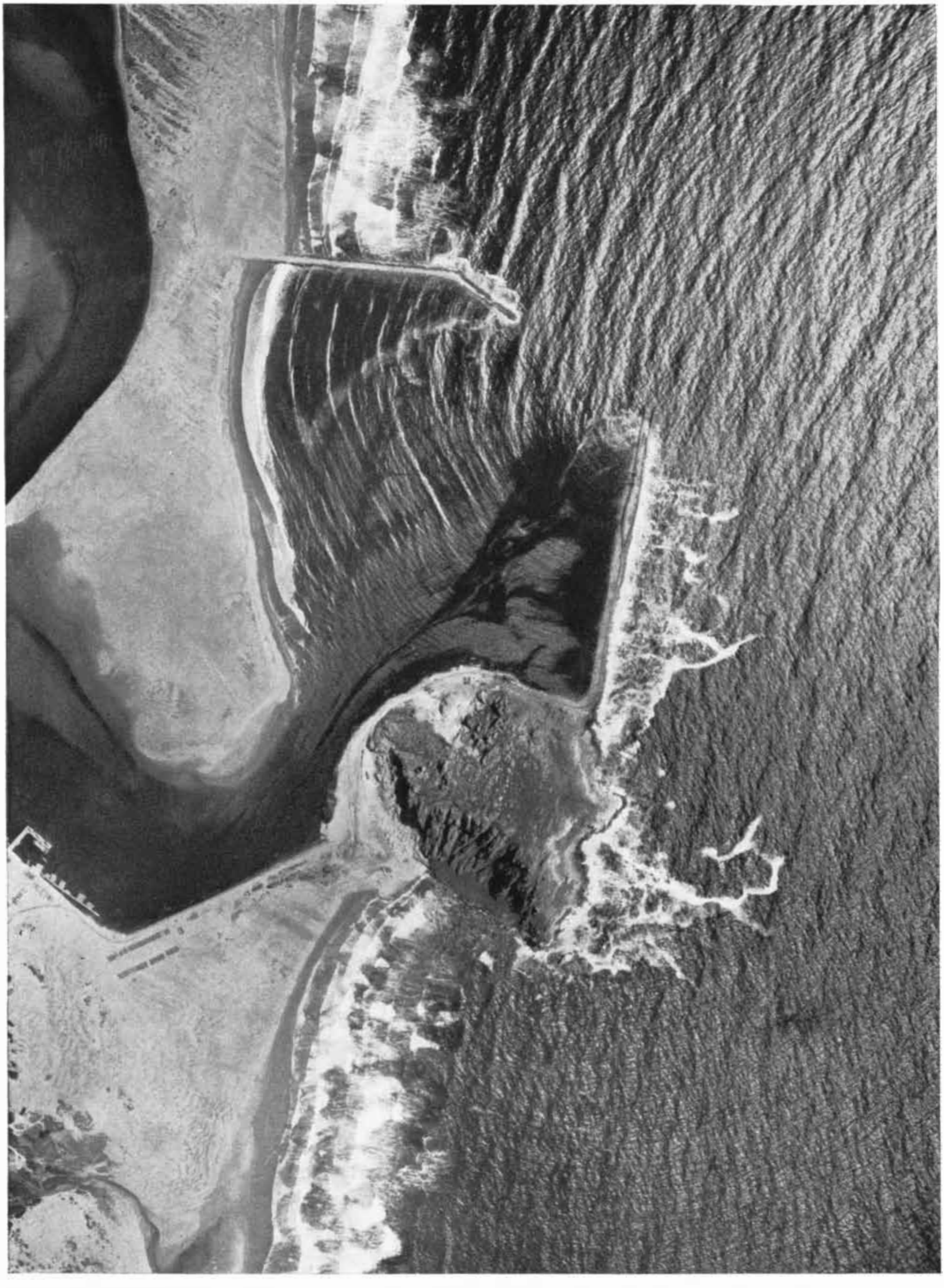


DIFFRACTION OF OCEAN WAVES is clearly visible in this aerial photograph of Morro Bay, Calif. The waves are diffracted as they pass the end of the lower jetty. Variations in the way the waves break are caused by contours of the shore and the bottom.

OCEAN WAVES

Men have always been fascinated, and sometimes awed, by the rhythmic motions of the sea's surface. A century of observation and experiment has revealed much about how these waves are generated and propagated

by Willard Bascom

Man is by nature a wave-watcher. On a ship he finds himself staring vacantly at the constant swell that flexes its muscles just under the sea's surface; on an island he will spend hours leaning against a palm tree absently watching the rhythmic breakers on the beach. He would like to learn the ways of the waves merely by watching them, but he cannot, because they set him dreaming. Try to count a hundred waves sometime and see.

Waves are not always so hypnotic. Sometimes they fill us with terror, for they can be among the most destructive forces in nature, rising up and overwhelming a ship at sea or destroying a town on the shore. Usually we think of waves as being caused by the wind, because these waves are by far the most common. But the most destructive waves are generated by earthquakes and undersea landslides. Other ocean waves, such as those caused by the gravitational attraction of the sun and the moon and by changes in barometric pressure, are much more subtle, often being imperceptible to the eye. Even such passive elements as the contour of the sea bottom, the slope of the beach and the curve of the shoreline play their parts in wave action. A wave becomes a breaker, for example, because as it advances into increasingly shallow water it rises higher and higher until the wave front grows too steep and topples forward into foam and turbulence. Although the causes of this beautiful spectacle are fairly well understood, we cannot say the same of many other aspects of wave activity. The questions asked by the wave-watcher are nonetheless being answered by intensive studies of the sea and by the examination of waves in large experimental tanks. The new knowledge has made it possible to measure the power and to forecast the actions of waves for the welfare of those who live and work on the sea and along its shores.

Toss a pebble into a pond and watch the even train of waves go out. Waves at sea do not look at all like this. They are confused and irregular, with rough diamond-shaped hillocks and crooked valleys. They are so hopelessly complex that 2,000 years of observation by seafarers produced no explanation beyond the obvious one that waves are somehow raised by the wind. The description of the sea surface remained in the province of the poet who found it "troubled, unsettled, restless. Purring with ripples under the caress of a breeze, flying into scattered billows before the torment of a storm and flung as raging surf against the land; heaving with tides breathed by a sleeping giant."

The motions of the oceans were too complex for intuitive understanding. The components had to be sorted out and dealt with one at a time. So the first theoreticians cautiously permitted a perfect train of waves, each exactly alike, to travel endlessly across an infinite ocean. This was an abstraction, but it could at least be dealt with mathematically.

Early observers noticed that passing waves move floating objects back and forth and up and down, but do not transport them horizontally for any great distance. From the motion of seaweeds the motion of the water particles could be deduced. But it was not until 1802 that Franz Gerstner of Germany constructed the first wave theory. He showed that water particles in a wave move in circular orbits. That is, water at the crest moves horizontally in the direction the wave is going, while in the trough it moves in the opposite direction. Thus each water particle at the surface traces a circular orbit, the diameter of which is equal to the height of the wave [*see illustration on next page*]. As each wave passes, the water returns almost to its original position. Gerstner observed that the surface trace of a wave is approximately a trochoid: the curve described by a point on a circle as it rolls along the underside of a line. His work was amplified by Sir George Airy later in the 19th century, by Horace Lamb of England in the present century, and by others.

The first wave experimentalists were Ernst and Wilhelm Weber of Germany, who in 1825 published a book on studies employing a wave tank they had invented. Their tank was five feet long, a foot deep and an inch wide, and it had glass sides. To make waves in the tank they sucked up some of the fluid through a tube at one end of it and allowed the fluid to drop back. Since the Weber brothers experimented not only with water and mercury but also with brandy, their persistence in the face of temptation has been an inspiration to all subsequent investigators. They discovered that waves are reflected without loss of energy, and they determined the shape of the wave surface by quickly plunging in and withdrawing a chalk-dusted slate. By watching particles suspended in the water they confirmed the theory that water particles move in a circular orbit, the size of which diminishes with depth. At the bottom, they observed, these orbits tend to be flattened.

As increasingly bolder workers contributed ideas in the 20th century, many of the complexities of natural waves found their way into equations. However, these gave only a crude, empirical answer to the question of how wind energy is transferred to waves. The necessity for the prediction of waves and surf for amphibious operations in World War II attracted the attention of Harald U.

Sverdrup and Walter Munk of the Scripps Institution of Oceanography. As a result of their wartime studies of the interaction of winds and waves they were the first investigators to give a reasonably complete quantitative description of how wind gets energy into the waves. With this description wave studies seemed to come of age, and a new era of research was launched.

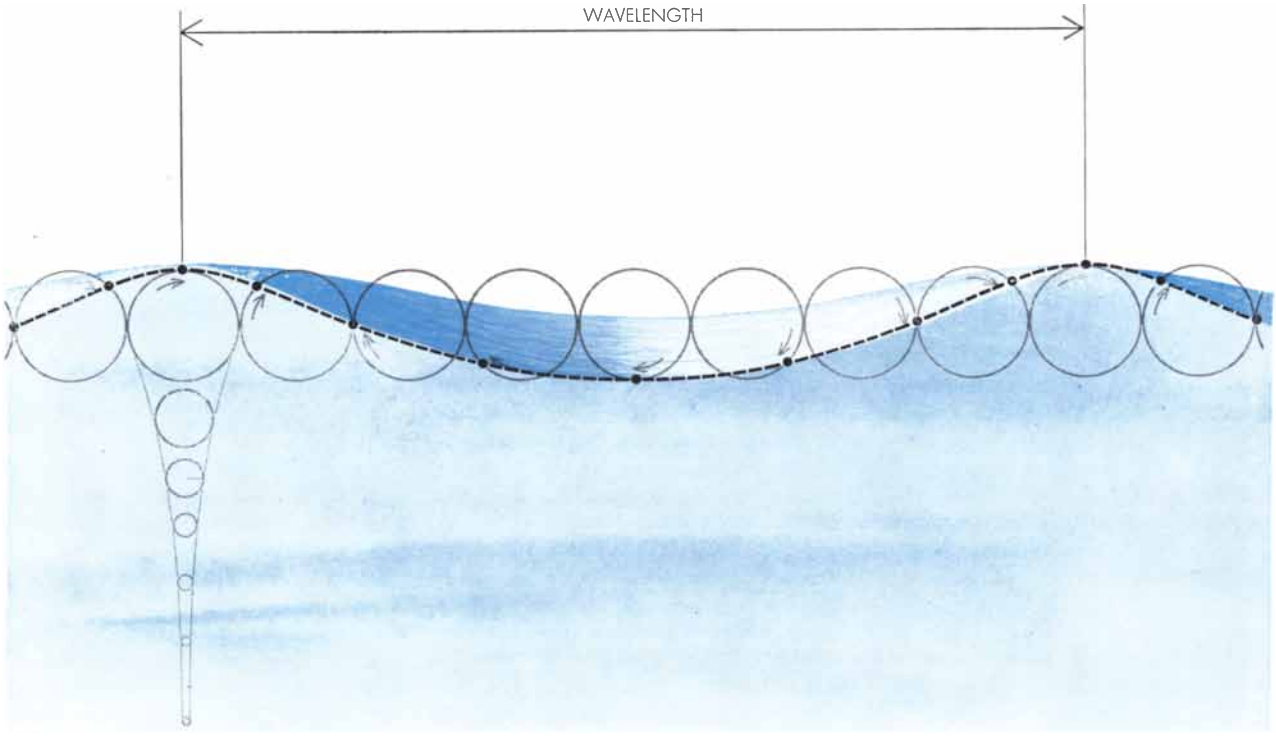
Let us follow waves as they are generated at sea by the wind, travel for perhaps thousands of miles across the ocean and finally break against the shore. The effectiveness of the wind in making waves is due to three factors: its average velocity, the length of time it blows and the extent of the open water across which it blows (called the fetch).

Waves and the Wind

Waves start up when the frictional drag of a breeze on a calm sea creates ripples. As the wind continues to blow, the steep side of each ripple presents a surface against which the moving air can press directly. Because winds are by nature turbulent and gusty, wavelets of all sizes are at first created. The small, steep ones break, forming whitecaps, releasing some of their energy in turbulence and possibly contributing part of it to larger waves that overtake them. Thus as energy is added by the wind the smaller waves continually give way to larger ones which can store the energy better. But more small waves are continually formed, and in the zone where the wind moves faster than the waves there is a wide spectrum of wavelengths. This is the generating area, and in a large storm it may cover thousands of square miles. If storm winds apply more force than a wave can accept, the crest is merely steepened and blown off, forming a breaking wave at sea. This happens when the wave crest becomes a wedge of less than 120 degrees and the height of the wave is about a seventh of its length. Thus a long wave can accept more energy from the wind and rise much higher than a short wave passing under the same wind. When the wind produces waves of many lengths, the shortest ones reach maximum height quickly and then are destroyed, while the longer ones continue to grow.

A simple, regular wave-train can be described by its period (the time it takes two successive crests to pass a point), by its wavelength (the distance between crests) and by its height (the vertical distance between a trough and a succeeding crest). Usually, however, there are several trains of waves with different wavelengths and directions present at the same time, and their intersection creates a random or a short-crested diamond pattern. Under these conditions no meaningful dimensions can be assigned to wave period and length. Height, however, is important, at least to ships; several crests may coincide and add their heights to produce a very large wave. Fortunately crests are much more likely to coincide with troughs and be canceled out. There is no reason to believe that the seventh wave, or some other arbitrarily numbered wave, will be higher than the rest; that is a myth of the sea.

Since waves in a sea are so infinitely variable, statistical methods must be employed to analyze and describe them. A simple way to describe height, for example, is to speak of significant height—the average height of the highest third of the waves. Another method, devised in 1952 by Willard J. Pierson, Jr., of New York University, employs equations like those that describe random noise in information theory to predict the behavior of ocean waves. Pierson superposes the regular wave-trains of classical theory in such a way as to obtain a mathematically irregular pattern. The result is most conveniently described in terms of energy spectra. This scheme assigns a value for the square of the wave height to each



CROSS SECTION OF OCEAN WAVE traveling from left to right shows wavelength as distance between successive crests. The time it takes two crests to pass a point is the wave period. Circles are orbits of water particles in the wave. At the surface their diameter equals the wave height. At a depth of half the wavelength (*left*), orbital diameter is only 4 per cent of that at surface.

frequency and direction. Then, by determining the portion of the spectrum in which most of the energy is concentrated, the average periods and lengths can be obtained for use in wave forecasting.

Over a long fetch, and under a strong, steady wind, the longer waves predominate. It is in such areas of sea that the largest wind waves have been recorded. The height of the waves in a train does not, however, bear any simple relationship to their other two dimensions: the period and the wavelength. The mariner's rule of thumb relates wave height to wind velocity and says that the height ordinarily will not be greater than half the wind speed. This means that an 80-mile-per-hour hurricane would produce waves about 40 feet high.

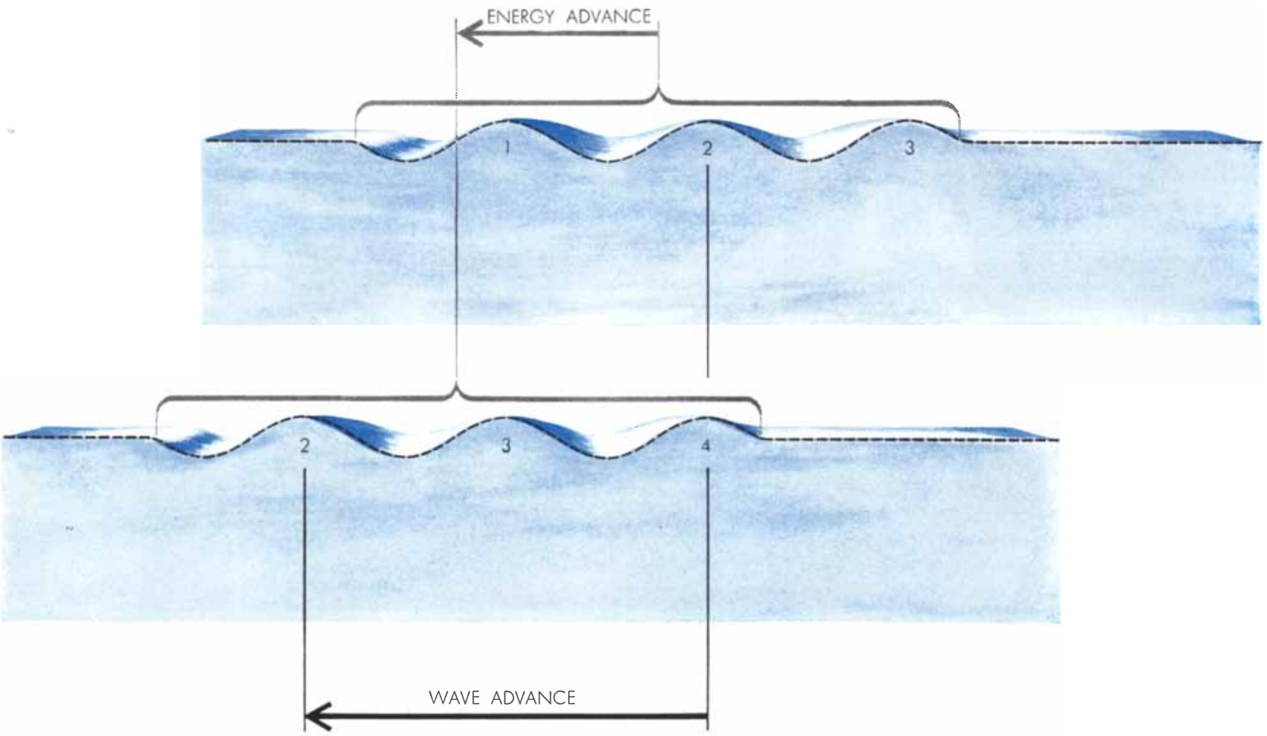
The question of just how large individual waves at sea can actually be is still unsettled, because observations are difficult to make and substantiate from shipboard in the midst of a violent storm. Vaughan Cornish of England spent half a century collecting data on waves, and concluded that storm waves over 45 feet high are rather common. Much higher waves have been fairly well authenticated on at least two occasions.

In October, 1921, Captain Wilson of the 12,000-ton S.S. *Ascanius* reported an extended storm in which the recording barometer went off the low end of the scale. When the ship was in a trough on an even keel, his observation post on the ship was 60 feet above the water level, and he was certain that some of the waves that obscured the horizon were at least 10 feet higher than he was, accounting for a total height of 70 feet or more. Commodore Hayes of the S.S. *Majestic* reported in February, 1923, that his ship had experienced winds of hurricane force and waves of 80 feet in height. Cornish examined the ship, closely interrogated the officers and concluded that waves 60 to 90 feet high, with an average height of 75 feet, had indeed been witnessed.

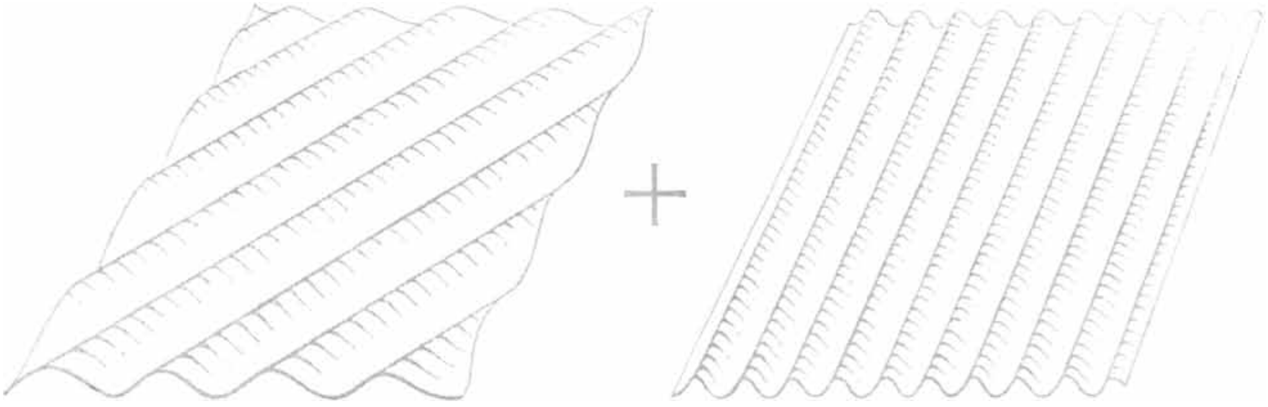
A wave reported by Lieutenant Commander R. P. Whitemarsh in the *Proceedings of the U. S. Naval Institute* tops all others. On February 7, 1933, the *U.S.S. Ramapo,* a Navy tanker 478 feet long, was en route from Manila to San Diego when it encountered "a disturbance that was not localized like a typhoon . . . but permitted an unobstructed fetch of thousands of miles." The barometer fell to 29.29 inches and the wind gradually rose from 30 to 60 knots over several days. "We were running directly downwind and with the sea. It would have been disastrous to have steamed on any other course." From among a number of separately determined observations, that of the watch officer on the bridge was selected as the most accurate. He declared that he "saw seas astern at a level above the mainmast crow's-nest and at the moment of observation the horizon was hidden from view by the waves approaching the stern." On working out the geometry of the situation from the ship's plan, Whitemarsh found that this wave must have been at least 112 feet high [*see illustration at the bottom of the next two pages*]. The period of these waves was clocked at 14.8 seconds and their velocity at 55 knots.

As waves move out from under the winds that raise them, their character changes. The crests become lower and more rounded, the form more symmetrical, and they move in trains of similar period and height. They are now called swell, or sometimes ground swell, and in this form they can travel for thousands of miles to distant shores. Happily for mathematicians, swell coincides much more closely with classical theory than do the waves in a rough sea, and this renews their faith in the basic equations.

Curiously enough, although each wave moves forward with a velocity



MOVING TRAIN OF WAVES advances at only half the speed of its individual waves. At top is a wave train in its first position. At bottom the train, and its energy, have moved only half as far as wave 2 has. Meanwhile wave 1 has died, but wave 4 has formed at the rear of the train to replace it. Waves arriving at shore are thus remote descendants of waves originally generated.



DIFFERENT TRAINS OF WAVES, caused by winds of different directions and strengths, make up the surface of a "sea." The various trains, three of which are represented diagrammatically here, have a wide spectrum of wavelengths, heights and directions. When

that corresponds to its length, the energy of the group moves with a velocity only half that of the individual waves. This is because the waves at the front of a group lose energy to those behind, and gradually disappear while new waves form at the rear of the group. Thus the composition of the group continually changes, and the swells at a distance are but remote descendants of the waves created in the storm [*see illustration on preceding page*]. One can measure the period at the shore and obtain from this a correct value for the wave velocity; however, the energy of the wave train traveled from the storm at only half that speed.

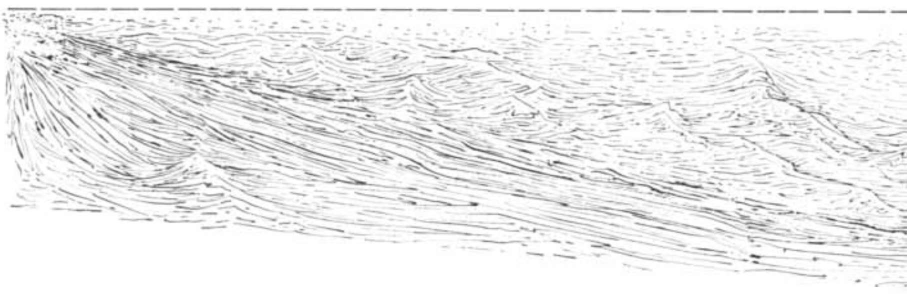
Waves in a swell in the open ocean are called surface waves, which are defined as those moving in water deeper than half the wavelength. Here the bottom has little or no effect on the waves because the water-particle orbits diminish so rapidly with depth that at a depth of half the wavelength the orbits are only 4 per cent as large as those at the surface. Surface waves move at a speed in miles per hour roughly equal to 3.5 times the period in seconds. Thus a wave with a period of 10 seconds will travel about 35 miles per hour. This is the average period of the swell reaching U. S. shores, the period being somewhat longer in the Pacific than the Atlantic. The simple relationship between period and wavelength ($\text{length}=5.12T^2$) makes it easy to calculate that a 10-second wave will have a deep-water wavelength of about 512 feet. The longest period of swell ever reported is 22.5 seconds, which corresponds to a wavelength of around 2,600 feet and a speed of 78 miles per hour.

Waves and the Shore

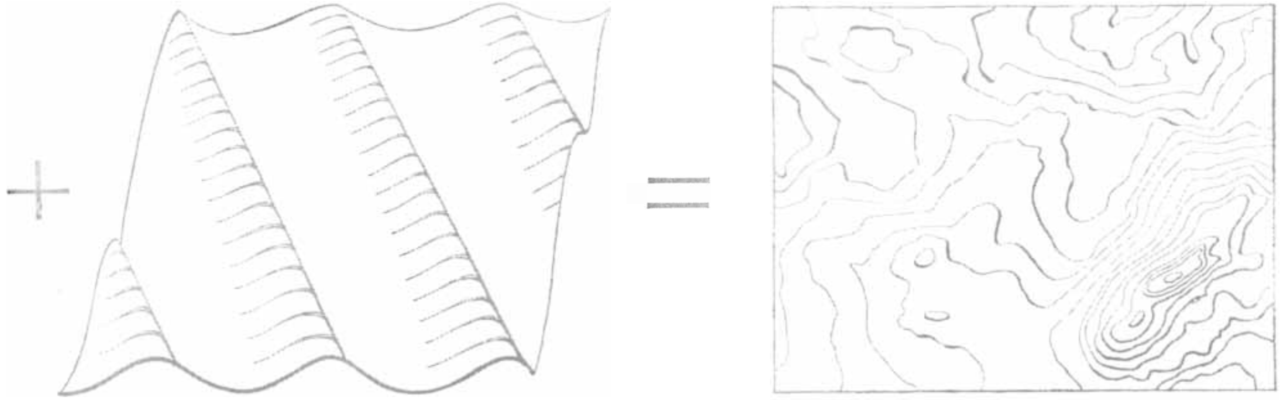
As the waves approach shore they reach water shallower than half their wavelength. Here their velocity is controlled by the depth of the water, and they are now called shallow-water waves. Wavelength decreases, height increases and speed is reduced; only the period is unchanged. The shallow bottom greatly modifies the waves. First, it refracts them, that is, it bends the wave fronts to approximate the shape of the underwater contours. Second, when the water becomes critically shallow, the waves break [*see illustration on page 84*].

Even the most casual observer soon notices the process of refraction. He sees that the larger waves always come in nearly parallel to the shoreline, even though a little way out at sea they seem to be approaching at an angle. This is the result of wave refraction, and it has considerable geological importance because its effect is to distribute wave energy in such a way as to straighten coastlines. Near a headland the part of the wave front that reaches shallow water first is slowed down, and the parts of it in relatively deep water continue to move rapidly. The wave thus bends to converge on the headland from all sides. As it does, the energy is concentrated in less length of crest; consequently the height of the crest is increased. This accounts for the old sailors' saying: "The points draw the waves."

Another segment of the same swell will enter an embayment and the wave front will become elongated so that the height of the waves at any point along the shore is correspondingly low. This is why bays make quiet anchorages and exposed promontories are subject to wave battering and erosion—all by the same waves. One can deal quantitatively with this characteristic of waves and can plot the advance of any wave across waters of known depths. Engineers planning shoreline structures such as jetties or piers customarily draw refraction diagrams to determine in advance the effect of waves of various periods and direction. These diagrams show successive



WAVE 112 FEET HIGH, possibly the largest ever measured in the open sea, was encountered in the Pacific in 1933 by the *U.S.S. Ramapo,* a Navy tanker. This diagram shows



they meet, the result is apparent confusion, represented at far right by a topographic diagram drawn from actual photographs of the sea surface. The pattern becomes so complex that statistical methods must be used to analyze the waves and predict their height.

positions of the wave front, partitioned by orthogonals into zones representing equal wave energy [*see illustration on next page*]. The ratio of the distances between such zones out at sea and at the shore is the refraction coefficient, a convenient means of comparing energy relationships.

Refraction studies must take into account surprisingly small underwater irregularities. For example, after the Long Beach, Calif., breakwater had withstood wave attack for years, a short segment of it was suddenly wrecked by waves from a moderate storm in 1930. The breakwater was repaired, but in 1939 waves breached it again. A refraction study by Paul Horrer of the Scripps Institution of Oceanography revealed that long-period swell from exactly 165 degrees (south-southeast), which was present on only these two occasions, had been focused at the breach by a small hump on the bottom, 250 feet deep and more than seven miles out at sea. The hump had acted as a lens to increase the wave heights to 3.5 times average at the point of damage.

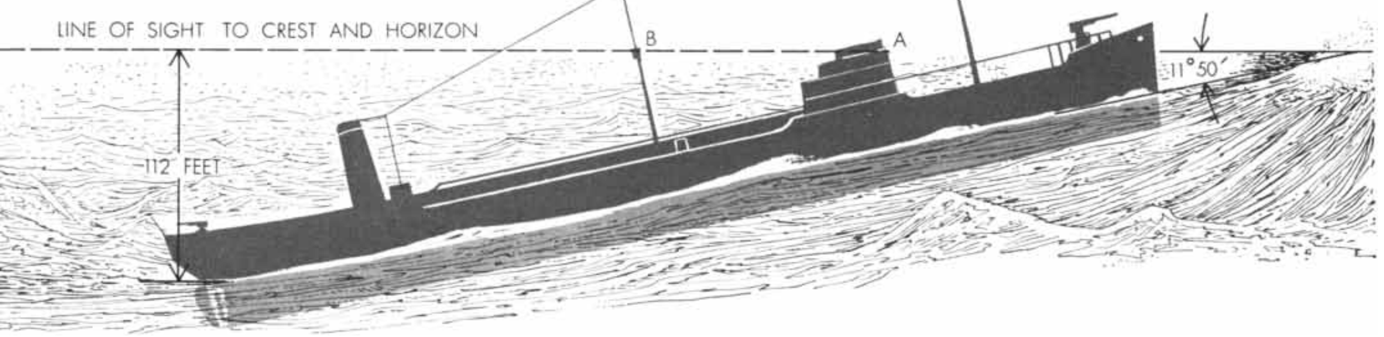
During World War II it was necessary to determine the depth of water off enemy-held beaches against which amphibious landings were planned. Our scientists reversed the normal procedure for refraction studies; by analyzing a carefully timed series of aerial photographs for the changes in length (or velocity) and direction of waves approaching a beach, they were able to map the underwater topography.

The final transformation of normal swell by shoal or shallow water into a breaker is an exciting step. The waves have been shortened and steepened in the final approach because the bottom has squeezed the circular orbital motion of the particles into a tilted ellipse; the particle velocity in the crest increases and the waves peak up as they rush landward. Finally the front of the crest is unsupported and it collapses into the trough. The wave has broken and the orbits exist no more. The result is surf.

If the water continues to get shallower, the broken wave becomes a foam line, a turbulent mass of aerated water. However, if the broken wave passes into deeper water, as it does after breaking on a bar, it can form again with a lesser height that represents the loss of energy in breaking. Then it too will break as it moves into a depth critical to its new height.

The depth of water beneath a breaker, measured down from the still-water level, is at the moment of breaking about 1.3 times the height of the breaker. To estimate the height of a breaker even though it is well offshore, one walks from the top of the beach down until the crest of the breaking wave is seen aligned with the horizon. The vertical distance between the eye and the lowest point to which the water retreats on the face of the beach is then equal to the height of the wave.

The steepness of the bottom influences

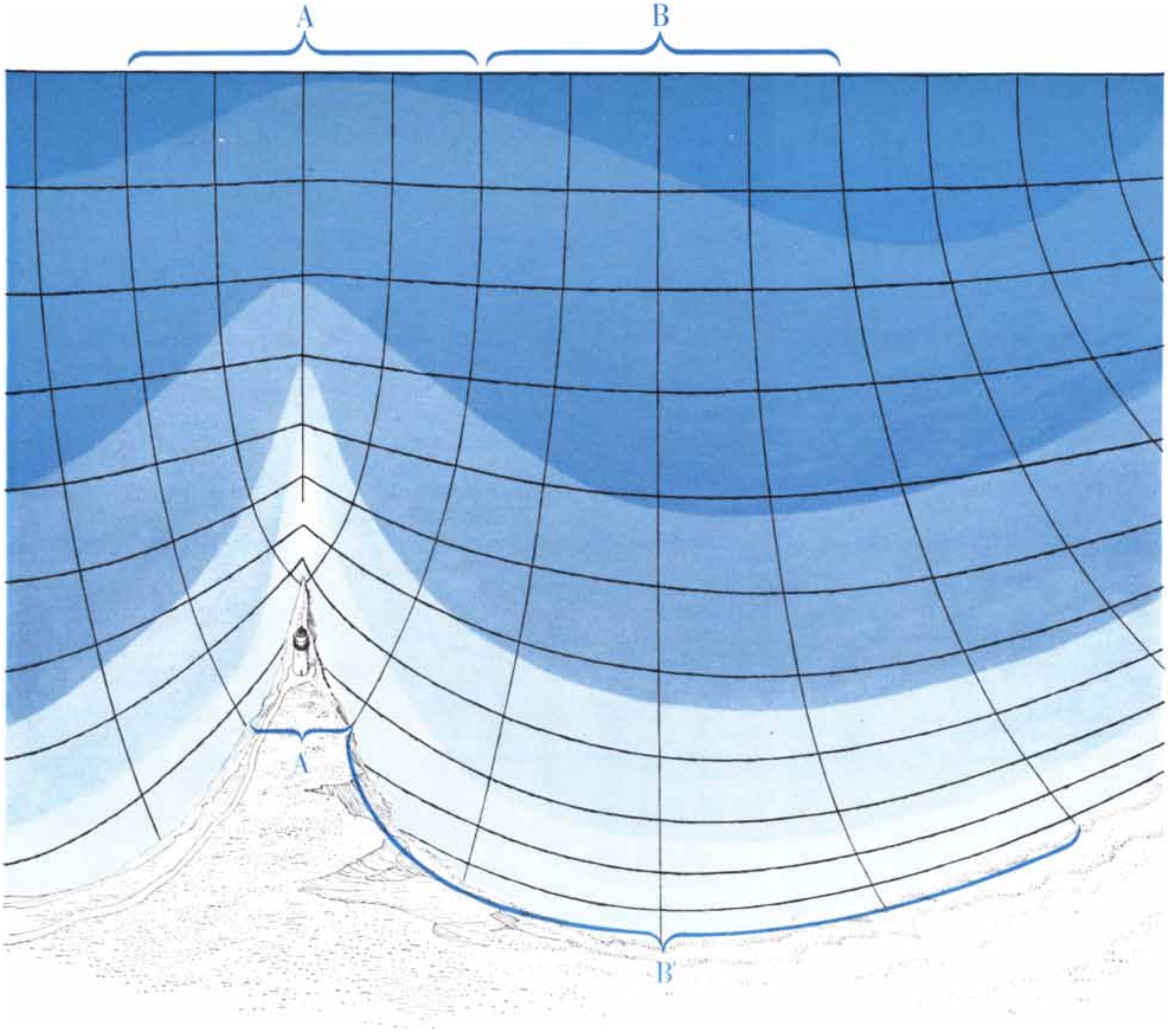


how the great wave was measured. An observer at A on the bridge was looking toward the stern and saw the crow's-nest at B in his line of sight to crest of wave, which had just come in line with horizon. From geometry of situation, wave height was calculated.

the character of the breakers. When a large swell is forced by an abrupt underwater slope to give up its energy rapidly, it forms plunging breakers—violent waves that curl far over, flinging the crest into the trough ahead. Sometimes, the air trapped by the collapsing wave is compressed and explodes with a great roar in a geyser of water [*see illustration on opposite page*]. However, if the bottom slope is long and gentle, as at Waikiki in Hawaii, the crest forms a spilling breaker, a line of foam that tumbles down the front of the partly broken wave as it continues to move shoreward.

Since waves are a very effective mechanism for transporting energy against a coast, they are also effective in doing great damage. Captain D. D. Gaillard of the U. S. Army Corps of Engineers devoted his career to studying the forces of waves on engineering structures and in 1904 reported some remarkable examples of their destructive power. At Cherbourg, France, a breakwater was composed of large rocks and capped with a wall 20 feet high. Storm waves hurled 7,000-pound stones over the wall and moved 65-ton concrete blocks 60 feet. At Tillamook Rock Light off the Oregon coast, where severe storms are commonplace, a heavy steel grating now protects the lighthouse beacon, which is 139 feet above low water. This is necessary because rocks hurled up by the waves have broken the beacon several times. On one occasion a rock weighing 135 pounds was thrown well above the lighthouse-keeper's house, the floor of which is 91 feet above the water, and fell back through the roof to wreck the interior.

At Wick, Scotland, the end of the breakwater was capped by an 800-ton block of concrete that was secured to the foundation by iron rods 3.5 inches in diameter. In a great storm in 1872 the designer of the breakwater watched in amazement from a nearby cliff as both cap and foundation, weighing a total of 1,350 tons, were removed as a unit and deposited in the water that the wall was supposed to protect. He rebuilt the structure and added a larger cap weighing 2,600 tons, which was treated similarly by a storm a few years later. There is no record of whether he kept his job



WAVE-REFRACTION DIAGRAM shows how energy of wave front at A is all concentrated by refraction at A′ around small headland area. Same energy at B enters a bay but is spread at beach over wide area B′. Horizontal lines are wave fronts; vertical lines divide energy into equal units for purposes of investigation. Such studies are vital preliminaries to design of shoreline structures.

and tried again. Gaillard's computations show that the wave forces must have been 6,340 pounds per square foot.

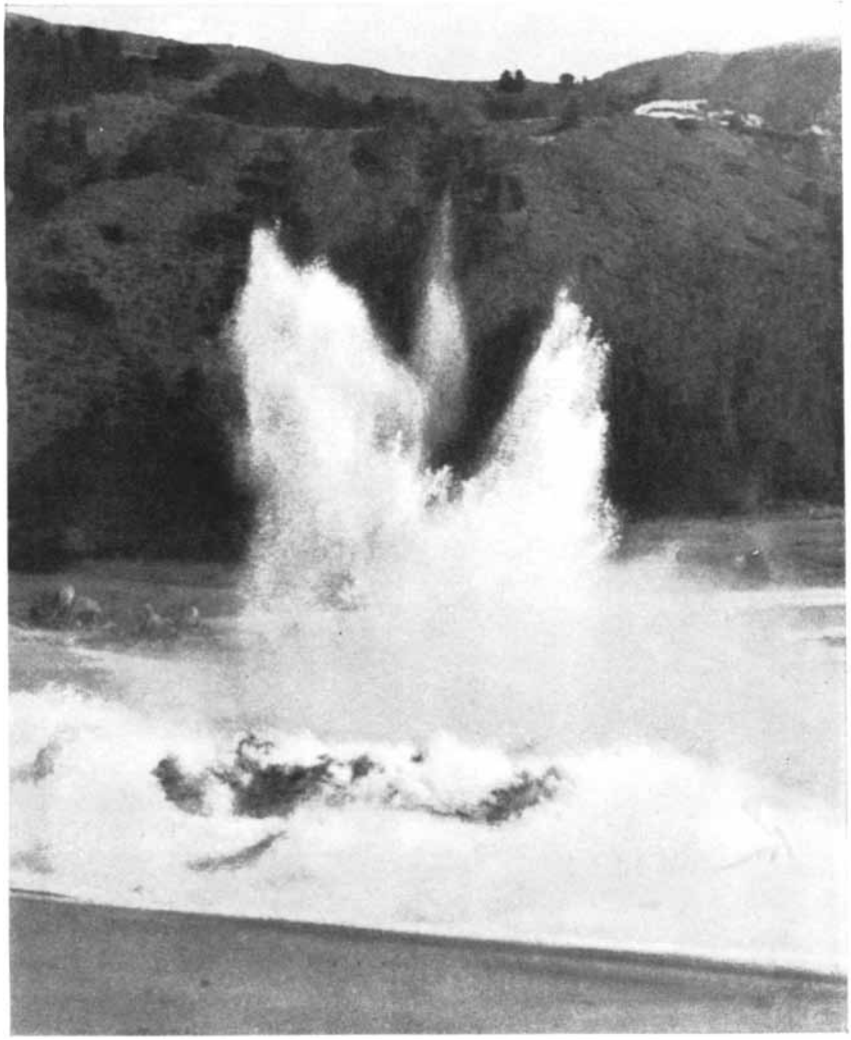
Tsunamis

Even more destructive than wind-generated waves are those generated by a sudden impulse such as an underwater earthquake, landslide or volcano. A man-made variation of the sudden impulse is the explosion of nuclear bombs at the surface of the sea, which in recent years have become large enough to be reckoned with as possible causes of destructive waves.

The public knows such waves as tidal waves, although they are in no way related to the tides and the implication has long irritated oceanographers. It was proposed that the difficulty could be resolved by adopting the Japanese word *tsunami.* Some time later it was discovered that Japanese oceanographers are equally irritated by this word; in literal translation tsunami means tidal wave! However, tsunami has become the favored usage for seismic sea waves.

Like the plunger in a wave channel, the rapid motion or subsidence of a part of the sea bottom can set a train of waves in motion. Once started, these waves travel great distances at high velocity with little loss of energy. Although their height in deep water is only a few feet, on entering shallow water they are able to rise to great heights to smash and inundate shore areas. Their height depends almost entirely on the configuration of the coastline and the nearby underwater contours. Tsunamis have periods of more than 15 minutes and wavelengths of several hundred miles. Since the depth of water is very much less than half the wavelength, they are regarded as long- or shallow-water waves, even in the 13,000-foot average depth of the open ocean, and their velocity is limited by the depth to something like 450 miles per hour.

These fast waves of great destructive potential give no warning except that the disturbance that causes them can be detected by a seismograph. The U. S. Coast Guard operates a tsunami warning network in the Pacific that tracks all earthquakes, and when triangulation indicates that a quake has occurred at sea, it issues alerts. The network also has devices to detect changes in wave period which may indicate that seismic waves are passing [see "Tsunamis," by Joseph Bernstein; SCIENTIFIC AMERICAN, August, 1954]. Curiously the influence of the system may not be entirely beneficial. Once when an alert was broadcast at Honolulu, thousands of people there dashed down to the beach to see what luckily turned out to be a very small wave.



WAVE-CREATED "GEYSER" results when large breakers smash into a very steep beach. They curl over and collapse, trapping and compressing air. This compressed air then explodes as shown here, with spray from a 12-foot breaker leaping 50 feet into the air.

Certain coasts near zones of unrest in the earth's crust are particularly prone to such destructive waves, especially the shores of the Mediterranean, the Caribbean and the west coast of Asia. On the world-wide scale, they occur more frequently than is generally supposed: nearly once a year.

A well-known seismic sea wave, thoroughly documented by the Royal Society of London, originated with the eruption of the volcano Krakatoa in the East Indies on August 27, 1883. It is not certain whether the waves were caused by the submarine explosion, the violent movements of the sea bottom, the rush of water into the great cavity, or the dropping back into the water of nearly a cubic mile of rock, but the waves were monumental. Their period close to the disturbance was two hours, and at great distances about one hour. Waves at least 100 feet high swept away the town of Merak, 33 miles from the volcano; on the opposite shore the waves carried the man-of-war *Berow* 1.8 miles inland and left it 30 feet above the level of the sea. Some 36,380 people died by the waves in a few hours. Tide gauges in South Africa (4,690 miles from Krakatoa), Cape Horn (7,820 miles) and Panama (11,470 miles) clearly traced the progress of a train of about a dozen waves, and showed that their speed across the Indian Ocean had been between 350 and 450 miles per hour.

A tsunami on April 1, 1946, originating with a landslide in the Aleutian submarine trench, produced similar effects,

HUNDRED-FOOT "TIDAL WAVE," or tsunami, wrought impressive destruction at Scotch Cap, Alaska, in 1946. Reinforced concrete lighthouse that appears in top photograph was demolished, as shown in lower photograph, which was made from a higher angle. Atop the plateau a radio mast, its foundation 103 feet above sea, was also knocked down. Lighthouse debris was on plateau. Same tsunami, started by an Aleutian Island earthquake, hit Hawaiian Islands, South America and islands 4,000 miles away in Oceania.

fortunately on less-populated shores. It struck hard at the Hawaiian Islands, killing several hundred people and damaging property worth millions of dollars. At Hilo, Hawaii, the tsunami demonstrated that such waves are virtually invisible at sea. The captain of a ship standing off the port was astonished upon looking shoreward to see the harbor and much of the city being demolished by waves he had not noticed passing under his ship. The same waves caused considerable damage throughout the islands of Oceania, 4,000 miles from epicenter, and on the South American coast, but they were most spectacular at Scotch Cap in Alaska. There a two-story reinforced-concrete lighthouse marked a channel through the Aleutian Islands. The building, the base of which was 32 feet above sea level, and a radio mast 100 feet above the sea were reduced to bare foundations by a wave estimated to be more than 100 feet high [*see illustration on opposite page*].

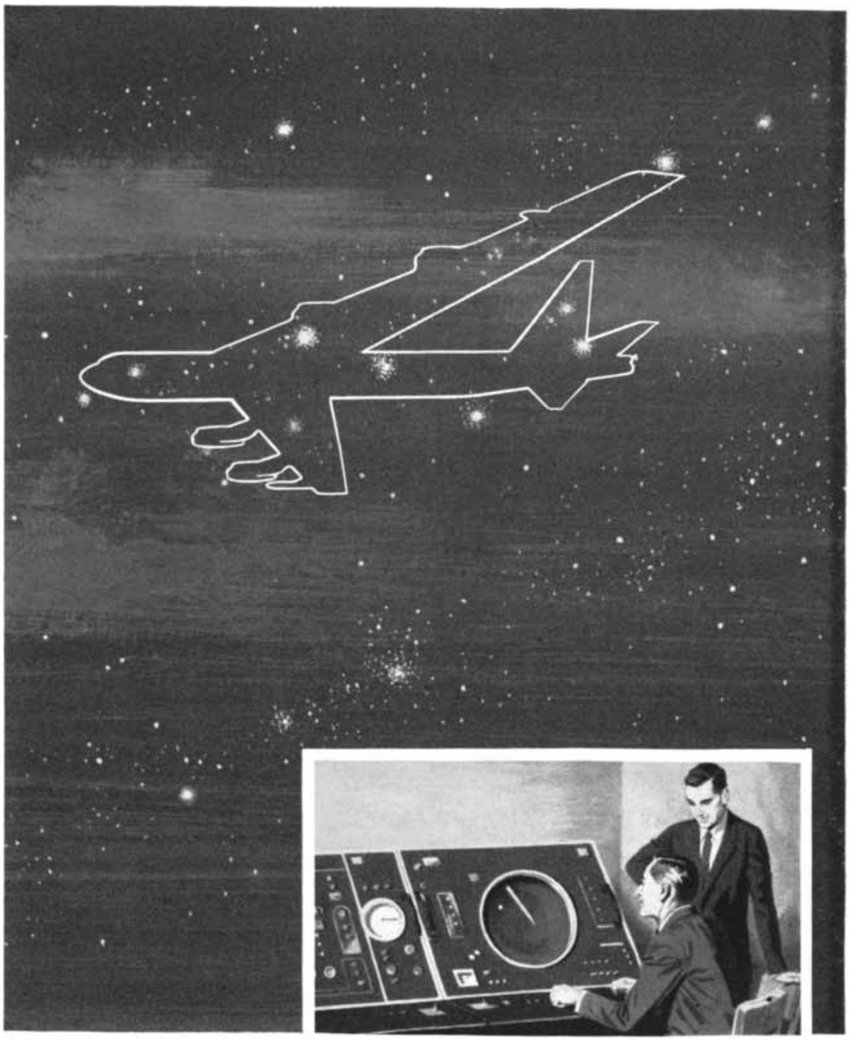
Uncontrollable geologic disturbances will cause many more seismic sea waves in the future, and since the world's coastal population is continuously increasing, the greatest wave disaster is yet to come. Within the next century we can expect that somewhere a wave will at least equal the one that swept the shores of the Bay of Bengal in 1876, leaving 200,000 dead.

Tides and Other Waves

The rhythmic rise and fall of the sea level on a coast indicate the passage of a true wave we call a tide. This wave is driven, as almost everyone knows, by the gravitational influence of the sun and the moon. As these bodies change their relative positions the ocean waters are attracted into a bulge that tends to remain facing the moon as the earth turns under it; a similar bulge travels around the earth on the opposite side. The wave period therefore usually corresponds to half the lunar day.

When the sun and the moon are aligned with the earth, the tides are large (spring tides); when the two bodies are at right angles with respect to the earth, the tides are small (neap tides). By using astronomical data it is possible to predict the tides with considerable accuracy. However, the height and time of the tide at any place not on the open coast are primarily a function of the shape and size of the connection to the ocean.

Still another form of wave is a seiche, a special case of wave reflection. All enclosed bodies of water rock with charac-



teristics related to the size of the basin. The motion is comparable to the sloshing of water in the bathtub when one gets out quickly. In an attempt to return to stability the water sways back and forth with the natural period of the tub (mine has a period of two seconds). Similarly a tsunami or a barometric pressure-change will often set the water in a bay rocking as it passes. In fact, the tsunami itself may reflect back and forth across the ocean as a sort of super-seiche.

In addition to seiches, tides, tsunamis and wind waves there are other waves in the sea. Some travel hundreds of feet beneath the surface along the thermocline, the interface between the cold deep water and the relatively warm surface layer. Of course these waves cannot be seen, but thermometers show that they are there, moving slowly along the boundary between the warm layer and the denser cold water. Their study awaits proper instrumentation. Certain very low waves, with periods of several minutes, issue from storms at sea. These long-period "forerunners" may be caused by the barometric pulsation of the entire storm against the ocean surface. Since they travel at hundreds of miles an hour, they could presumably be used as storm warnings or storm-center locators. Other waves, much longer than tides, with periods of days or weeks and heights of less than an inch, have been discovered by statistical methods and are now an object of study.

The great advances both in wave theory and in the actual measurement of waves at sea have not reduced the need for extensive laboratory studies. The solution of the many complex engineering problems that involve ships, harbors, beaches and shoreline structures requires that waves be simulated under ideal test conditions. Such model studies in advance of expensive construction permit much greater confidence in the designs.

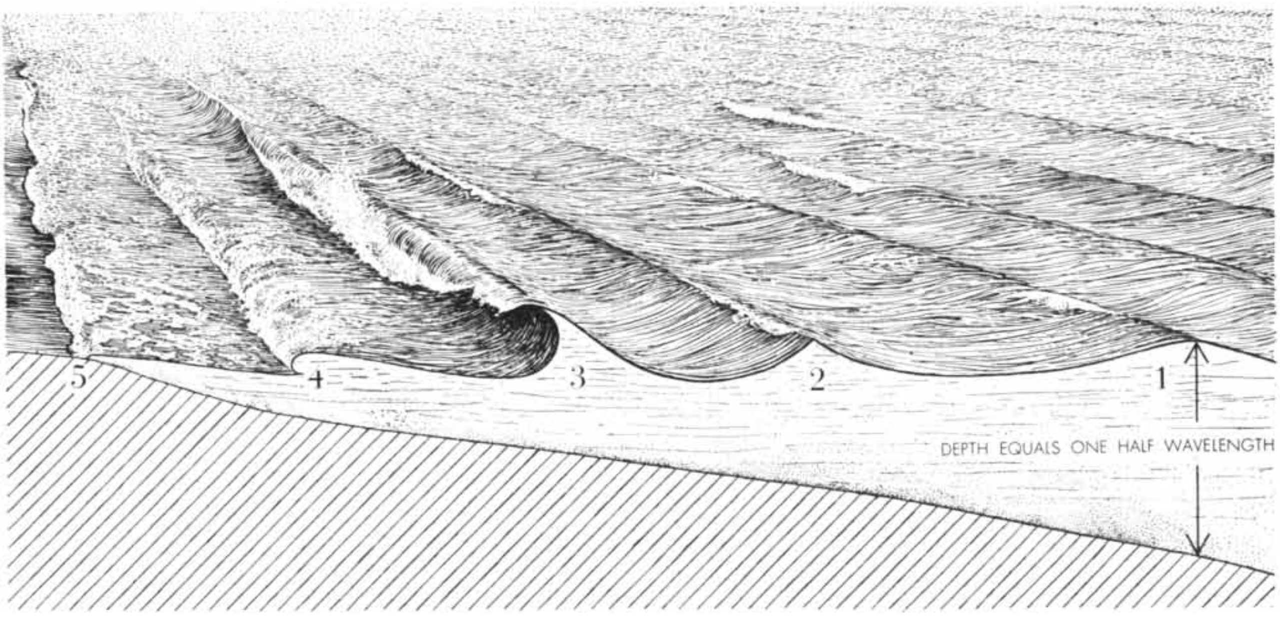
Experimental Tanks

The traditional wave channel in which an endless train of identical small waves is created by an oscillating plunger is still in use, but some of the new wave tanks are much more sophisticated. In some the channel is covered, so that a high velocity draft of air may simulate the wind in making waves. In others, like the large tank at the Stevens Institute of Technology, Hoboken, N.J. [*see cover*], artificial irregular waves approach the variability of those in the deep ocean. In such tanks proposed ship designs, like those of the America's Cup yacht *Columbia,* are tested at model size to see how they will behave at sea.

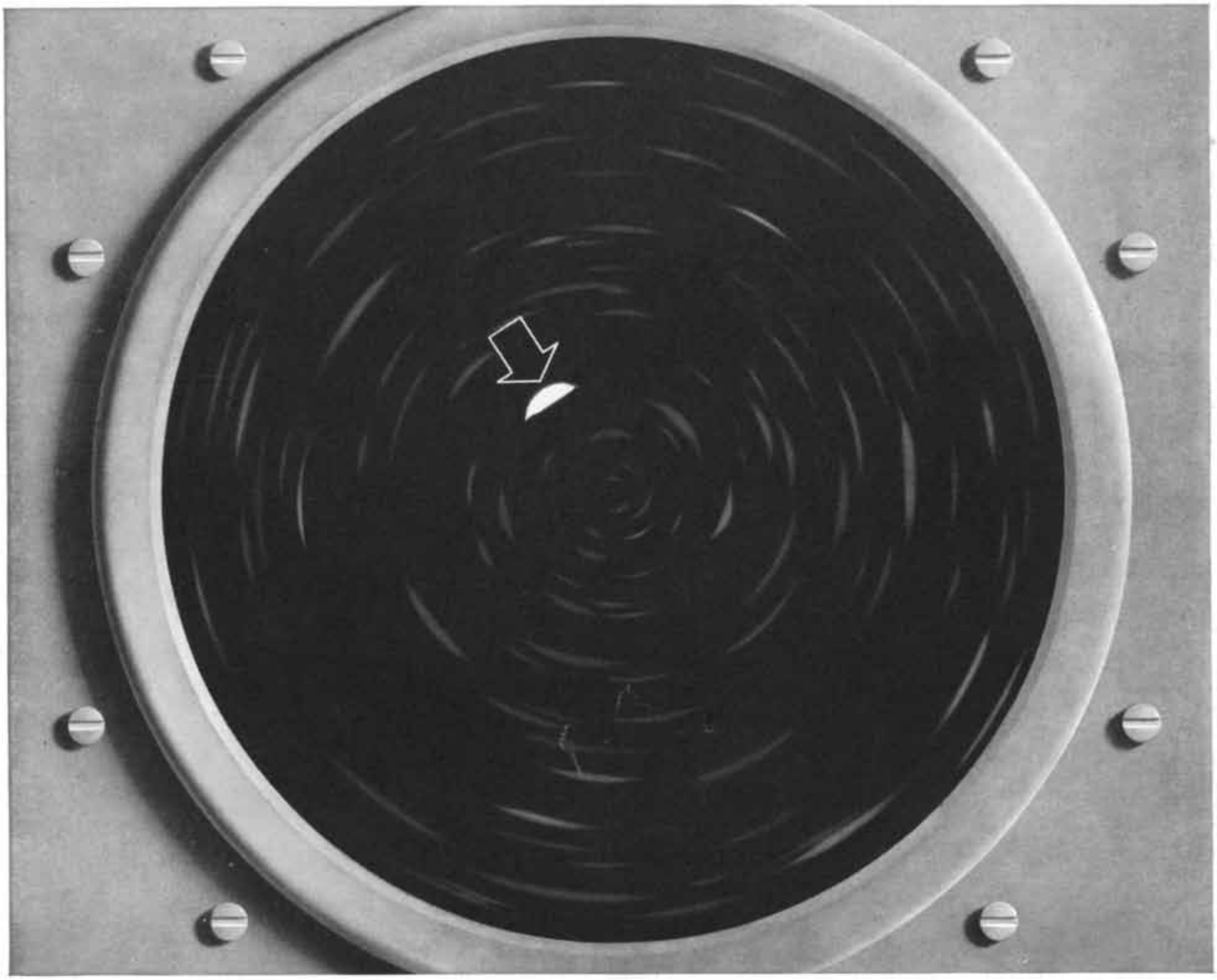
The ripple tank, now standard apparatus for teaching physics, has its place in shoreline engineering studies for conveniently modeling diffraction and refraction. Even the fast tsunamis and the very slow waves of the ocean can be modeled in the laboratory. The trick is to use layers of two liquids that do not mix, and create waves on the interface between them. The speeds of the waves can be controlled by adjusting the densities of the liquids.

To reduce the uncertainties in extrapolation from the model to prototype, some of the new wave tanks are very large. The tank of the Beach Erosion Board in Washington, D.C. (630 feet long and 20 feet deep, with a 500-horsepower generator), can subject quarter-scale models of ocean breakwaters to six-foot breakers. The new maneuvering tank now under construction at the David Taylor Model Basin in Carderock, Md., measures 360 by 240 feet, is 35 feet deep along one side and will have wave generators on two sides that can independently produce trains of variable waves. Thus man can almost bring the ocean indoors for study.

The future of wave research seems to lie in refinement of the tools for measuring, statistically examining and reproducing in laboratories the familiar wind waves and swell as well as the more recently discovered varieties. It lies in completing the solution of the problem of wave generation. It lies in the search for forms of ocean waves not yet discovered—some of which may exist only on rare occasions. Nothing less than the complete understanding of all forms of ocean waves must remain the objective of these studies.



WAVE BREAKS UP at the beach when swell moves into water shallower than half the wavelength (1). The shallow bottom raises wave height and decreases length (2). At a water depth 1.3 times the wave height, water supply is reduced and the particles of water in the crest have no room to complete their cycles; the wave form breaks (3). A foam line forms and water particles, instead of just the wave form, move forward (4). The low remaining wave runs up the face of the beach as a gentle wash called the uprush (5).



Artist's drawing shows enemy submarine position (white pip indicated by arrow) as it appears on Bendix Sonar viewing scope in helicopter. It is the first airborne system to provide a visual presentation which pinpoints a target below the surface.

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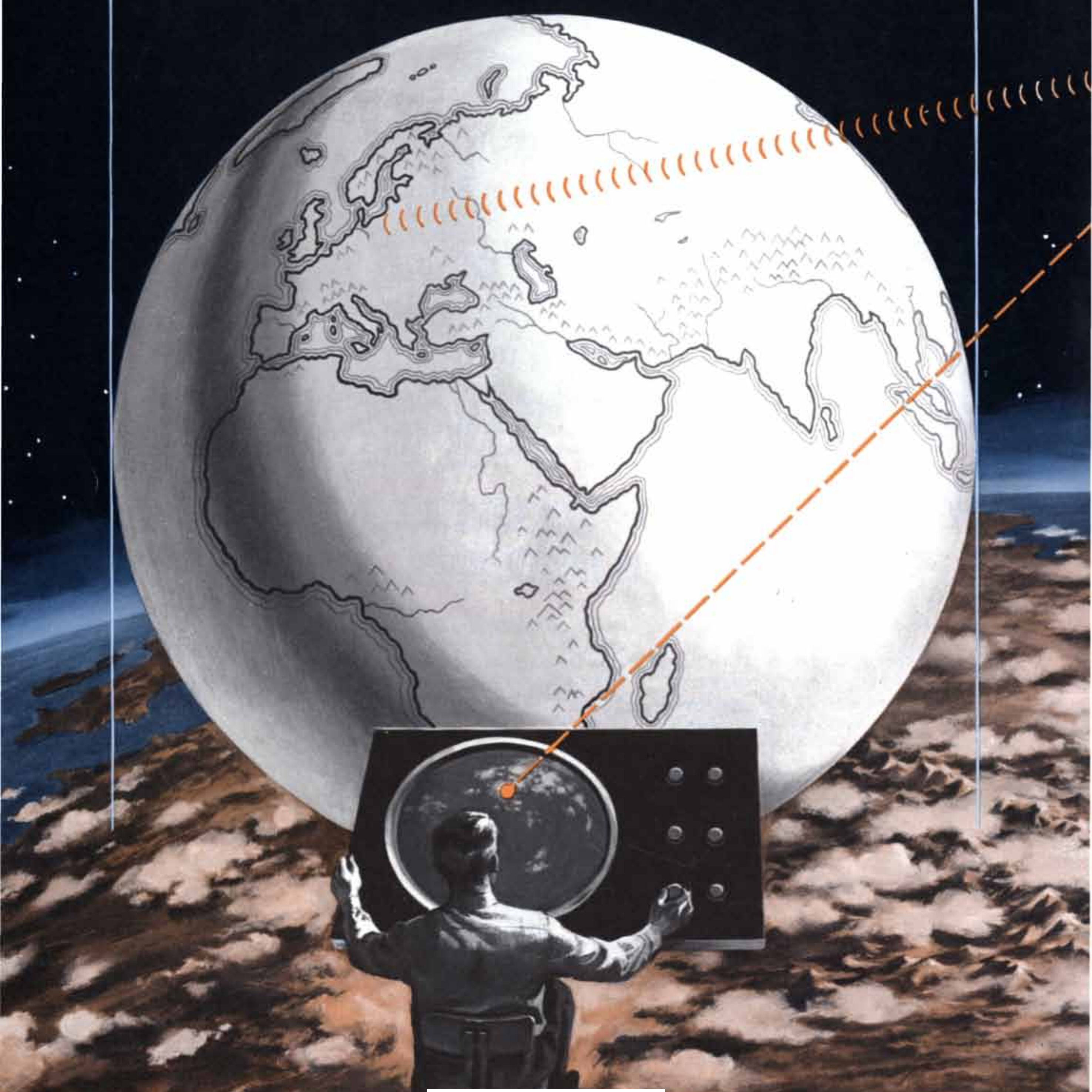

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a report by LINDSAY

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