CHAPTER 24

SOME DYNAMIC ASPECTS IN THE DESIGN OF MARINE STRUCTURES ON THE GREAT LAKES

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INTRODUCTION

An investigation of the failures of a number of marine structures located in the southern portion of Lake Michigan has shown that forces must have existed at the time of failure of a type and of a magnitude whose significance to adequate design had not always been fully realized. The purpose of this paper is to indicate the probable nature of these forces and in one or two instances to estimate their magnitudes.

NATURE OF FORCES

The forces believed to be critical in the structures studied are the following:

1. Up-pressures acting on component elements of composite type breakwaters. These forces appear to be the result of hydrostatics as well as of the dynamic action of waves.

2. Horizontal dynamic pressures of high intensity resulting from breaking waves which act in the vicinity of the mean storm water surface.

3. Vibration resonance phenomena in certain structures which occur when the natural period of the structural system and sustained storm wave action coincide.

TYPES OF FAILURE

Rubblemound breakwaters. Repair and maintenance records for rubblemounds in the Chicago area indicate that this type of structure is subjected to disintegrating forces acting more or less continuously. The zone of marked destructive influence extends downward to approximately 12 feet below the mean lake level. The average annual loss of rock is often nearly as great for periods of little storm activity as for periods which included severe storms. Frequently the loss of stone is of the same order of magnitude for rubblemounds whose orientation and exposure would prevent direct storm attack as for breakwaters that are aligned and exposed so as to insure more direct storm wave action. Although no measurements are available it is believed that the disintegration is caused by long continued action of up-pressures induced by direct as well as reflected waves.

Sheet piling retaining walls. Two instances of failure of sheet piling walls so located as to expose them to frequent and sustained storm wave action shows the decided possibility of the existence of action of resonance between the applied period of the storm waves and of the natural period of the structural systems. In both cases the structures failed during storms of moderate intensity but of sustained duration (30 to 42 hours). The structural and corresponding storm wave periods were in the range of 6.5 to 7.0 seconds.

Walls on composite breakwaters. The displacement of very large cap stones on rubblemound breakwaters and the rupture of heavy concrete foot blocks on timber crib structures during intense storms supports the contention that severe dynamic forces must have occurred in the vicinity of the mean storm water surface. Evidence also indicated that dynamic wave action took place not only on sloping structures in relatively shallow water but occurred as well on breakwaters with vertical faces in water as deep as 35 feet. The concurrent action of up-pressures and of horizontal wave forces was evident in the cases investigated.

Cellular breakwaters. There has been only one case of complete failure of a cellular steel sheet piling breakwater in the lower Lake Michigan region (1949). These cells were sand filled with a water depth of 25 feet. An analysis of the causes of failure showed that wave forces of high intensity probably existed near the mean water surface and that vibration and wave overtopping caused loss of the sand fill. The resulting reduction of friction between the fill and the walls of the cells allowed slippage to occur along the vertical interlocks of the piling so that the structure was caused to fail by tipping. The possibility of this form of failure of sand filled cellular breakwaters had been pointed out by Dr. Karl Terzaghi in 1945.

DYNAMIC WAVE FORCE

The large forces exerted on breakwaters by storm waves in Lake Michigan, as is borne out by the destructive effects noted at or near the mean storm water surface, precludes the use of any design criteria which does not include the dynamic effects of breaking waves. Formulas such as those developed by Sainflou find application in the Chicago area only in those rare instances in deepest water where waves do not readily break. Perhaps this is due to the fact that the relatively short period waves representative of the Great Lakes break more frequently in moderately deep water than do the longer period waves of the oceans.

The following linear relationship between wave height and dynamic wave pressure was developed from the hydraulic bore equation, as modified by velocity coefficients evaluated from the solitary wave profile curves of Munk, and the dynamic resisting force of a stationary flat plate.

$$P_{max} = 133.6\ H \text{ (lbs./sq. ft., in fresh water)} \qquad (1)$$

Concerning factual information on maximum dynamic wave pressures, the measurements made by Capt. D. D. Gaillard, U.S.A., represents the only observations of prototype forces to be expected in the Great Lakes. A comparison of those observations and the pressures predicted by equation (1) is shown in Figure (1).

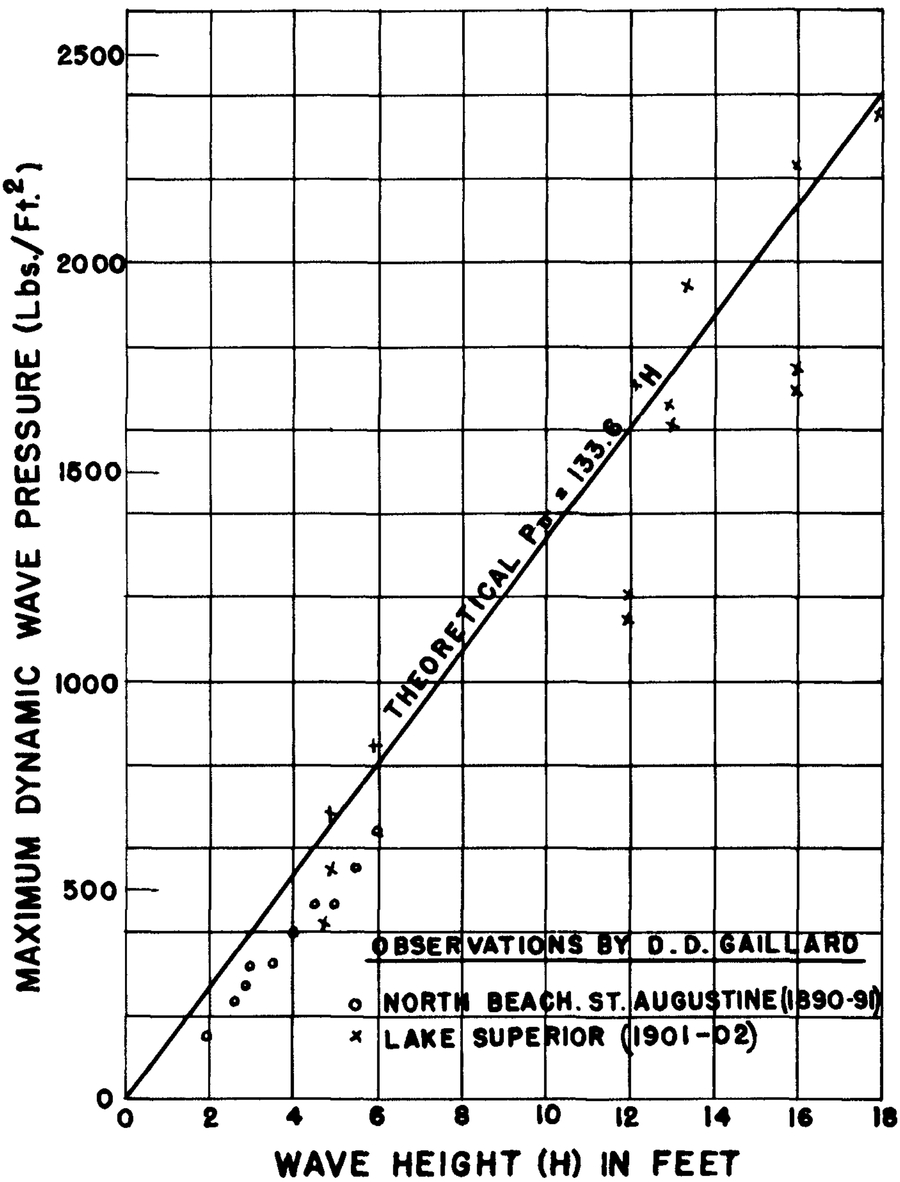

Fig. 1. Relationship between wave heights and maximum dynamic wave pressures.

EXAMPLES OF FAILURE

Gary Breakwater. As an example of the failure of a composite breakwater the United States Steel Company's structure at Gary, Indiana (Figure 2) will be analyzed so as to estimate the forces which had acted. This breakwater, see Figure 3, is a rock filled timber crib that had been capped with concrete. As a result of a severe storm on 25 and 26 November 1950 a 200 foot long section (2 crib lengths) of concrete cap slid laterally a distance of 3 to 4 feet. (Figure 5).

An anemometer located on the U. S. Steel unloading bridge at Gary, adjacent to the breakwater, recorded wind from NNW averaging 36 m.p.h. for 18 consecutive hours. During this period wave heights of 14 feet were estimated by attendants at the Chicago Water Intake Crib (Dunne). Recording wind gages at the South Side Filtration Plant and at the Navy Pier, Chicago, showed wind velocities similar to those at Gary.

Using wind duration-velocity and wave height curves it was estimated that the deep water waves were 17 feet in height with a 7.2 second period. The corresponding wave height at Gary breakwater (water depth of 35 feet) was computed to be 13.5 feet.

The concrete cap (Figure 4) weighs 25,600 lbs. per lineal ft. On the basis of a coefficient of friction = 0.6 (probably higher at failure), the force required to displace cap = 0.6 x 25,600 = 15,630 lbs. per lineal ft. Additional resistance to displacement was provided by 1⅛ " drift bolts spaced at 3'-0" centers in both walls. A conservative value for the resistance of drift bolts would be 1000 lbs. per lineal ft. based on the fact that they were probably stressed to the yield point before displacement of the cap could have occurred. Therefore, the total resistance to sliding was 16,630 lbs. per lineal ft.

Depending upon the magnitude and distribution of uplift that acted, it appears that the wave force acting on the Gary breakwater to cause failure had a peak intensitv of from 1440 lbs. per sq. ft. to 2500 lbs. per square foot (based on a horizontal force pressure distribution curve in which the average intensity is 50% to 67% of peak intensity).

Cellular Breakwater, Indiana Harbor. During the same storm of November 1950, a sand filled steel sheet piling cellular breakwater failed by tipping at Indiana Harbor (located NW of Gary, Figure 2). In this instance the maximum dynamic pressure to cause failure for a computed wave height at the breakwater (depth = 25 ft.) of 12 feet was approximately 1800 lbs. per sq. ft.

Other Cases. Captain Gaillard has reported similar earlier failures of marine structures in the Great Lakes. A notable example occurred at the north breakwater, Buffalo Harbor, New York, during the storm of 12 September 1900. The breakwater was of the crib type with capstones 5 feet high, and bases 7 ft. x 8 ft. Each block weighed 27,800 lbs. A rough computation indicates that in the vicinity of the mean storm water surface the average wave force required to displace the stones must have been in the range 600-1000 lbs. per square foot with corresponding peak pressures

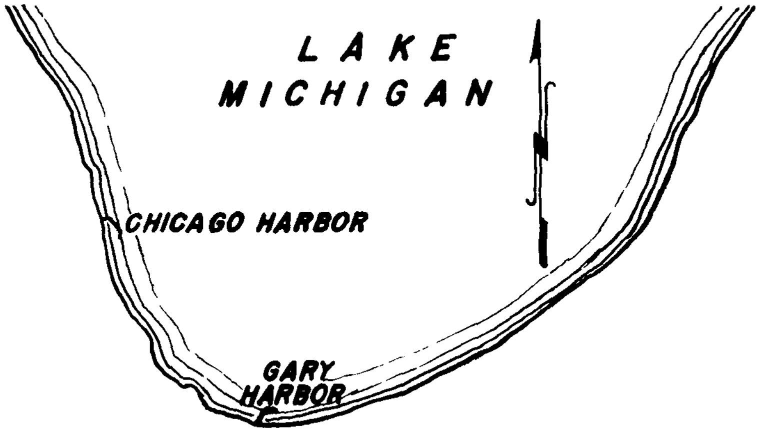

Fig. 2. Vicinity map, Gary Harbor, Indiana.

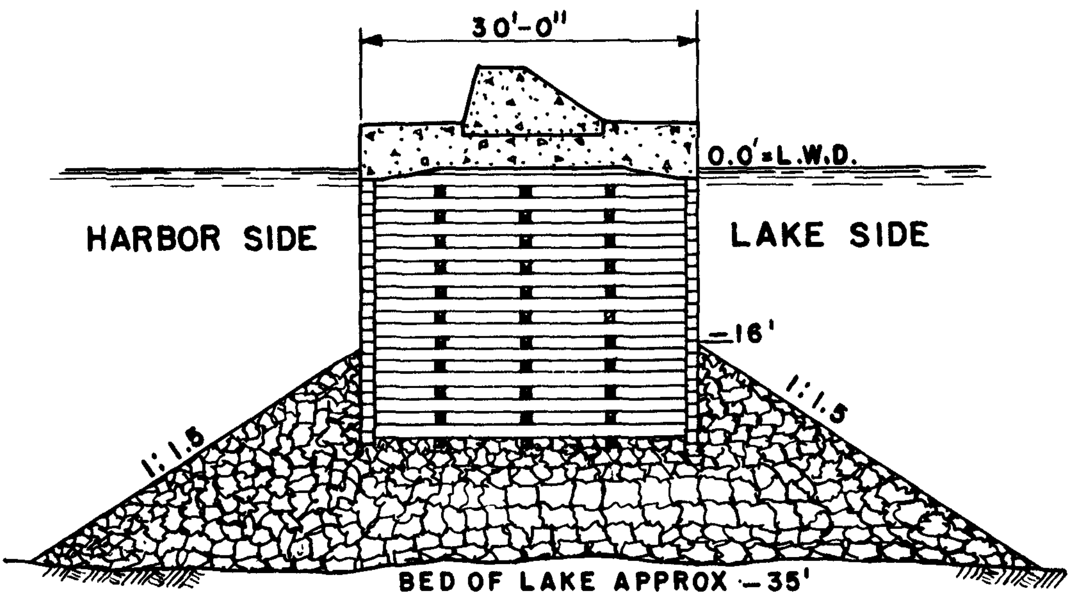

Fig. 3. Cross-section of Gary breakwater

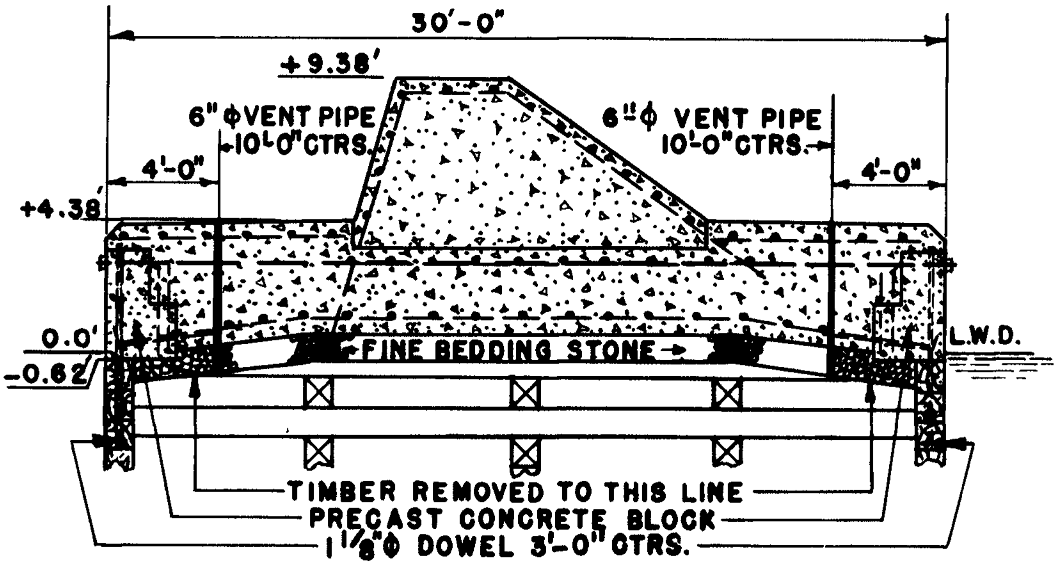

Fig. 4. Details of cap stone construction.

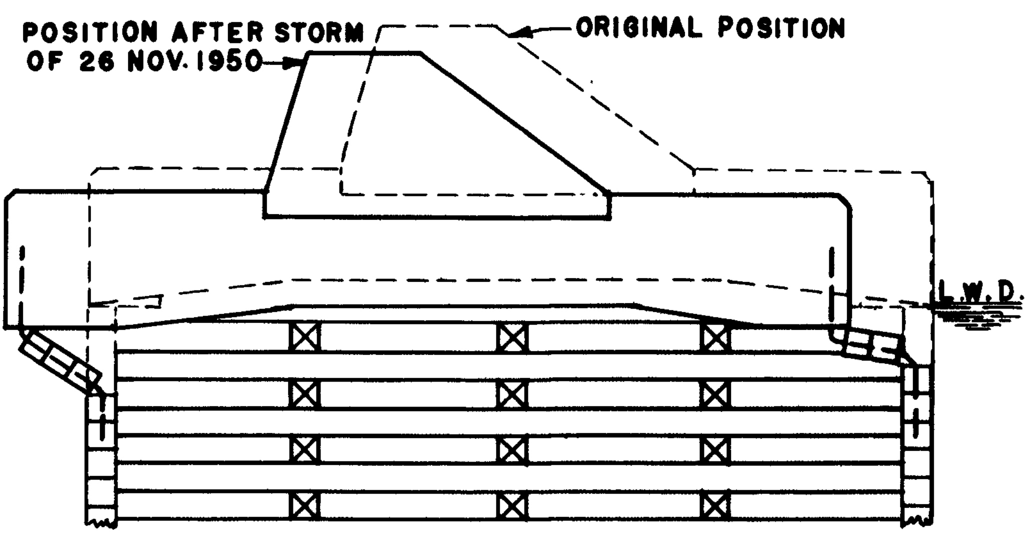

Fig. 5. Displacement of cap stone during storm of 25-26 November, 1950.

of 1000 to 1900 lbs. per square foot, depending upon the uplift assumed acting concurrently.

CONCLUSIONS

The foregoing description and analyses of failures of marine structures in the Great Lakes indicates the not infrequent occurrence of heavy wave pressures (and concurrent uplifts) that can only be adequately accounted for as resulting from forces set up by waves breaking in relatively deep water. Studies of this type indicate the desirability of further study of the nature and measurements of the magnitude of these forces so as to be able to determine adequate design criteria.

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