Chapter 26

STRUCTURAL ASPECTS OF LIGHTHOUSE DESIGN

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INTRODUCTION

The purpose of this paper is to provide an acquaintance with lighthouses, the types of structures which have been erected, the reasons for their shape and form, and the basis for design. It will be revealed as the treatise proceeds, that the technique of design of lighthouses has improved with the increase in knowledge of the forces that are acting and the behavior of materials while subjected to stresses and strains of these forces.

The subject under consideration is termed "pharology" which is defined as the scientific theory and treatment of signal lights and lighthouse construction. The paper confines itself to a concise discussion on lighthouse construction, covering briefly structures of historical importance to some contemporary designs. The concluding portion of this treatise deals with a proposed replacement of a lightship by a fixed structure.

The development of lighthouse construction has been evolutionary. Thousands of years ago an aid-to-navigation consisted of a massive tower, atop of which a fire was burned. The exuding smoke aided the mariners in sighting landfall by day and the glow of the fire served the same purpose at night. The last century and one half has seen rapid strides in the improvement of lighthouse techniques. Progressively, the tallow candle replaced the open fire which in turn was supplanted by the oil and wick lamp and so on until today lamps and lenses have been developed to produce a beam of light with the magnitude of intensity of 25 million candlepower.

HISTORICAL

The Pharos of Alexandria is one of the Seven Wonders of the Ancient World (Fig. 1). Pharos, from which the term "pharology" is derived, was the name of the islet upon which the lighthouse structure was erected. The island was a long, narrow strip of land protruding in front of the ancient city of Alexandria, protecting the harbor from wind storms and high tides of the Mediterranean Sea. It was claimed that the light could be seen for 35 miles. A structure erected at sea level would have to be about 550 feet high to be seen at such a distance. If the description of the edifice is to be believed, then the Pharos of Alexandria is the most remarkable lighthouse structure of all time.

Fig. 1
The Pharos of Alexandria

WINSTANLEY'S LIGHTHOUSE AT THE EDDYSTONE.

Fig. 2

Fig. 3
Smeaton's lighthouse at Eddystone, England.

Fig. 4
Rare print of the old Boston lighthouse.

Erected in the second century B.C., it withstood the vicissitudes of time and the elements until destroyed by an earthquake in the 13th Century. Historian Edrisi, 600 years ago wrote: "This pharos has not its like in the world for skill of construction or for solidity; since, to say nothing of the fact that it is built of excellent stone of the kind called Redan, the layers of these stones are united by molten lead and the joints are so adherent the whole is indissoluble, though the waves of the sea from the north incessantly beat against it. From the ground to the middle galley the measurement is exactly seventy fathoms and from this galley to the summit twenty-six." This measurement would credit the edifice with a height of 576 feet.

The Romans, in the expansion of their empire, carried on the construction of lighthouses and while virtually all of them have fallen into decay, their existence is confirmed through coins and medallions unearthed by archeologists.

Skipping the Dark Ages of Western Europe, the next endeavors of historical significance were the British efforts at Eddystone in the English Channel. Eddystone is a reef of rocks lying in deep water fourteen miles southwest of Plymouth Harbor. The lighthouse is notable for many reasons. It is the anchor light in the chain of lights which enables safe navigation close to the English shore and it also marks the entrance to Plymouth Harbor. At high water the rocks are barely visible; at low water, the rocks appear as a low ridge of land. The existing structure is the fourth replacement, and the accounts of the design and construction of the first three structures make very interesting reading. For instance, Winstanley, the builder of the first tower, erected an ornamental structure consisting of an iron-legged tower with an architectural clothing of granite, and was convinced of its invincibility to the sea (Fig. 2). He expressed the wish to be in the tower during the greatest storm known in the English Channel. His wish was fulfilled about a year after completion of the structure when the tower gave way to the onslaught of the sea. Six lives were lost in the tragedy. The second structure was erected on a timber grillage with alternate courses of oak timber and granite. It was totally lost in a fire which started in the lantern housing. No sketch is available of the design. The third attempt was made by John Smeaton, an instrument maker (Fig. 3). It was of solid granite construction and marks a milestone in the annals of construction history in that he was the first designer to use natural cement as the binder in masonry construction. Smeaton's structure was replaced after 125 years of service. It might still be in existence were it not that the foundation partially gave way, rendering the superstructure unstable. The committee evaluating Smeaton's handiwork expressed the opinion that the tower itself was good for another century of use but that the difficult problem of underpinning the foundation and the need for a higher tower warranted the erection of a new structure.

The pattern for the lighthouse was set. Only a massive granite structure resting on a firm foundation can withstand the forces of the wind and the sea. Solid foundations immediately break up or deflect the heavy seas, and the spray alone rises up to the height of the lantern gallery.

EARLY AMERICAN LIGHTHOUSES

The first lighthouse established in this country was the Boston Lighthouse located on Little Brewster Island in Boston Harbor in 1716 (Fig. 4). Its construction was authorized by the Massachusetts Assembly. Initially the maintenance of the light was paid for by a tonnage tax, but the formation of the Federal Government brought the colonial lights, toll free, under a single jurisdiction. At the first session of Congress, an act was passed and subsequently approved in 1789 creating the Lighthouse Service which was later placed under the Department of Commerce. The Reorganization Act of 1939 made the Lighthouse Service a part of the Coast Guard under the Treasury Department.

In 162 years of activity, the Lighthouse Service and its successor, the Coast Guard, has built many major aids-to-navigation. Today, there are over 400 major structures in active service operated by the Coast Guard through its several district offices. Each of these structures has a story to tell and the romance of several has been compiled and published (U. S. Coast Guard, 1951).

Advancements made in the design of lighthouses and the techniques of construction, while not spectacular, have been notable. Each site offers some new challenges not previously experienced. Superficially, lighthouses appear to have a set pattern, but a perusal of the files of drawings reveals wide variations in foundation requirements for structures which are otherwise similar. The mariners' needs dictate heights for the lantern housing, and geography and the elements determine the materials of construction. There are no standard drawings or typical structures for the primary lights. You will discern from the accompanying illustrations that not all lighthouses are massive, high, conically shaped masonry towers, atop of which sets a lantern housing. The design of lighthouse structures has kept pace with architectural and engineering trends of the times.

Lighthouses may be classified as to site location which forms a criterion for design. They are as follows:

1. Spray-swept Structures - located on shore or on promontories.
2. Wave-swept Structures - located at water's edge or in the water.
3. Structures resisting ice pressures - located on inland waterways and lakes.

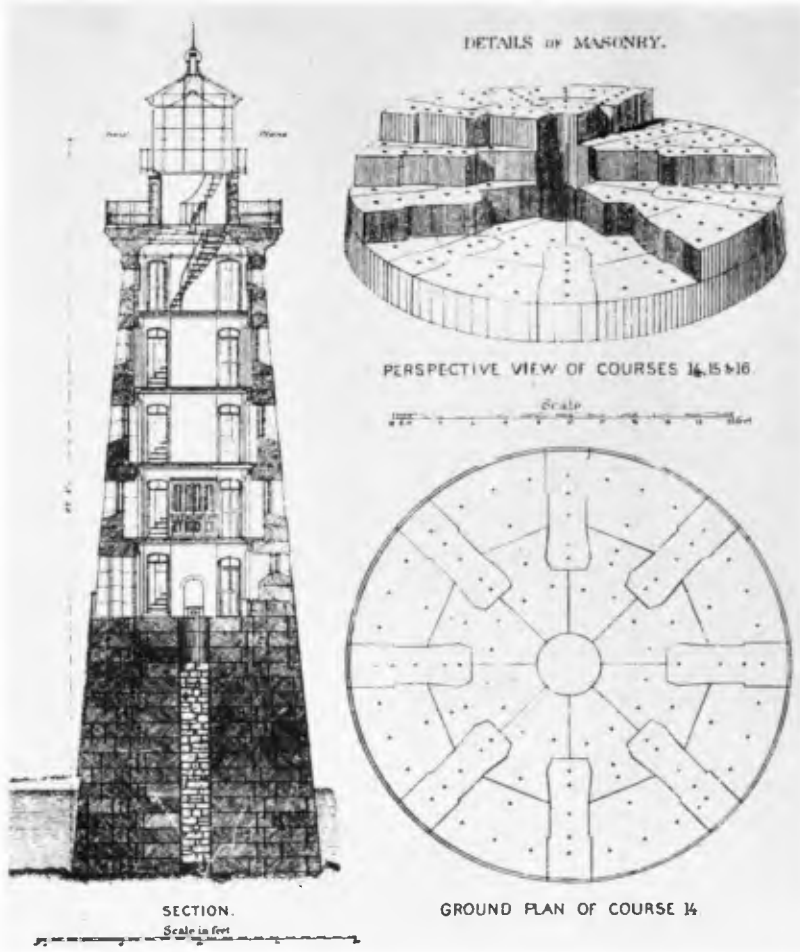


Fig. 5
Spectacle Reef lighthouse, Lake Huron.

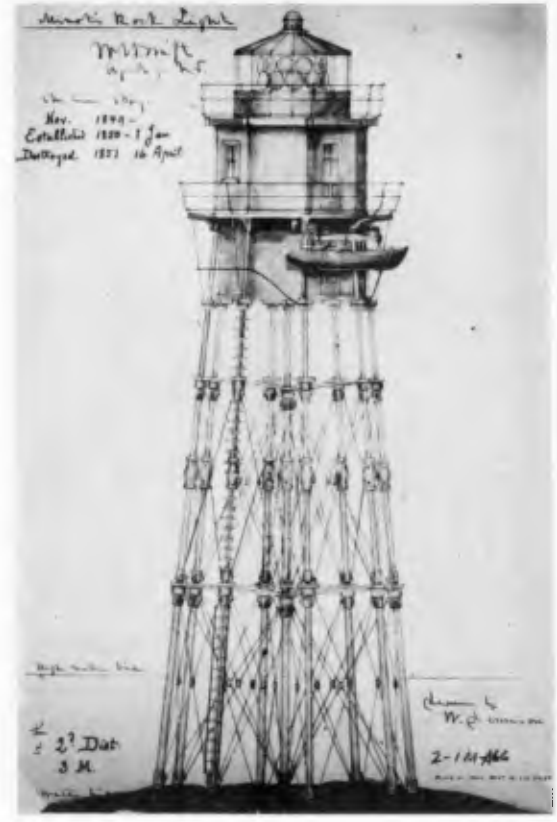


Fig. 6
Iron-legged lighthouse at Minot's ledge, outer Boston Harbor, Mass. Erected 1850, destroyed 16 months later.

The nature and intensity of external forces in a large measure dictate the materials of construction. The forces expected to be encountered also depend on the geographic location of the site. Superstructures are made of the following materials:

1. Granite
2. Brick
3. Cast-iron plate towers
4. Skeleton steel structures
5. Reinforced concrete

One aspect of the type of foundation to be used is dictated by the depth of water which is encountered. Water depths may be classified as follows:

0 to 10 feet	shallow depths
10 to 20 feet	moderate depths
20 feet and over	deep water

The superstructure in combination with the subsoil conditions, of course, governs the type of foundation to be used. Foundations may be classified as follows:

1. Screw pile foundations (helicoidal screws of cast-iron or steel attached to the piles)

2. Gravity foundations
    a. Pile supported
    b. Rock near surface
    c. Sand foundations
        (1) Open end caisson
        (2) Pneumatic caisson
        (3) Interlocking steel pile structure
        (4) Crib supported
        (5) Grillage and cylinder

Wave swept structures are located on sites where wave action must be taken into consideration both as to the stability of the structure and the difficulties encountered in construction. Two general types have been successfully used: (a) Solid masonry towers wherein the mass of masonry counteracts the external forces created by wave and wind actions and (b) open skeleton towers so designed that the structure offers the least possible resistance to the kinetic energy produced by the waves.

Some of the most famous lighthouse towers have been built of solid masonry construction (Fig. 5). After repeated losses the lesson brought to bear was that the relentless pounding of the sea could only be withstood by structures having solid masonry bases with all joints dovetailed, circular in cross section, and having the exterior surfaces free from obstructions.

Fig. 8

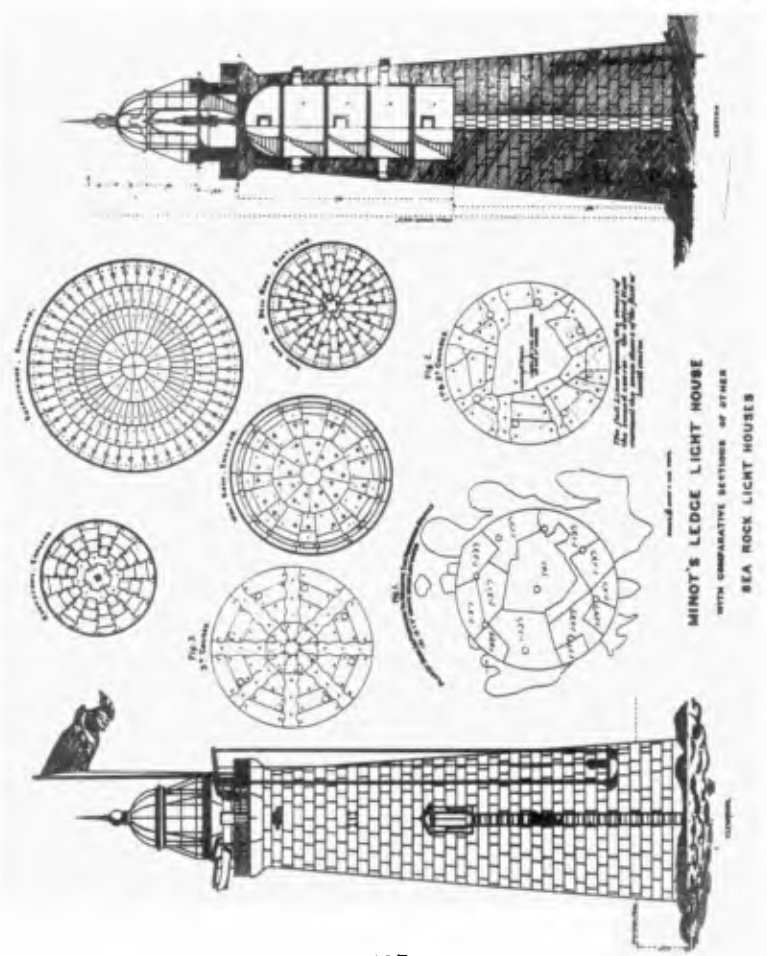


Fig. 7 Minot's ledge lighthouse.

A case in point is the Minots Ledge Lighthouse, the sentinal located one mile offshore and 6 miles southeasterly of Boston Harbor. In 1850, a 75-ft. iron frame structure was completed (Fig. 6). It lasted only 16 months before being swept to sea by a furious storm in which two of the assistant light-keepers lost their lives. The principal keeper survived to relate the terrifying experiences of the ordeal. The rock at the site is exposed only at low water and then only for a short period of time during spring tides. The frame structure consisted of 9 ten-inch wrought iron pipes, grouted into holes drilled five feet into the rock. Eight of these pilings were symmetrically spaced on the circumference of a 25-foot diameter circle with the ninth piling at the center. This operation took the greater part of two seasons to complete. The piling converged to the circumference of a 14-foot circular cast iron cap, 38 feet above the base on which the keeper's quarters were erected. The top of the lantern housing was 75 feet above the base. Two sets of cross bracing were provided for the posts but the lower set was never installed. The center of gravity was high, the lighthouse was fully exposed to the sea, and during intense storms the waves overtopped the lantern housing. Basically, the structure was inadequate, made particularly so by omission of the lower level crossbracings. The structure failed at the intended juncture of the crossbracing.

The present structure, started in 1855 and completed five years later, ranks as one of the great sea-rock lighthouses of the world from the viewpoint of overcoming the engineering difficulties encountered and the skill and science used in construction (Figs. 7 and 8). The rock bed had to be cut to proper shape before any of the stones for the courses could be laid. Preparation of the foundation took three years to complete. The conical tower is thirty feet in diameter near the base and 115 feet high. The lower forty feet is solid except for a central well. The tower contains 1079 granite blocks each weighting approximately 2 tons. The stones were cut on the mainland and check assembled before shipment to the site. They are cut so that each stone vertically dovetails to the neighboring stones. The courses, two feet thick, are held together vertically by bonding bolts wedged in place. The tower is massive and excellently constructed as attested by almost a century of service. Keepers report that in exceptionally heavy seas the lashing waves cause the tower to tremble to its very foundation.

REEF LIGHTS OF THE FLORIDA COAST

The Florida Reefs have always been a menace to navigation because of the convex nature of the reefs with respect to the channel in the Straits of Florida. The Gulf Stream runs close by, and the reefs of coral extend offshore for several hundred yards in shallow water ranging in depth from three to eleven feet. The shelf then drops abruptly.

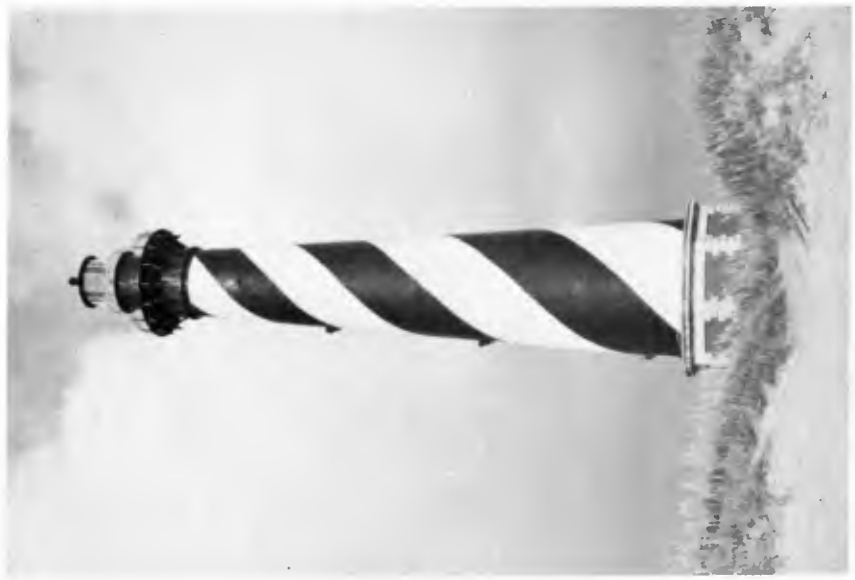


Fig. 10 Cape Hatteras lighthouse, North Carolina (constructed in 1870).

Fig. 9 Carysfort Reef light station, Carysfort Reef, Florida.

To give some idea of the treachery of this water, from 1831 to 1844 there was always work in the channel to keep 50 wrecker vessels busy. To alleviate this deplorable condition, a series of six lighthouses was constructed between 1852 and 1880 marking the Florida Reefs from Fowey Rocks to Sand Key. These sentinels of the sea are generally referred to as the Reef Lights, and are all similar in construction, being of the steel skeleton type. The structural material used was wrought iron which has successfully withstood the action of the elements with a minimum of expense for maintenance and replacement of brace rods.

Carysfort Lighthouse: The Carysfort Lighthouse which was completed in 1852 stands in three feet of water about three hundred yards from the edge of the reef on a surface stratum of hard coral over a softer material below (Fig. 9). It is one hundred and seventeen feet high above the reef. The two-story dwelling is thirty-three feet above the water, with a cylindrical inclosure above containing a winding stair leading to the lantern housing. The framework is pyramidal in shape with a fifty foot diameter base with eight wrought iron piles forming an octagon. An additional pile is located in the center. The stratum of coral was deemed to have insufficient bearing power to support the piles, and large cast iron discs or foot plates, six feet in diameter, were used to spread the load over the coral. The discs have a hole in the center through which the piles pass. The piles were driven into the coral until a collar attached to the piles rested on the discs.

Sand Key Lighthouse: Sand Key is a low deposit of sand on a coral reef. In violent storms or hurricanes, the key is submerged and the surface sand is shifted. Shortly after subsidence of the storm, the key reappears in its original position but in a slightly modified form. Sand Key Lighthouse is similar to the Carysfort Lighthouse except that it is supported on piles screwed into the earth. The piles are of wrought iron, 8-inches in diameter, having attached at their tip ends cast-iron helicoidal screws with flanges two feet in diameter. The piles and screws total 13 feet in length and were slowly bored into the sand to a depth of ten feet below low water. Nineteen piles were installed in this manner. In addition to the screws, the 12 exterior piles pass through heavy cast-iron discs four feet in diameter which rest on beds of concrete. The Officer-in-Charge of Construction was Lieutenant George G. Meade who ten years later was in command of the Union forces at Gettysburg. Three years after completion of the structure, the island was washed away in a gale. In 1865, a hurricane again took away the island and everything on it except the lighthouse, which speaks well for the screw type anchor foundations. Today, after nearly a century of service, the framework is in good condition. Work is underway to protect the structure from corrosion by means of cathodic protection.

Sombrero Key Lighthouse: The Sombrero Key Lighthouse is the tallest of the Key lights and was designed by Lt. Meade after his experience in constructing the Sand Key structure. It is fifty six feet in diameter and one hundred and sixty feet high, supported on nine wrought iron piles twelve inches in diameter, resting in cast-iron discs eight feet in diameter. The lighthouse was built in six feet of water.

LIGHTS ON ISLANDS AND PROMONTORIES

The caprices of nature sometime fall in the category of the spectacular. There are numerous instances where the seas have swept away aids-to-navigation, both large and small. In the history of lighthouse construction, in the United States and in foreign countries, many primary lighthouse structures have succumbed to the relentless pounding of the sea and surf. However, there are two instances wherein engineering has successfully stayed the hand of doom. They are the lighthouses at Sand Island and at Cape Hatteras.

Sand Island Lighthouse: Sand Island Lighthouse is situated in the entrance to Mobile Bay, Alabama. The present tower, with granite trimmings, is the third to have been built, and was completed in 1873 on what was then a bank of sand, 400 acres in extent. At the time of construction, it was acknowledged that sands of the island were shifting, but a more suitable location nearby was not available. The present structure, 132 feet high, resting on a foundation of 178 piles, was located on what was thought to be the most stable part of the island, but in 60 years the outer edge of the island has moved more than a half mile. The hurricane of 1906, which brought such disaster to the Gulf Coast, completely washed away the island. Since then, riprap in prodigious quantities has been laid to protect the structure from being undermined by scour. During the hurricane of 1916, the keeper reported that the vibration of the tower was so great as to displace half the water in a fire bucket in the watch tower.

Cape Hatteras Lighthouse: Cape Hatteras has experienced the erection of three towers. The first tower, 90 feet high and made of stone masonry was built in 1798. It was in use for over seventy years before being replaced by the second tower which was completed in 1870. The second tower, 193 feet above the ground, is the highest brick lighthouse in the world (Fig. 10). It was struck by lightning eight years after completion and subsequently large cracks appeared in the masonry walls. Remedial action was taken which saved the tower, but soon after its completion, there began a very gradual encroachment of the sea upon the beach. This erosion became serious when, in 1919, the high water line came within 300 feet of the base of the tower. Several attempts were made to arrest this erosion, by dikes and breakwaters, but these courses of action proved of no avail, In 1935, a

light was established on a skeleton steel tower placed farther back from the sea on a sand dune. The brick tower was then abandoned by the Lighthouse Service and placed in the custody of the National Park Service. The Works Progress Administration erected a series of wooden revetments which checked the wash that was carrying away the beach to the extent that in 1942, the Coast Guard resumed its control and established a lookout station in the old tower which by this time was 500 to 900 feet inland from the sea, and again tenable as a site for a light.

DEEP WATER FOUNDATION LIGHTHOUSES

Fourteen Foot Bank Lighthouse: The Fourteen Foot Bank Lighthouse is located in Delaware Bay (Fig. 11). Completed in 1887, it was a daring project for the times because it was the first lighthouse constructed in the United States using a pneumatic caisson process for placing the foundation. Plans were modeled after the Rothersand Light Station, Weser River, Germany. Both structures were built about the same time and in the same depth of water.

This lighthouse is presented because it clearly illustrates the method of constructing a pneumatic foundation. A timber working chamber 40 feet square with sides seven feet high was built on shore and launched. Over the crib were placed three courses of cast-iron cylinders 35 feet in diameter, 6 feet high made of built-up plates bolted together along the flanges (Fig. 12). An air shaft with air lock, through which the men passed to the working chamber, was erected on the foundation cylinder and braced to the shell plates. The portion above the working chamber was filled with concrete to give the caisson a draft of $15\frac{1}{2}$ feet. The caisson was towed to the site and was lowered into position in about twenty feet of water, by admitting water in the cylinder. The current produced considerable scour as soon as the caisson was grounded and it continued to sink about 8 feet until the roof of the working chamber rested on a mound of sand. Sufficient air pressure was maintained in the working chamber to keep out the water. The excavation was made in the caisson within the cutting edges, the sand being blown out through a blow pipe within the air shaft. The space within the shell was filled with concrete as the work progressed and about 1000 tons of riprap was placed around the base to prevent scour. The total height of the foundation cylinder is 73 feet. After 65 years, an inspection of the station indicates the structure is in excellent condition.

Many cylindrical structures of the type of architecture represented by the Fourteen Foot Bank Lighthouse have been built. However, the type of foundation and consequently the method of construction have been varied to suit the subsoil conditions encountered. In shallow water, the cylinder is placed directly on the prepared bed with riprap protection around the base. As deeper penetrations were required to secure mass to resist external forces, the site was dredged to achieve the desired depth. In deeper waters, the cofferdam and caisson methods have been adopted.

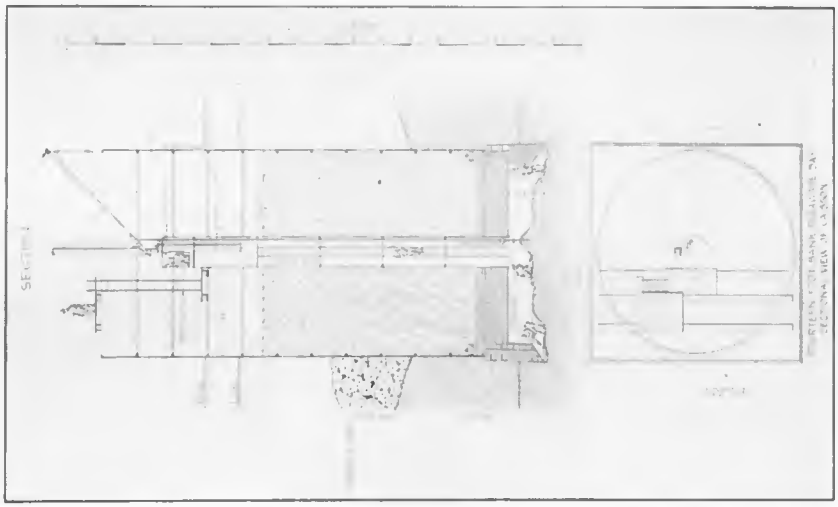


Fig. 12

Fig. 11
Fourteen Foot Bank lighthouse, Delaware Bay
(Established 1876, rebuilt 1886)

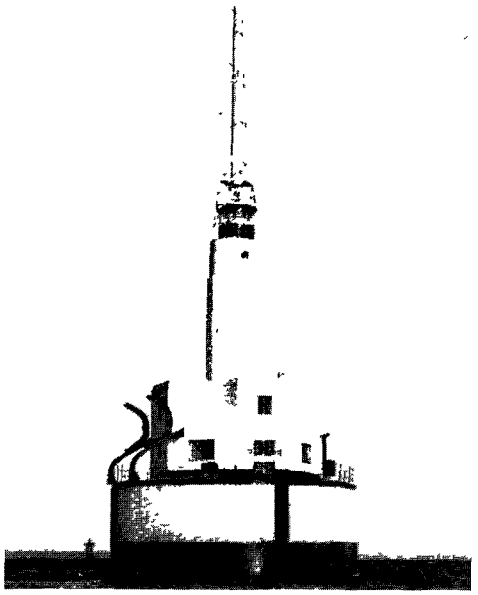
Cleveland Ledge Lighthouse: The Cleveland Ledge Lighthouse is one of the primary light structures most recently designed and built by the Coast Guard (Fig. 13a). It is located in Buzzards Bay, Massachusetts, at the western entrance to the Cleveland Ledge Channel approach to the famous Cape Cod Canal. The light station was commissioned on June 1, 1943, after three years of construction. The contract price for the project was a quarter million dollars, but the contractor defaulted after eight attempts to sink the foundation and the bonding company completed the job.

The structure is located in 21 feet of water on a sea bed of glacial drift consisting of sand, gravel and small boulders. The presence of boulders ruled out a sheet pile cofferdam type of design and a prefabricated caisson design was adopted instead. The steel caisson was erected on a timber grillage at a marine launchway. It was launched in the usual manner of launching a ship and then ballasted before being towed to the site and sunk.

The shell consisted of two concentric cylinders (Fig. 13b). The inner cylinder, which was assembled first, was 42 feet in diameter and 40 feet high. The outer cylinder, 52 feet in diameter and also 40 feet high, was erected around the small cylinder. Horizontal struts between the outer and inner shells of 2-inch pipe were spaced three feet on centers both horizontally and vertically. The two cylinders were assembled on a timber grillage of two layers of 12 by 12 inch full length timbers with a 1/2 inch space between each timber. The two layers were laid crosswise one to the other and drift pins at alternate crossings integrated the timbers into a unit. The shell was secured to the grillage by curved steel angles riveted to the outer and inner cylinders and bolted to timbers below.

A reinforced concrete mat 3 feet thick was then cast inside the inner cylinder over the timber grillage. The reinforcing bars of the mat were extended into the five foot annular space through holes drilled through the wall of the inner cylinder. Concrete was also cast in the annular space to a height of 8 feet. High-early-strength concrete was used throughout the job. The caisson was launched at this stage of construction.

Prior to towing to the site, reinforced concrete cross-walls, 3 feet thick and 18 feet high, were built within the inner cylinder, forming four quadrants. Each quadrant was then subdivided in half by an 18 inch thick wall and 10 feet high above the concrete mat. The reinforcing bars of the cross-walls extended into the 5-foot annular space, through holes drilled in the inner cylinder wall. Sufficient reinforced concrete was placed in the annular space to provide a draft of 19 feet. A temporary timber platform was then erected over the top of the structure and the caisson was towed to the site.



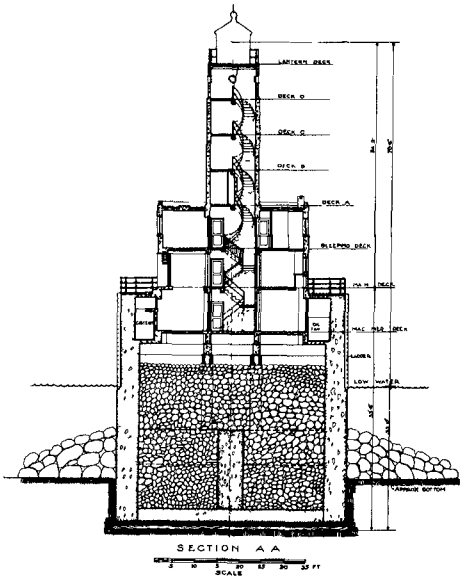


Fig. 13a

Fig. 13b

Cleveland Ledge lighthouse, Buzzards Bay, Mass.

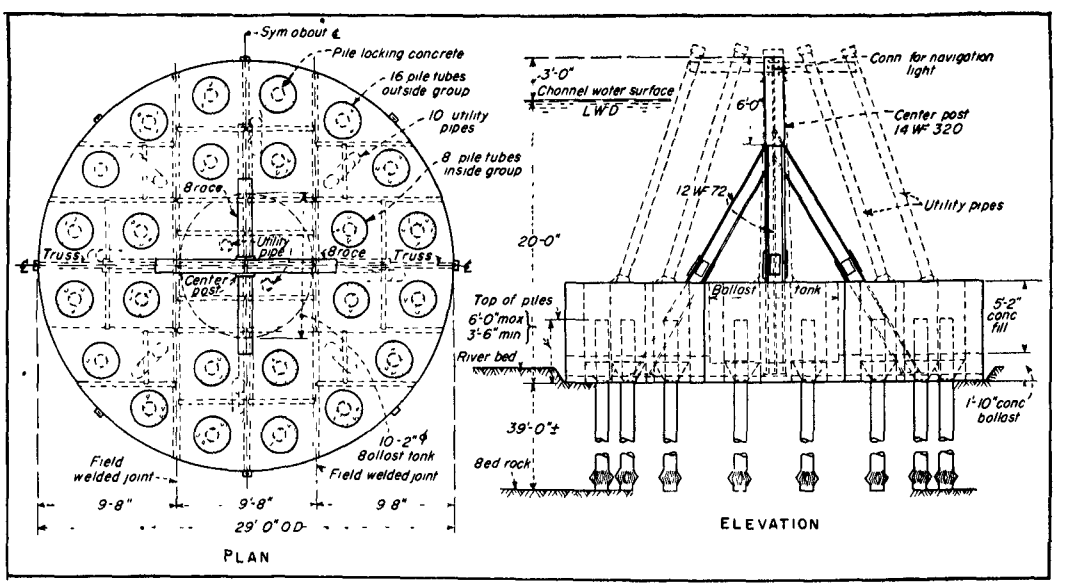


Fig. 14

The "Aquapad". Special expansion piles driven through pile tubes anchor the structure.

Meanwhile, the site was prepared by dredging a circular hole about 13 feet deep. The foundation was leveled off by divers and a one foot layer of crushed stone was spread over the bottom of the hole and leveled.

The caisson was lowered onto the prepared bed by opening flood valves and flooding the inner compartments and the annular space. The sinking operation was completed in $1\frac{1}{2}$ hours. However, the caisson did not come to rest properly on the prepared bed. The structure had to be refloated in order to redress the bed. This cycle of operations was repeated 9 times before the structure was acceptably seated. Prolonged foul weather, a listing of caisson while afloat and strong currents which made controlled sinking difficult proved too much for the contractor.

Sand fill then was dumped into the depression around the structure and leveled off by divers using a fire pump and hose. Riprap of stone from 1 to 3 tons each was placed around the structure to prevent scour.

The inner cylinder was ballasted with stones up to 10 inches in diameter and the compartments were de-watered to the top of the stones. The annular space was completely de-watered and filled with reinforced high-early-strength concrete. All subsequent operations were accomplished in the dry. The portion of the structure exposed to the sea from below low-water and above high tide is protected by a band of 3/8 inch thick wrought iron plate.

West Neebish Channel Light No. 13: The lighthouse structures so far described have been constructed either on land or in moderate depths of water. Primary lights in deep water are invariably installed on lightships. Lightships, of course, are not fixed structures and it is not unusual for them to drag anchor and be off position during severe storms. Then, again, lightships are unsuitable where heavy shifting ice or deep land-locked ice is encountered. For example, the yearly recurrent drama that makes newspaper headlines, is the great race which ore boats wage against ice floes on the Great Lakes. A premium is paid the boat and crew that succeeds in bringing the season's last shipment of ore from the Mesabi Range in Minnesota to the open ports in the lower lakes. These 600 foot goliaths must navigate the St. Mary's River via the West Neebish Channel which is only 300 feet wide. The channel is beacon-lighted quite similar to an airport runway, the lights being located at the edge of the channel where the water depth is 25 feet or more. Before the arrival of spring, Coast Guardsmen traverse the ice to prepare the lights for the ice-breakers which precede the first ore boats on their initial trip back to the range. It can be seen, therefore, that only fixed light structures are suitable for this waterway. They must be stable against both ice floes and stationary ice. Heretofore, the gravity type

structures depended on dead weight to resist the overturning and sliding forces imposed on them. The greater the assumed external forces, the more massive became the structure which in turn increased the surface presentment to the external forces of wind, ice and waves.

This paper so far has developed two basic concepts of design for lighthouses. Massive structures whose gravity loads are adequate, with a factor of safety, to overcome the external forces applied, and secondly, skeleton structures with relatively small applied forces and which are anchored in firm bottoms. The first mentioned type structure is exemplified by the Fourteen Foot Bank Lighthouse. In order to construct such structures, a large amount of equipment and large numbers of men working under hazardous conditions are necessary. The Cleveland Ledge Lighthouse required a cumbersome caisson which had to be floated into position. Subaqueous excavation and site preparation was necessary. The principle of using mass as the counteracting force is not very efficient because of Archimedes' law of buoyancy. There was also described the skeleton type lighthouses as exemplified by the Reef Lights of Florida wherein the surface presentment to the externally applied forces is comparatively small. The almost free standing piles which are characteristic of skeleton type structure would not be practical in deep waters especially where ice is encountered. It was found that the screw-tip type piles are subject to scour in the presence of ice floes. Many of the minor light structures supported on screw piles in the Delaware estuary had to be replaced for this reason.

The problem which presents itself, therefore, is to keep to the minimum the surface presentment to the external forces and to incorporate the desirable features of gravity type structures. The late Mr. John P. Emschwiller, formerly Chief Structural Engineer in Coast Guard Headquarters has solved the problem with an underwater foundation called the "Aquapad" (Anonymous, 1951). In essence, the aquapad is a prefabricated foundation which is towed to the site and sunk into position by ballasting with water. The aquapad is fixed to the sea bed by driving piles into pile tubes and interlocking the two structural elements with concrete or grout (Fig. 14). Anchorage for the integration are deformation rings both on the pile tubes and on the heads of the pile.

The principles of design of the aquapad can best be described by referring to the West Neebish Channel Light No. 13. The shell is made of 3/8 inch thick plate, 27 feet in diameter and 7 feet high. The proportions of the structure and the sizes of the elements are determined from the principles of ship design and are predicated on the depth to which the structure is to be sunk. Light No. 13 rests

in 24 feet of water. There are 24 pile-receiving tubes 30 inches in diameter which also serve as supplementary supports for the bottom plate and the top deck. The shell is further supported and integrated by internal trusses and circumferential angle iron bands and split Tee beams. The shell is watertight and contains a water ballast tank in the center. The heavy vertical post is the sole support of the superstructure, while braces at the quadrant positions laterally stay the center post and compel the structure to act as a unit when under stress. The feature especially to be noted is the small area of the center post which presents itself to ice action. For purposes of discussion, say that under the given circumstances, ice has a crushing strength of 800 lbs. per square inch and that the ice thickness is 20 inches. The center post, a 14 WF 320 lb. column core section, has a flange width of 16-3/4 inches with the major axis placed parallel to the direction of the prevailing ice movement. The center post accepts an ice thrust under these conditions of approximately 267 kips. Existing structures of the gravity type are about 20 feet in diameter which results in an ice presentment of about 4800 square inches. The ice thrust for gravity structures is approximately 4,000 kips. It becomes evident why almost all of the gravity type structures in the West Neebish channel have been replaced at least once, and practically all of them in use today have a definite list. The continued use of the gravity type structures entails a program of periodic replacement.

The Aquapad was designed to be fabricated in three sections and to be shipped by rail to an assembly and launching site. Shop fabrication included the installation of the stub sections of the center post and the four braces. Assembling of the three sections and installing the portions of the center post and braces above the deck was accomplished by field welding. The shell was launched and moored to a dock where the work of installing the reinforcing bars was completed. A predetermined amount of concrete ballast was poured in the bottom of the shell to give it a freeboard of $6\frac{1}{2}$ inches. The shell was lashed to the back of a scow and towed to the site. Despite inclement weather, the aquapad was lowered into position in $6\frac{1}{2}$ minutes by flooding the ballast tank. About half of the piles were driven in place and grouted in before the shell was de-watered. Driving the remainder of the piles completed construction.

Lake Huron Lightship Replacement: The aquapad installation at the West Neebish Light No. 13 has passed its initial winter's test and is considered a success. Coast Guard Headquarters has plans under way towards applying the aquapad principle to the replacement of the Lightship in Lake Huron at the entrance to Port Huron. The depth of water at the proposed site is 26 feet. The subsoil exploration reveals the strata below the lake bed to be sand.

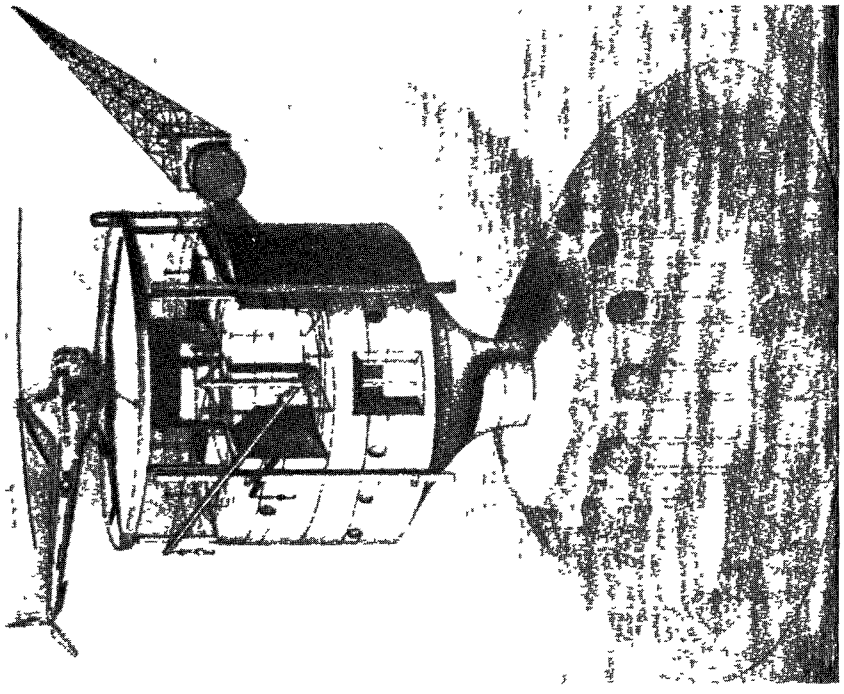


Fig. 16
Design concept of future aid-to-navigation.

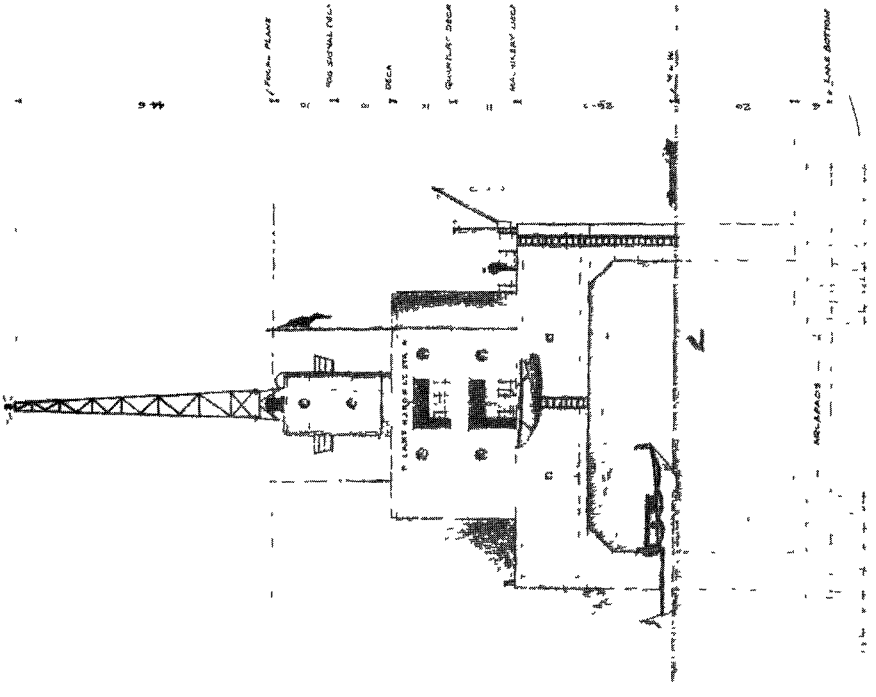


Fig. 15
Lake Huron lightship replacement.

A fixed structure is proposed as the replacement for the lightship on a foundation consisting of four aquapads. Four columns will emerge upright from the pads without interference of crossbracings at the water line and tied together at the top by haunched beams forming a three dimensional rigid frame (Fig. 15). Construction difficulties immediately present themselves. For instance, the question arises as to the practicability of setting the 4 aquapads sufficiently accurate in plan and elevation to subsequently accept the prefabricated superstructure. This requirement of construction is not too demanding when it is recalled that an aquapad is in effect a submarine and is easily maneuverable under water. In other words, with almost a nominal holding force, the aquapad can be either held in position or moved into any other position to make adjustments so necessary for prefabricated rigid frame construction in steel. The superstructure will be erected well above the high-water level. The lower deck will have a 5-foot working area around its periphery and will also be the machinery room floor. The upper deck will be quarters for the lighthouse attendants. Rising above the upper deck will be the tower structure supporting the lantern housing, with radio beacon antenna tower on top of the structure. The Lake Huron Lightship replacement will soon crystallize and in its successful completion will bring into full realization the significance of the aquapad principle of design in submarine construction.

The Coast Guard is projecting its design concepts even farther into the future. With the experience gained in successive applications of the aquapad, it is within the realm of practicability that lighthouses will someday have an architectural appearance of the nature shown in Figure 16. It is entirely functional and expressive of its structural system. Ice pile-ups will be of moderate significance since the spherical shape of the aquapad will minimize the effect of ice thrust against the structure. Further, the columnade of the superstructure will in some measure dissipate the energy of the waves. The radio antenna can be lowered by remote control to permit helicopter landings. It will be feasible to make helicopter landings when swells and rough water prevent tenders from approaching the lighthouse.

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