. Much work remains to be done in understanding the world ocean climate, in the development of more accurate hydrodynamic theories and statistical representations of waves and currents and in the understanding of life processes in the sea. It is hoped that the following overview of the problems involved in the design of ocean structures will serve to point out areas where information is still lacking.

The overall behavior of the oceans and causes of sea motions and propagation of sea life are most complex and fascinating, but only the ultimate effects they have on sea structures are considered here.

As to the ocean waters themselves they are relatively homogeneous and exhibit subtle differences in temperature, salinity, and density. Seawater has a mean specific gravity of 1.026 which varies slightly with differences in temperature and salinity. The temperature of the oceans is relatively constant at depth. Mean surface temperatures vary from near 29°F (-1.5°C) in the Arctic to as high as 85°F (29°C) in the tropics. The mean salinity, or saltiness, of the ocean is 35 parts per thousand, ranging in extremes from 33 to 38 parts per thousand in the open sea. Near shore, coastal water, salinities may be considerably less due to fresh water runoff. Oceanic surface water contains approximately 5 ml/liter of dissolved oxygen at a temperature of 68°F (20°C). Seawater is slightly basic, with a mean pH of about 8.3. Under certain conditions when the water becomes rich in nutrients, marine organ-

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isms utilize all the free oxygen, and hydrogen sulfide is produced by certain anaerobic bacteria, causing accelerated corrosion of metal structures. The pH drops considerably under these conditions.

The sea floor in many harbors is covered with a layer of soft organic silts. The high water content, low unit weight, and low shear strength which are characteristic of ocean bottom sediments give rise to difficult foundation problems.

All sea motions, waves, currents and tides, can be described by differences in velocity and pressure as functions of space and time. Basic sea motions are discussed herein as to their effect on structural design. Further description of the oceans and of their processes and movements of particular interest to engineers is found in references [1] through [5].

NOMENCLATURE

C = wave velocity (celerity)

C_D = drag force coefficient

d = water depth

g = acceleration of gravity

γ = unit weight

H = wave height

h = extreme high water depth above M.H.W.

L = wave length

n = wave crest height above S.W.L.

P = force per unit area (pressure)

V = velocity

ABBREVIATIONS

L.W.O.S.T. = low water on spring tide

M.H.W. = Mean high water

M.L.W. = Mean low water

psf = pounds per square foot

S.W.L. = Stillwater level

R.H. = Relative humidity

General Concepts

Some general design considerations are illustrated in Figure 1. Primary considerations would be those of direct structural loadings such as those imposed by wind, waves, currents, ice, and hydrostatic pressure. Secondary considerations (although sometimes they are of primary importance) would include operational and functional effects, such as the variation of water levels (tides and stormwater levels), secondary effects of currents such as scour and deposition and the possibility of induced vibrations, general deterioration manifested as corrosion of metals, decay of wood, attack by marine organisms, fouling, secondary effects of ice, i.e., freezing and thawing, and general deterioration due to the random and cyclic nature of the loadings.

Wind, wave and current loadings exhibit both temporal and spatial varia-

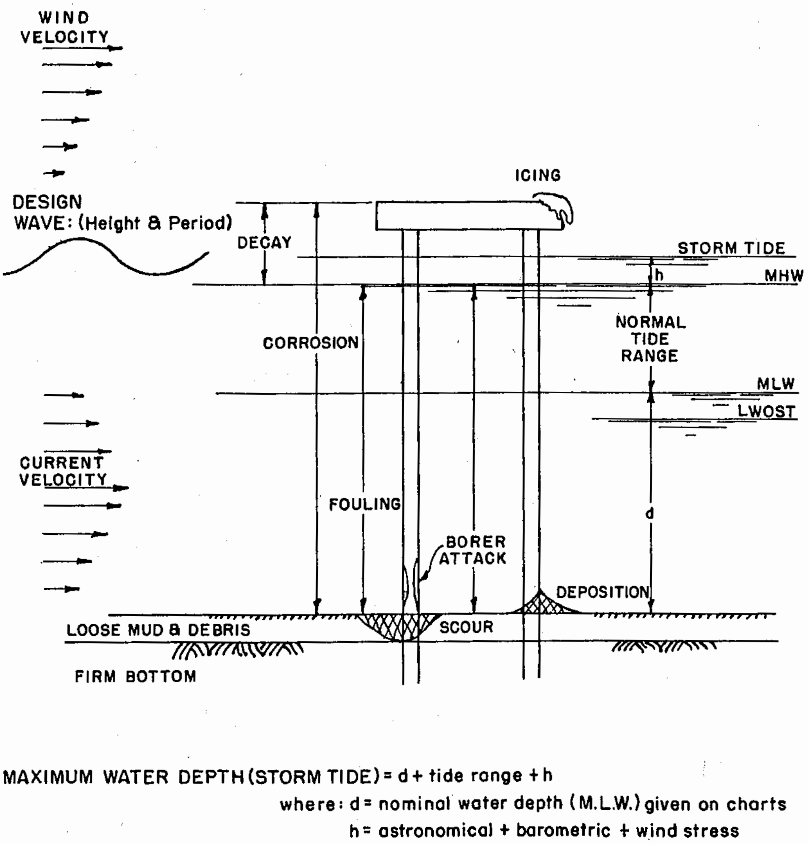


Figure 1. Ocean Structure-Design Considerations

tions, for example, the unsteady and non-uniform loads due to wind gusts; also, the multi-directional nature of loadings such as rotary and reversing tidal currents must be considered. As there is generally *uncertainty* as to what severity of storm conditions a given structure might be subjected to, the concepts of *risk* and *design life* become important. Once the lifetime over which a structure is required to operate usefully has been determined, then the most severe storm and resulting sea conditions that may occur during that lifetime may be evaluated by hindcasting techniques or more theoretical forecasting methods [6] [7]. When the likelihood of a given storm occurring at the structure site is predicted, then the risk of designing for that storm or something less can be evaluated in terms of economics or safety requirements. Such likelihood is conveniently expressed in terms of a *return period* (in years) associated with the recurrence of extreme events [8].

The previously mentioned factors are next discussed individually with regard to how they should be considered in structural design. In addition some special effects that may be of local concern are mentioned that may be discarded as a problem or delved into further as the occasion warrants. Design of marine structures in general is covered in references [9] through [14].

Overwater Wind

Wind effects on structures are certainly not peculiar to marine structures; however, in general, marine structures are subjected more to the full fury of the wind and at greater frequency than land-based structures. Further, at high wind speeds, the air can become entrained with sea water, thus imparting higher effective wind pressures [5]. Wind speed is normally recorded at 33 feet (10 meters) above sea level. The velocity at the sea surface is near zero and it increases with altitude approximately as the one seventh power of the altitude in the open sea. In coastal areas however this exponent will be greater due to retardation of the lower level of air by the land (see Figure 2). It is customary to design for the so-called *fastest mile of wind,* which is the maximum velocity corresponding to a gust length of one mile. This accounts for the fact that wind forces are unsteady or vary with time. The averaging time interval, therefore, depends upon the maximum velocity recorded; that is, a 60 mile per hour wind would have to be sustained for one minute to be considered as the fastest mile of wind. Guidance for design windspeeds in the United States can be found in the work of Thom [15].

Because of the extreme exposure, due consideration should be given to both the vertical distribution and multi-directional nature of the wind at sea. As, in general, no building codes are in effect governing design wind pressures for sea structures, the designer must have a good grasp of basic aerodynamics, particularly as regards the choice of proper drag coefficients on various structural configurations. Figure 3 represents a plot of the dynamic drag force equation; when the design wind speed has been selected the problem of wind force can be reduced to one of selecting the proper drag coefficient [16]. In bottom supported sea structures wind forces become more significant as they are applied at a height where they create the maximum moment per unit of force.

Winds are the direct cause of what are the major design loadings for offshore structures namely: waves.

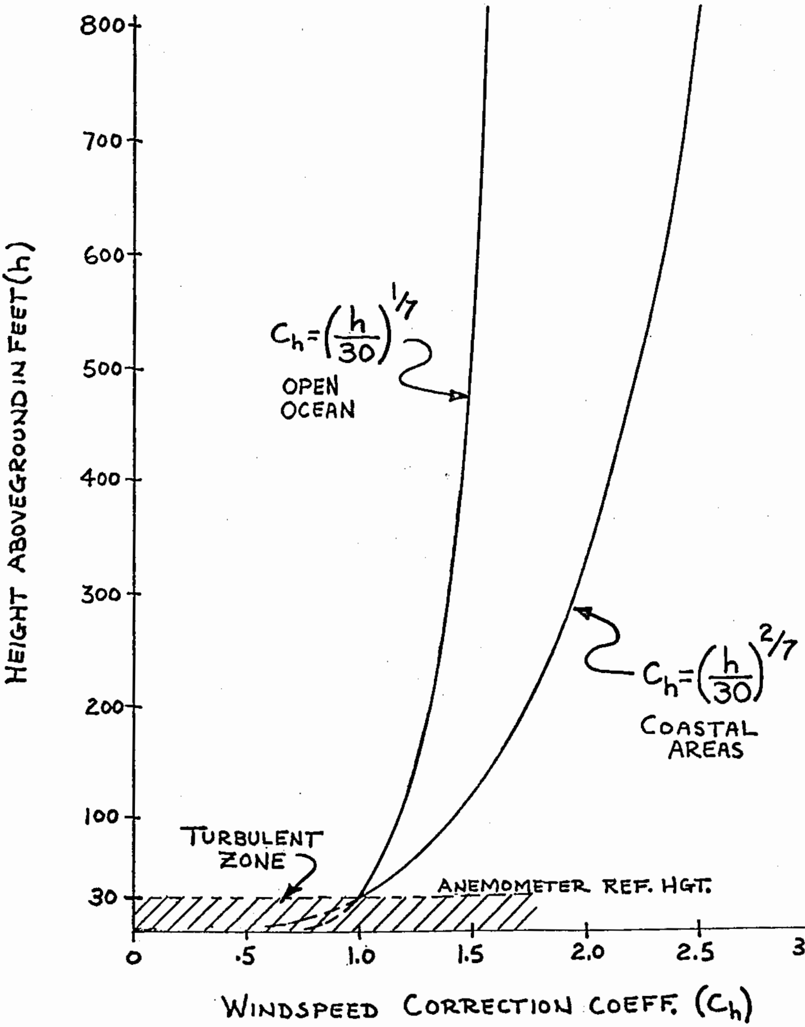
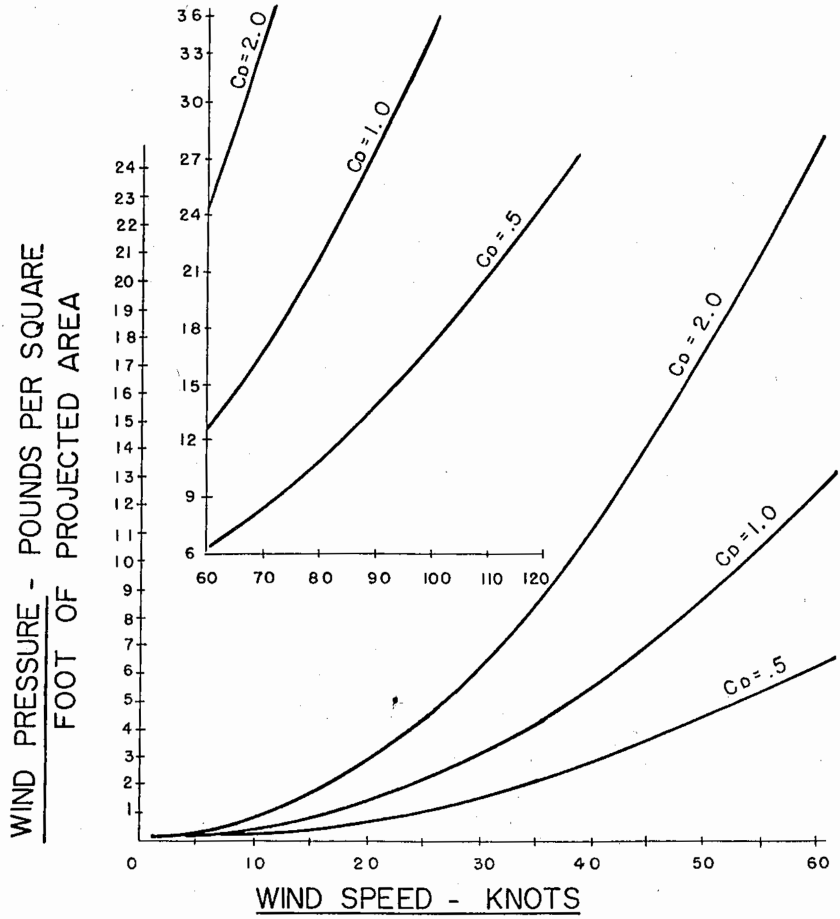


Figure 2. Vertical Distribution of Wind Velocity



From Dynamic Drag Equation : $P = \frac{1}{2}\,\frac{8}{g}\,V^2 C_D$
For V in knots and P in p s f : $P = .0034\,V^2 C_D$

Based on Standard Atmosphere: air at 29.92" hg
59° F R.H. = 0 %

Figure 3. Wind Pressure vs. Wind Speed

Waves

Waves are periodic undulations of the sea surface. The majority of waves, especially those of interest in structure design, are caused by the wind. The maximum dimensions of a wave depend upon three parameters basic to wave forecasting. They are: *fetch* or the distance over which the wind blows, the velocity of the wind, and the duration of time for which the wind blows. A fully developed sea occurs when the fetch is essentially unlimited and the wind blows for a minimum required length of time for the given wind speed; a more or less steady state situation is reached when the average wave heights no longer increase. The concept of a fully developed sea is basic to wave forecasting and to estimating the maximum wave height that may occur at a given site.

A real sea is composed of waves of seemingly randomly varying lengths, heights and periods. Oceanographers attempt to make order of such chaos by characterizing the sea in terms of a so-called significant wave. A significant wave is defined as the average of the highest one third in a wave train over a given period of time. The tabulation below, compiled from data given in reference [5], gives the significant wave heights to be expected at sea for a uniform wind of constant velocity provided the wind blows over the minimum fetch and for the minimum duration.

Wind Velocity	Significant Wave Height	Minimum Fetch	Minimum Duration
(knots)	(feet)	(nautical miles)	(hours)
10	1.4	10	2.4
20	8.0	75	10.0
30	22.0	280	23.0
40	45.0	710	42.0
50	78.0	1420	69.0

For wind velocities greater than 50 knots, fetch lengths and/or minimum durations required to develop the sea fully are seldom obtained. Approximate relationships between significant wave height and other statistical values are as follows:

Average height	0.64
Significant	1.00
Highest 10%	1.29
Highest	1.87

Wave height (H) is the distance from trough to crest and wave length (L) is the distance between successive crests (see Figure 4). The period (T) is the time taken for two successive crests to pass a fixed point.

Wave speed (C), sometimes referred to as celerity to emphasize that it is the wave form that is moving and not the water itself, is related to the period by the approximate relation:

$$C = 5.12\ T$$

for C in feet per second and T in seconds, and the length in feet is:

$$L = 5.12\ T^2$$

These relations are valid for so-called *deep water* waves where the water depth (d) is greater than about half the wave length. When waves approach shallow water, or shoal, their heights begin to increase and lengths decrease until the particle velocities in the wave crest exceed the retarded forward motion and the wave breaks. The speed of shallow water waves, where d is less than L/2, is given by: $C = \sqrt{gd}$ where g is the acceleration of gravity and d is the water depth as before. These formulas, based upon Airy's small amplitude wave theory [17], are summarized in Figure 5.

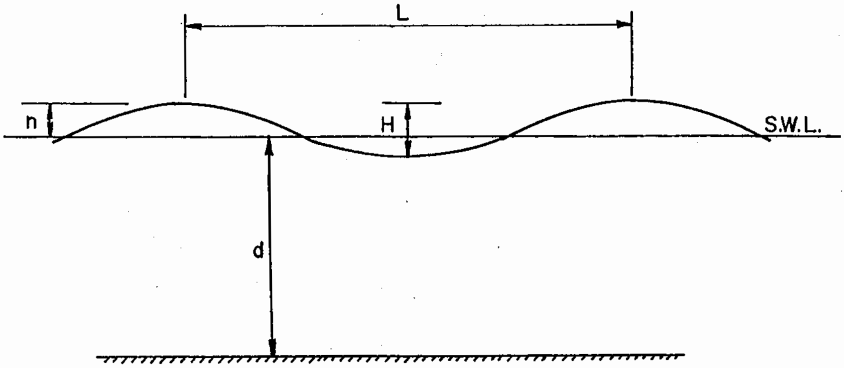


Figure 4. Wave Definition Sketch

Waves in the open ocean generally begin to break when their steepness (H/L) exceeds 1/10 approaching the theoretical limit H/L = 1/7. The maximum crest elevation (n) is usually from .55H to .75H above the nominal still water level (S.W.L.). This fact may determine the bottom elevation of a fixed offshore platform; for example, when the maximum crest elevation of the design wave is added to the maximum storm water depth.

The concept of a *design wave* [18] and [19], which is a wave of selected dimensions to give maximum structural loadings, is based on forecasting techniques and statistical analysis of the probability of such a wave occurring at the site. It is customary to select a design wave height and period and then choose an appropriate wave theory for the water depth and site conditions which will yield the water particle velocities and geometry of the wave surface.

Waves impose various types of loads on various types of structures. The basic kinds of structural loadings result from the wave patterns illustrated in Figure 6. Fairly massive structures situated in shallow water may be subjected to breaking wave pressures. Waves typically break when the water depth becomes less than 1.3H, or if the water depth is too great for the wave to break, it may be reflected by the structure, imposing very different pressure distributions for each case.

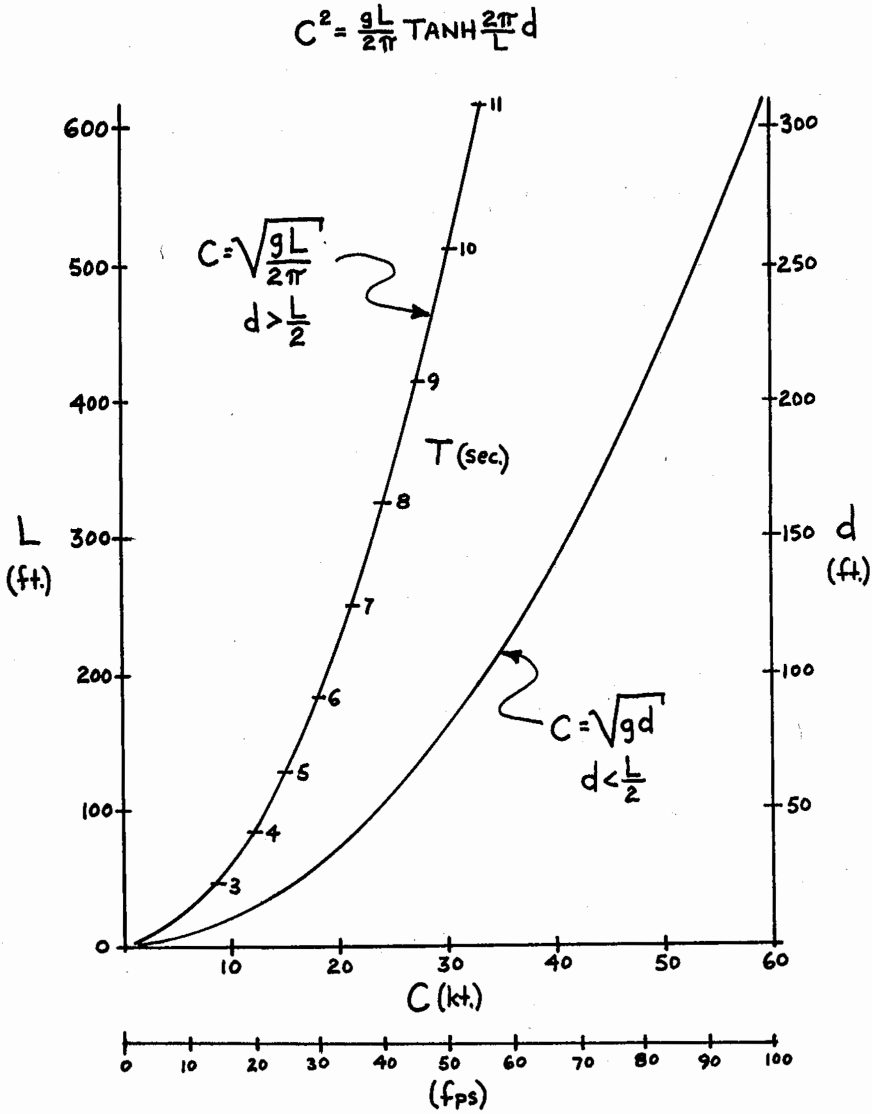


Figure 5. Wave Speed vs. Wavelength and Water Depth

Breaking waves impose by far the highest peak pressures as the full energy of the wave impact has to be dissipated on the structure. Reflected waves of the same height impose much milder loadings as their energy is used in forming new waves and in running up the face of the structure. For example, Denny [20] found the maximum shockwave pressures to range from 28 to 100 times γH (where γ is the unit weight of water and H is the incident wave height) for breaking waves, while Minikin [10] suggests a design value of 1.66H for reflected wave pressures. In addition to direct inertial loadings breaking waves cause scour at the base of structures and high velocity vertical water movements that may shear off appurtenances on the face of the structure. Concrete and stone walls may eventually be destroyed by a repetitive water hammer or air compression effect when pockets of water or air are trapped in crevices in the face of the wall. Sand entrained in breaking waves can have a tremendous abrasive effect and quickly erode bulkheads and retaining walls located on sandy beaches.

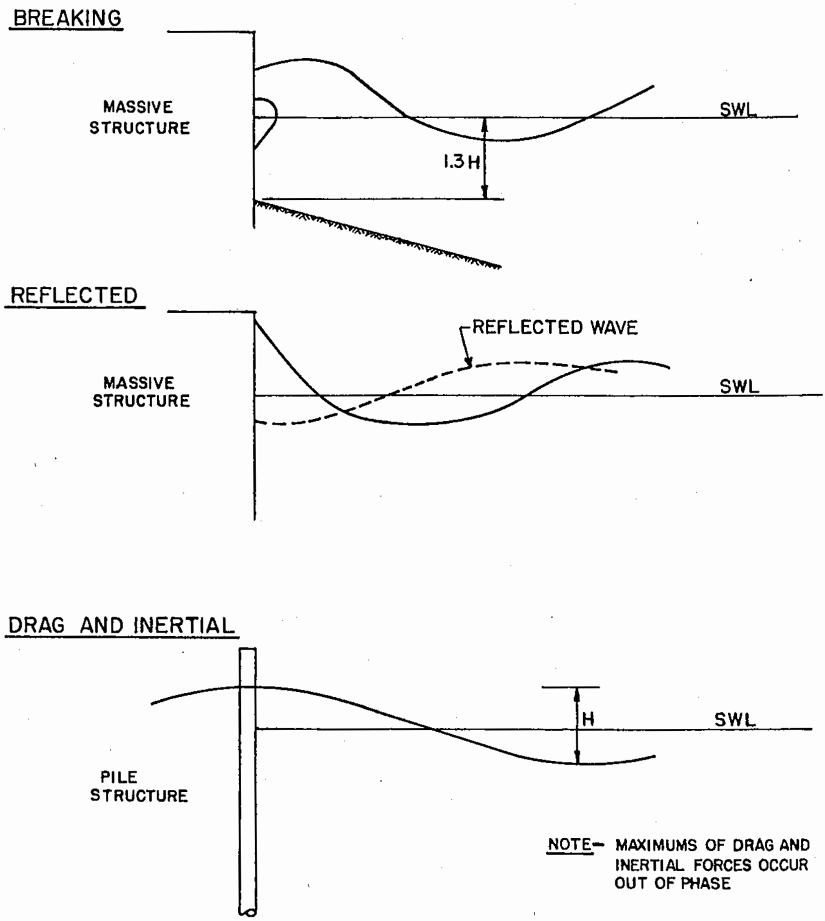


Figure 6. Types of Wave Forces

Waves also exert drag and inertial forces in deep water open type structures. It is customary to calculate the drag and inertial components of force independently and then add them vectorially as maximums occur out of phase. The maximum drag force occurs at the wave crest position where water particle velocities are maximum, and the peak inertial force occurs about one quarter of the wave length after the passage of the crest where the water particle accelerations are greatest. Standard methods of wave force calculations are given in references [5], [9], and [14].

When waves approach a shoreline or fixed barrier they change direction, called refraction and diffraction respectively, just as light changes direction in passing from one medium to another. Refraction and diffraction studies are of the utmost importance in planning many coastal facilities, particularly shore protection structures such as breakwaters and jetties. Such topics are beyond the scope of this paper, as are littoral processes such as rip and longshore currents set up by breaking waves, and transport of beach sands, all of which are well covered in references [12] and [14].

Currents

Major ocean currents are of two different types: the surface wind-driven currents that form the great clockwise gyres in the northern hemisphere, counterclockwise in the southern hemisphere, and the deeper running thermohaline circulation that responds to differences in density of water masses. Although the ocean circulation is of intense interest to the oceanographer, it is not usually a consideration in structural design as the major ocean currents are slow moving and remote from shore. Nearshore and over the continental shelves, tidal currents and storm generated wind-stress currents are of primary interest to the structural designer. Offshore, tidal currents are rotary, changing in speed and direction through all points of the compass during a tidal cycle; while along coastlines and in harbors and estuaries they are reversing, flowing in opposite directions during flood and ebb.[1] Nearshore tidal currents range from speeds of 1 knot (1 nautical mile per hour) or less to extremes of 8 knots or more. During spring tides they may run 20% or more in excess of their normal velocity. The usual vertical distribution of current speed in shallow water shows minimum speeds (*strengths*) at the bottom, with maximum velocity occurring near the surface. However, in many river entrances and harbor channels, flood and ebb currents may flow in opposite directions at the surface and on the bottom during the changing of the tide. In lieu of actual measurements the vertical profile can be assumed to vary as the one-seventh power of the water depth [21], [22], & [23] as shown in Figure 7.

[1]Incoming currents corresponding to a rise in water level are called *flood* currents (or tides) while outgoing currents and falling water levels are referred to as *ebb* currents (or tides).

Strong winds blowing for durations of 12 hours or more set up wind stress surface currents which usually run at about 1% to 3% of the nominal wind speed. Wind stress currents flow 15 to 45 degrees to the right of the wind direction in the northern hemisphere and to the left of the wind in the southern hemisphere due to deflection by Coriolis[2] force. Wind stress currents diminish rapidly with depth, however reference [22] suggests assuming a linear distribution from zero at the seabed to maximum at the sea surface. Figure 7 shows the vectoral addition of tidal and wind stress currents to yield the final design profile. The *Tidal Current Tables* published annually by the National Oceanic and Atmospheric Administration (N.O.A.A.), National Ocean Survey, contain valuable information on both tidal and wind driven currents for United States coastal waters.

The possibility of dynamic effects such as induced vibrations via vortex shedding[3] should be considered, especially at shallow water sites with fast currents. Current velocities should be added vectorially to the design wave particle velocities to get the maximum total forces to be expected. Currents opposing the wave direction have the effect of increasing wave heights and

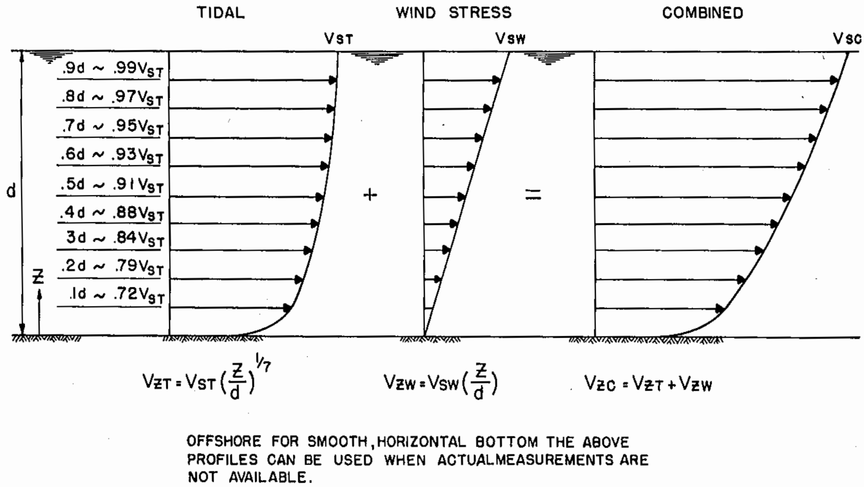


Figure 7. Current Velocity Profiles Assumed for Structure Design

[2]Coriolis force is not really a force at all but is the apparent deflection of a particle trajectory due to the rotation of the earth. It is most pronounced near the equator and least effective near the poles.

[3]Vortex shedding is the fluid dynamic phenomenon of vortices being shed from the trailing edge of a body in a stream. At certain relative flow speeds vortices may be shed alternately from one side and then the other of a flexible structure, which exacerbates this process by its own movement; thus resonance is achieved and the structure may vibrate wildly.

steepness, while following currents have the opposite effect. Currents cause scouring at the base of structures, or a newly placed structure may cause currents to drop their sediment load causing unwanted deposition.

Underwater landslides may cause the fastest and most devastating of currents known as turbidity currents. Such currents may rush down a slope at velocities of up to 50 knots and are known to have caused damage to underwater cables [24].

Currents increase the rate of galvanic corrosion. In the case of steel for example, the quiescent rate of corrosion may be doubled by a 2-knot current; the corrosion rate is proportional to water velocity. Currents may also serve as a transport mechanism for marine organisms such as the larval stage of the teredo (to be discussed).

The calculation of current forces can be carried out using the fluid drag equation (already introduced) and applying the proper drag coefficient (C_D). This equation is plotted in Figure 8 for various C_D's at normally encountered current speeds. For moored objects such as ships, it is customary to add to the dynamic drag a friction drag component by multiplying the immersed surface area, the square of the velocity, and a semi-empirical coefficient [9]. Also, a term for complicated appendages may be added, such as the additional drag caused by a ship's propeller. Another approach is to conduct model tests to get the dynamic portion of the current drag. The results of model tests of similar structures can be pro-rated using the laws of similitude. Reference [11] presents model test data for several ship types in various current speeds through all angles of yaw.

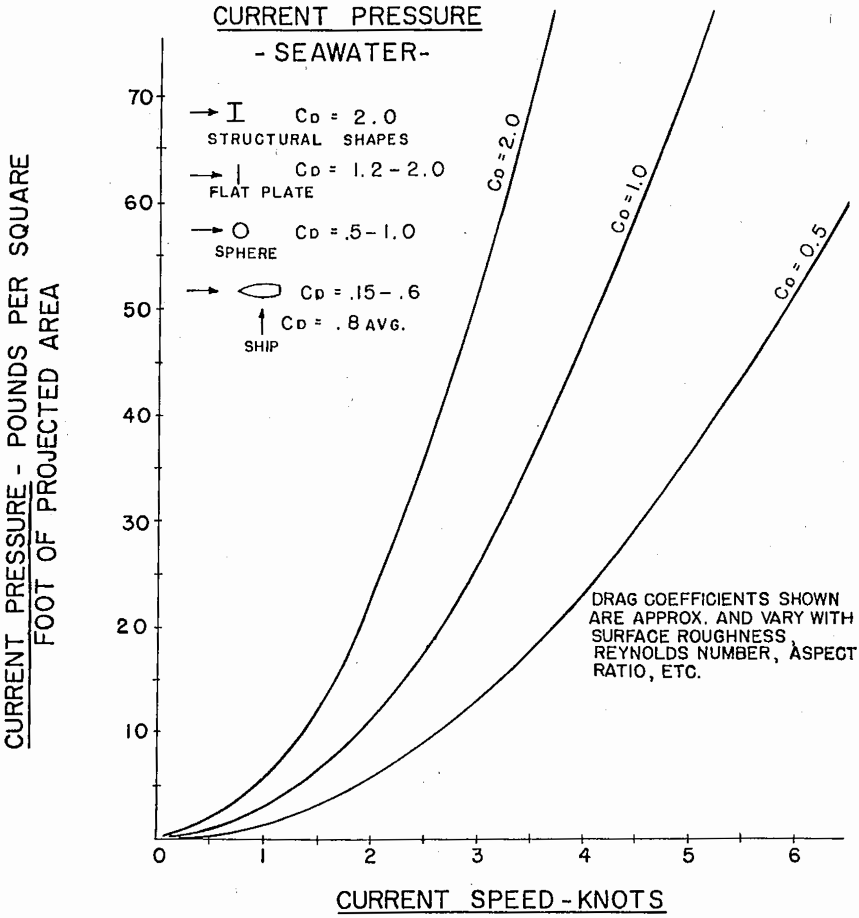
It is important to recall that drag coefficients vary with Reynolds number, aspect ratio, configuration and surface roughness. Local proximity effects, as for example of bracing in multi-legged platforms should be considered as they tend to increase drag forces. In special cases where an accurate assessment of current loads must be made, it would be wise to consider also an added mass effect due to the unsteady nature of the loading. During design the effects of fouling should be accounted for by an appropriate increase in projected area and/or surface friction coefficient.

Tide

Tide is a vertical rise and fall of the ocean in response to the gravitational attractions of the sun and moon. As gravitational attraction varies with the square of the distance, the relative closeness of the moon means that tidal variations closely follow the moon's motion. At times when the sun and moon are in line with respect to the earth, their gravitational effects are additive and higher than average *spring tides* result. Tidal ranges are correspondingly lower with *neap tides,* when the moon is at quadrature.

Tidal datums such as mean low water (MLW) as used in the United States serve as *bench marks* (reference datums) to engineers working in the ocean and the meaning of them and extreme variations from them must be well understood. Tidal datums for the world are well covered in reference [25]. All tidal datums should be based on a 19-year averaging period as the moon completes a cycle of characteristic motions during this period of time.

Tides vary in the number and extremes of highs and lows each day. The normal tide is a *semi-diurnal* type exhibiting two highs and two lows of about equal height, each day. The normal semi-diurnal interval is about 6 hours and 13 minutes between highs and lows. The semi-diurnal tide normally



From Dynamic Drag Equation: $P = \frac{1}{2}\,\frac{8}{9}\,V^2\,C_D$

For V in fps and P in psf: $P = V^2 C_D$

Figure 8. Current Pressure vs. Current Speed

begins its rise from low water at an increasing rate to about mid-height whereupon the rate of flood decreases until high water. A period of *stand* of about one hour is normally observed where the water remains at relatively constant elevation.

Tides are modified by Coriolis force, shape and location of land, friction and inertial forces and locally by other oscillations of the sea surface. At some locations one high and one low water a day are observed; this is known as a *diurnal* tide. Tidal variations somewhere between semi-diurnal and diurnal tides are known as *mixed tides.* Figure 9 presents typical tide curves for several U. S. ports which illustrates the variations discussed. Tides also go through more subtle seasonal variations such as perigean and apogean tides, occurring when the moon is closest and farthest from the earth respectively, and those variations associated with the moon's declination and long term aberrations and earth's distance from the sun. Tide prediction is very complex and it is sufficient to rely on published tide tables for most engineering purposes. Tide tables are published annually by N.O.A.A., National Ocean Survey, which cover most all world ports in four volumes.

Storm Tide

During periods of intense storm activity the reduced atmospheric pressure allows a rise in sea level. This rise due to reduced barometric pressure alone may be on the order of 1 to 2 feet (.3 to .6 meters). A good rule of thumb is that a 1 foot rise in sea level corresponds to about a 1 inch drop in a mercury barometer. Dynamic enhancement of this effect may occur in some locations when the storm low pressure center moves at a synchronous speed with the shallow water wave velocity.

High winds blowing onshore or even parallel to shore may cause water to pile up against the land due to wind stress and its associated surface currents [26]. In some areas, especially in narrow estuaries, this pile-up may amount to several feet.

If both barometric and wind stress tides occur at the same time as spring tides, exceptionally high water elevations may be reached. The frequency and probability of extreme high tides for the U.S. Atlantic Coast is covered in reference [27]. When working in areas where storm records do not exist the engineer should investigate carefully potential extreme high water conditions, as such conditions can exert an excessive buoyant uplift on a structure or cause overtopping and consequent flooding.

Figure 10 summarizes factors contributing to extreme high (design) water levels. Beaches are susceptible to a *wave set-up* in water level in addition to the barometric and wind stress tides previously discussed. Hansen [28] found the maximum set-up can reach values of up to 30% of the incident significant wave height at the set-up line.

Reference [14] lists high water records for various U.S. coastal locations and gives graphs for estimating values of storm surge. In general, storm surge

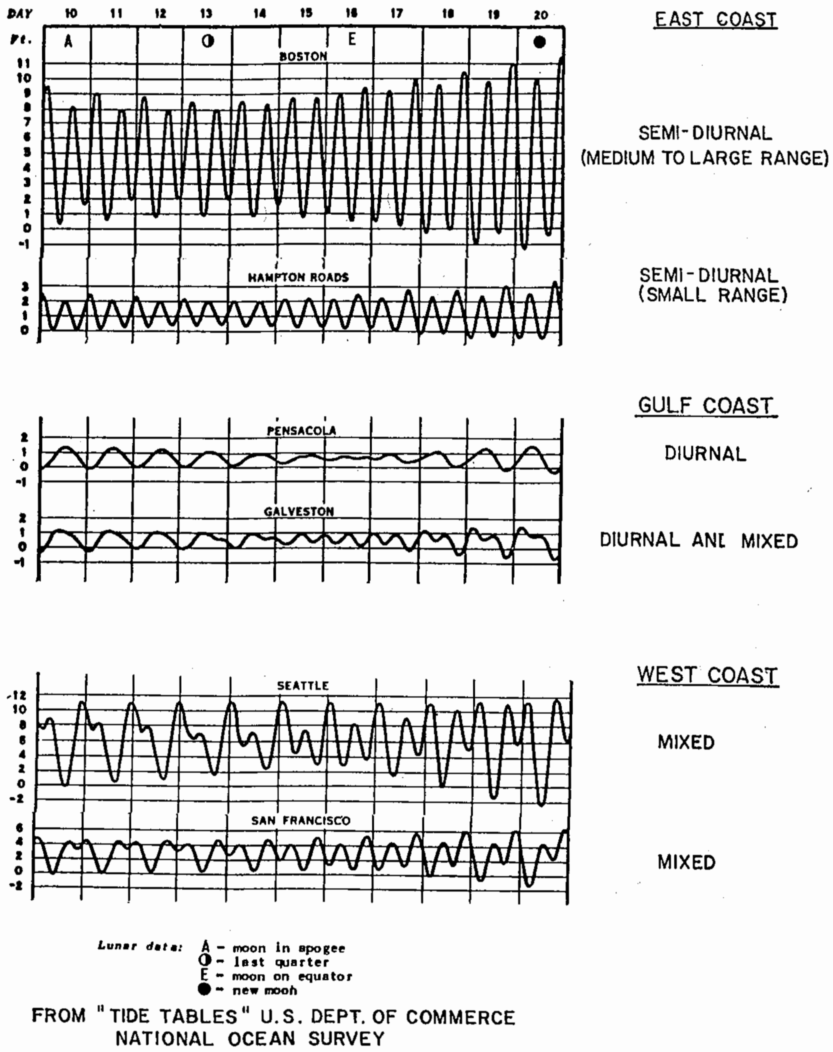


Figure 9. Typical Tide Curves for Selected U.S. Ports

calculations are carried out by experienced meteorologists and oceanographers using high speed computers.

For structures with long design lives some designers may add an increase in design water level to account for the long term rise in sea level which averages approximately ⅛ inch/year (.34cm/yr.) for the coastal United States. This centennial rise is discussed in detail by Hicks and Shofnos [29].

Special Considerations

Other considerations of particular concern at certain locations, but not of general concern, include forces of impact, harbor oscillations, seismic sea waves (tsunami's), fatigue and wear, and geological conditions peculiar to the marine environment.

Impact should be considered in structures that are likely to have vessels moored alongside or that are exposed to floating debris (flotsam), logs or icebergs, for example. Impact forces are normally calculated by energy methods assuming a mass and velocity, and direction and angle of incidence of the impacting body. Designing for berthing ships and impact forces is discussed in references [9] and [13].

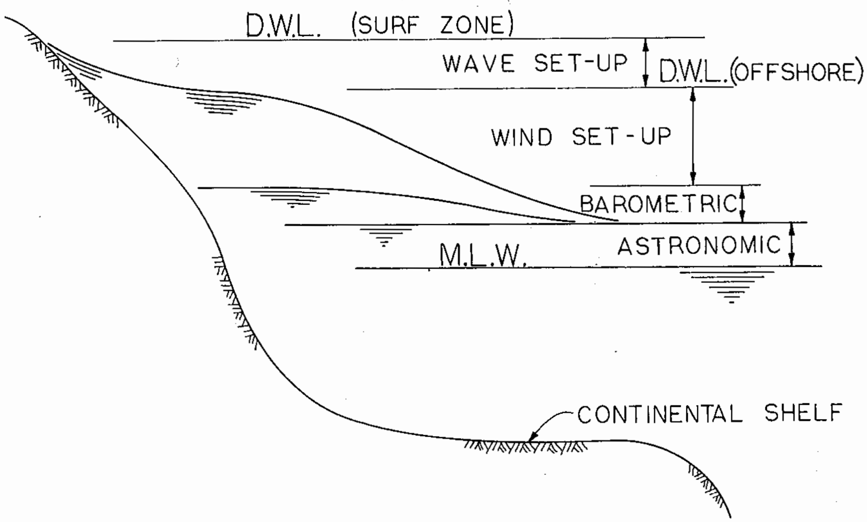


Figure 10. Design Water Levels (Storm Tide)

Certain harbors and even larger basins open to the ocean experience a sloshing motion manifested in a periodic rise and fall of water level due to resonance with a disturbing force. The disturbing force may be meteorological, such as a low pressure system travelling rapidly eastward, or oceanographical, such as the period of wave trains at the mouth of a harbor coinciding with the natural period of oscillation of the harbor basin. Such harmonic oscillations in harbors are known as *seiches.* Seiches may be of critical importance in the planning of ports and harbor facilities [13] but are beyond the scope of this paper.

Very high velocity waves of long wave length but small height, are produced by underwater earthquakes and landslides. Such seismic waves are called "tsunami's" (Japanese for tidal wave!) and travel near the maximum theoretical wave speed: $C = \sqrt{gd}$, governed only by the depth of water and the acceleration of gravity. When such waves approach a shoreline their height builds tremendously, even though they may not even be detectable at sea, causing large scale destruction and flooding of coastal facilities in the more severe instances [3].

The susceptibility of a structure to tsunami waves should be considered in the siting as it may be virtually impossible to design a tsunami-proof structure because of the tremendous forces and high water levels involved. Van Dorn [30] summarizes the engineering aspects of tsunamis. Direct earthquake effects should of course be considered as in the design of land-based structures. The ocean however, may provide a greater damping effect than observed in shore structures.

A *tidal bore* is a single wave front charging up a narrow estuary. Bores exist only in a few locations, such as in the Petitcodiac River in the upper regions of the Bay of Fundy, and their influence on structural design would require designing for the full impact of a wall of water travelling at a given velocity. Since bores exist only under special topographic conditions, they are not considered further here.

Because of the repetitive and periodic nature of wave loadings, fatigue should be considered in the design of offshore structures, especially if the structure is susceptible to vortex shedding and induced vibrations. When the period and amplitude of waves of significant spectral energy are predicted for various storm conditions they can be compared with the natural periods of oscillation of the structure itself.

Floating structures are particularly susceptible to the resonant effects of waves and wave trains and may respond to many different wavelengths and their corresponding frequencies in a wave spectrum if there is sufficient energy in that spectral band. Floating breakwaters in particular should be carefully investigated in this respect [4].

Wear and chafe is a constant problem at sea, especially of mooring lines and cables where they lead across or are attached to a structure. Extra thickness of metal or metal rubbing plates should be provided where such wear is likely.

The ocean bottom is typically covered with a layer of detritus material and dead organisms which have settled to the bottom. In the open sea, oozes[4] and fine sediments may be many feet thick and present obvious foundation problems. Harbor bottoms are typically covered with a black organic silt which must be accounted for when making soundings to firm bottom.

[4]Oozes are the accumulation of the calcareous and/or silicious skeletons of tiny marine organisms that have settled to the bottom after the organisms' death.

Ice

Ice exerts uplift and crushing forces on structures and adds to the gravity loads. Ice freezing around a pile may lift it on a rising tide. This is usually a progressive process and is called *jacking*. Ice sheets held against a structure by wind or current stress or constrained ice which is subject to expansion due to a rise in temperature develop a horizontal thrust which is proportional to the ice thickness. Gerritsen [31] discusses the effects of ice on hydraulic structures.

Some typical values of the mechanical properties of sea ice are summarized in Figure 11. These values are based upon a review of a wide range of experimental results and should be applied with caution as the properties of sea ice are difficult to predict and vary greatly with temperature, salinity, age and rate of freezing etc. Brown [32] has summarized the results of some recent investigations into arctic ice mechanics.

Ice expands 9% in volume on freezing due to a rearrangement in the crystal lattice of water molecules; therefore care must be taken not to create pockets where the freezing water does not have adequate room to expand. Frost heaving in pavements and freeze-thaw damage to concrete are problems caused indirectly by the expansion of water on freezing.

Impact of raft ice being carried by wind or current must be considered in exposed locations. Ice floats with greater than 90% of its volume below the surface and may travel at up to about 7% of the wind speed.

Marine Corrosion

Corrosion, in general, is due to an electro-chemical process whereby atoms of a given metal lose electrons (oxidation) thus becoming positively charged. The free electrons then combine (reduction) with atoms of an adjacent area or surrounding substance. The migration of electrons (an electric current) from an *anodic* area to a *cathodic* area may be caused by, or accelerated by, various conditions. Corrosion can be classified according to the conditions or type of electro-chemical process. Some of these processes are briefly mentioned here.

General and pitting corrosion is exhibited by the scaling or pitting of the surface of one metal from reaction with its surroundings and/or a difference in potential between different areas of the same metal. All metals form a thin oxide film when exposed to the atmosphere. This protective film is more or less easily broken down or washed away in some types of metals resulting in further corrosion. Water, especially sea water or acidic water, serves as a transport medium (electrolyte) for electrons and thus accelerates the corrosion process. Alternate wetting and drying accelerates the corrosion process by successively washing away layers of oxide film.

PROPERTIES OF SEA ICE*

SUGGESTED DESIGN VALUES

FOR GENERAL ENGINEERING PURPOSES

SPECIFIC GRAVITY	-	.86 to .92 (average values)
COMPRESSIVE STRENGTH	-	400 to 600 psi (up to 3000 psi for pure fresh water ice)
TENSILE STRENGTH	-	100 to 200 psi
SHEAR STRENGTH	-	few test results
MODULUS OF ELASTICITY	-	1.4×10^6 psi
MODULUS OF RUPTURE	-	200 psi
POISSONS RATIO	-	.35
COEFFICIENT OF THERMAL EXPANSION	-	.000028 (average between -20 and 32° F)
COEFFICIENT OF FRICTION	-	.15 metal to sea ice .10 metal to fresh water ice .01 "wet" ice
ADHESION (FOR PILE JACKING)	-	30 to 100 psi
VOLUMETRIC EXPANSION	-	9% (on freezing) maximum pressure exerted: 30,000 psi

*Above values to be used in lieu of observations or experimental data. Note well that the properties of sea ice are highly variable with respect to temperature, salinity and the rate of freezing. Ice is an ANISOTROPIC material!

Figure 11. Properties of Sea Ice

Crevice corrosion is formed in isolated areas where less oxygen may be available for the repair of the oxide film than on an adjacent exposed surface; thus, a difference in potential is set up.

Selective corrosion, such as the dezincification of some brasses, is a process whereby one particular metal of an alloy is attacked, eventually destroying the alloyed metal's properties.

Stress-corrosion cracking is a process whereby normal corrosion is accelerated by tensile stresses within the material.

Corrosion fatigue occurs in cyclically loaded members or members subject to continual load reversals. The working of the material accelerates the corrosion process.

Galvanic corrosion is caused by a difference in electric potential of two dissimilar metals in contact or metals near one another in a conducting medium such as sea water. Electric potentials of various metals are known and therefore galvanic corrosion can be avoided by not using metals with large differences in electric potential in the same area.

Corrosion can be initiated by and accelerated by stray electric currents, various marine organisms such as barnacles, and exposure to wear such as the erosion-corrosion of steel sheeting by exposure to wave and sand action. Structural steel corrodes at an average rate of .005 inch (.13 mm) per year in quiet seawater, but pit growth may be up to ten times as much. In comparison, brasses and other copper alloys corrode at an average rate of .001 inch (.03 mm) per year under the same conditions. Moving water accelerates corrosion of all materials.

Corrosion of steel piles in seawater often follows a characteristic vertical distribution [33]. The rate of corrosion, for example, in a vertical pile is typically light to moderate in the upper part exposed only to the atmosphere as only oxidation corrosion with atmospheric moisture takes place. In the *splash zone* where the structure is intermittently wetted and dried and the protective film of corrosion is continually washed away, the rate of corrosion is usually the greatest; perhaps 3 to 5 times as great as that exposed only to the atmosphere. Just below the high tide mark it often decreases to near minimum as this zone is somewhat protected by an oxygen concentration cell effect; however, in some structures, other than vertical piles, corrosive attack may be heavy in this zone. Increased rates are also found near the low water mark. The rate may be relatively uniform in the continuously immersed portion of the pile, but greater in the upper layers where there is plenty of dissolved oxygen or when there are strong currents to accelerate the galvanic effect. Below the mud line corrosion becomes minimal as there is little or no oxygen present and protective films remain intact. Sometimes, however, increased corrosion rates are observed just above the mud-line due to the prescence of sulfate reducing bacteria.

Corrosion can be minimized by functional design, proper selection of materials, protective coatings, inhibitors, impressed currents, and cathodic protection systems using sacrificial anodes. When dissimilar metals are used a galvanic series table should be consulted to verify the potential difference between them. Functional design details would include the avoidance of overlapping plates, discontinuous welds, and connection details that provide crevices or stress concentrations. The use of back-to-back angles or open-ended tube and pipe sections that cannot be maintained is tantamount to inviting future problems.

Marine corrosion in general is well covered in reference [34].

Decay

Wood structures are vulnerable to attack by various forms of fungi, this attack being generally known as *rot.* White rot manifests itself in a bleached, whitish appearance of the wood surface. Brown rot or dry rot sometimes leaves a brown powder residue and the wood surface is visibly eaten away and punky. Fungi require air, water, food and warmth to live and reproduce. Rot will cease when one or more of the above is removed. Isolated areas where fresh water has been trapped are where rot is generally found. Preventing fresh water from collecting is the best way to help prevent rot. Painting and sheathing exposed surfaces also helps in preventing rot from starting and adequate ventilation helps to evaporate trapped moisture.

Marine Borers

Certain mollusks, members of the teredinidae and pholadidae families, and crustaceans, the limnoria, chelura and sphaeroma, bore into and destroy timber exposed in sea water. In general, destruction by marine borers occurs from the high tide level down to the mud line; however, borer attack is usually concentrated from the low water level to the mud line.

The nacerda, known as the *wharf borer,* makes its home in decayed timber above high water. It is a beetle about ¼ to ½ inch (6 to 12 mm) long; its whitish grub is about 1 inch (25 mm) long and it eats into and destroys timber [35].

The molluscan borers enter the wood as larvae and only a pinhole is visible at the surface. The borer matures inside the wood, tunneling as it grows, leaving the wood porous on the inside.

The teredo (*shipworm*) is by far the most common and destructive borer. Adult teredos have been recorded as large as 2 inches (50 mm) in diameter and up to 6 feet (2 meters) long. More commonly, they are about ½ inch (12 mm) in diameter and from 6 to 10 inches (15 to 25 cm) long in the tropics and smaller on the average in more temperate climates. They typically line their tunnels with a calcareous deposit. They have a hard, clam-like shell with which they rasp through the wood; their slender, cylindrical bodies are mostly outside the shell. The teredo and its close relative the bankia are generally inactive in water of salinity less than 8 parts per 1000.

The pholads, the martesia being the most common, are known to bore into clay, soft rock, and porous concrete. The martesia's body fits entirely inside its shell and it generally makes a smooth oval pocket exposed at the surface of the wood.

The limnoria (*wood gribble*) is the most common and destructive of the crustacean borers. The limnoria is an isopod usually about ⅛ inch (3 mm) to ¼ inch (6 mm) long. The limnoria eats away at the surface of the wood making shallow furrows which are easily washed out, exposing more surface for attack. Timber piles attacked by limnoria have an hour glass, necked-down, appearance from the mud line up to the low water level. Limnoria are sensitive to salt content and are generally inactive in salinities below 12 to 16 parts per 1000.

Both molluscan and crustacean borers are distributed worldwide and are relatively abundant as far north as the Arctic circle and as far south as approximately latitude 60 degrees. They are most active in the warmer climates, since in the teredo especially the breeding period is regulated by water temperature [36].

If timber must be used in waters known to be infested, it would be preferable to use a naturally resistant (dense) wood, such as greenheart, azobé, angelique, or other tropical hardwood. Pressure treatment slows down the initial attack but is of little effect in the tropics. Structural woods, such as oak and douglas fir, are not amenable to pressure treatment. Most pines will accept creosote treatment, the normal specification being 16 to 24 pounds per cubic foot (.26 to .39 g/cc.) applied under pressure to a minimum penetration of 4 inches (10 cm).

Various methods of sheathing such as ship's felt with creosoted sheathing boards, metal cladding, and plastic wrapping, have had varying degrees of success. Various systems of impressed alternating currents have been tried without great success. Below the mudline, however, wood will last indefinitely. A new structure in a non-contaminated area will not be attacked unless an infested piece of wood is brought into the near vicinity.

Fouling

Fouling is the attachment of marine organisms to exposed surfaces. Fouling of newly immersed clean surfaces usually follows a characteristic temporal pattern; however, the attachment of the many types of organisms involved may vary widely with local conditions [37]. Within the first week, bacteria and algal slimes give the surface a slimy appearance and form the foundation for the attachment of higher life forms such as hydroids and barnacles and possibly serpulids (tube worms) which usually thrive after three weeks or more immersion in normal temperate to tropical climates. After approximately ten weeks' immersion, larger sessile organisms such as grasses (actually marine algae), tunicates *(sea squirts),* and mussels become prevalent. Fouling organisms are prolific in the euphotic zone (zone of light penetration which extends 500 to 600 feet, 150 to 180 meters, below the sea surface) and taper off rapidly at greater depths.

Barnacles are probably the most tenacious of fouling organisms and are capable of attaching themselves in water velocities of up to 4 knots. Present day anti-fouling paints may discourage such organisms for periods of up to possibly two years after which time they begin to proliferate. Systems of impressed electrical currents have been employed to eliminate fouling with varying degrees of success. Some alloys such as the copper-nickel alloys, which unfortunately are far too expensive for structural members, exhibit a natural resistance to fouling [38].

The effect of fouling on structural design is to increase both gravity and especially wave and current loads by increasing projected area and surface roughness. In the tropics 6 inches to 1 foot (15 to 30 cm) or more thickness of fouling can be expected on most exposed surfaces. In piling, for example, marine growth can increase the effective pile diameter by a factor of 2 or more. Fouling, therefore, should be considered in current and wave load calculations and structural members should be designed with ease of cleaning and maintenance in mind. The attachment of marine organisms, such as barnacles, may cause differences in electrical potential on the same piece of metal, thus inducing galvanic corrosion.

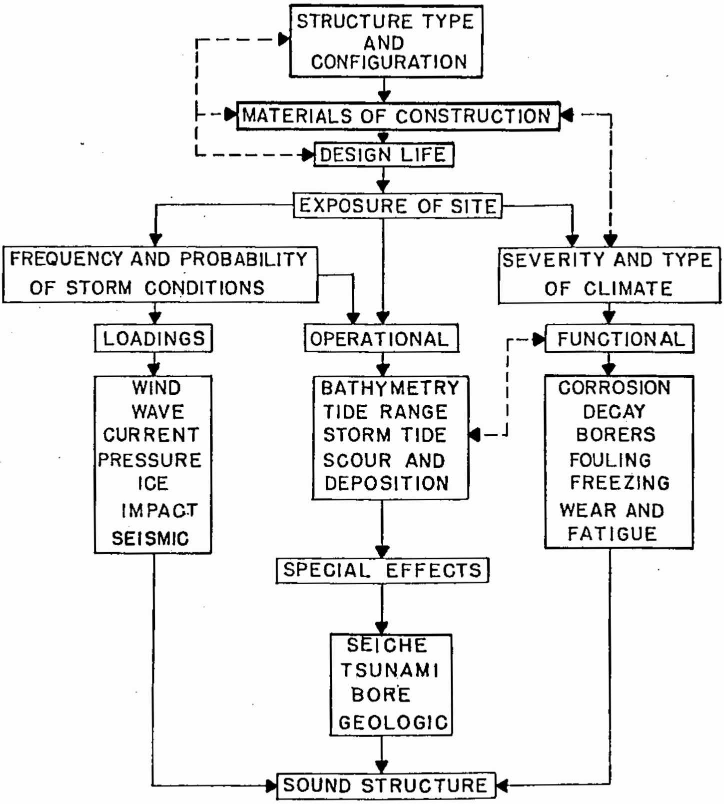


Figure 12. Summary of Design Considerations

Summary and Conclusions

Various factors peculiar to the marine environment, affecting structural design, have been discussed and are summarized in Figure 12. All of these factors should be considered for their potential effect, although they ultimately may not affect a given structure. The ocean environment is one in which environmental loadings must be more carefully investigated than on land-based structures and is an environment in which materials generally deteriorate much more quickly.

Wind, waves, currents, ice, hydrostatic pressure, and impact are the primary sources of loadings a structure must contend with, while it must also stand up to deteriorating agents such as corrosion, attack by marine organisms, wear, and fatigue. It must additionally remain serviceable under the effects of everyday and extreme changes in water levels and scouring and deposition of surrounding bottom material by waves and currents.

There is much work to be done in man's understanding of the ocean environment, of which structural design is an important part, and it is hoped such knowledge will bring about more lasting and compatible structures which will satisfy man's needs while at the same time preserving the beauty and splendor of the oceans.

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