CHAPTER 16

LITTORAL PROCESSES IN LAKES

W. C. Krumbein
Department of Geology
Northwestern University
Evanston, Illinois

INTRODUCTION

Lakes differ from the oceans in being smaller, shorter lived, and tideless. Lakes may have fresh or salt water, in some instances with salinity far exceeding the normal ocean. In the most general case, a lake is a body of standing water occupying a depression in the earth's surface. The depression may be produced by a variety of geological processes, giving rise to several classes of lakes.

Lakes are classified according to origin into the following groups:

1. Glacial lakes
2. Flood plain lakes
3. Coastal or deltaic lakes
4. Deflationary lakes
5. Lakes of volcanic origin
6. Lakes of diastrophic origin
7. Artificial lakes

Each of these classes has certain attributes, of which some are important in application of engineering principles to construction problems. The characteristics are briefly reviewed as a preliminary to discussion of littoral processes.

CHARACTERISTICS OF LAKES

Glacial lakes. Glacial lakes occupy depressions developed by glaciation. Cirque lakes in rock basins are characteristic of upper parts of glaciated mountain areas. "Paternoster lakes" are chains of lakes along glaciated valleys, occupying rock basins or depressions in glacial deposits. The High Sierra and the Rocky Mountains provide numerous examples.

Continental glaciation, represented by ice sheets of the Pleistocene, produced several kinds of lakes. In areas of ice erosion (eastern Canada) many of the lakes occupy scoured rock basins. In the north central United States the glacial lakes are associated with depositional features.

The lake regions of Wisconsin and Minnesota are almost entirely of glacial origin. The lakes occupy irregularities of the glacial drift surface, produced by damming of drainage lines, by moraines, and by associated meltwater processes. These glacial lakes range from small ponds to large bodies of water with sufficient fetch to develop significant wave action.

Glacial lakes as a class are shallow. Shore features, other than rims of boulders or pebbles, are uncommon in mountain lakes. Glacial lakes in drift may have well-developed beaches, but they are commonly narrow and may be localized. The bottom deposits in glacial lakes in Wisconsin and Minnesota include sand or silt, soft dark mud, and marl (a calcareous clay), lying on the original foundation of stony clay (glacial till) or bedded sand and silt.

Flood plain lakes. Flood plain lakes are formed in valleys by normal stream processes. Ox-bow lakes are most common, produced by meander cut-off. Other lakes may occur along the flood plains of wide valleys, especially where the river level is higher than the flood plain and confined behind a levee. Less common flood plain lakes may be produced by land slides or similar phenomena.

Flood plain lakes are mainly small and ephemeral. They seldom show shore features, and tend rapidly to be occupied by vegetation to become swamps and marshes. The deposits are mainly organic-rich mud, lying on the foundation of normal flood plain deposits below.

Coastal or deltaic lakes. Lakes may form along coasts by development of barrier beaches, bars, spits, or migration of dunes which isolate bodies of water from the sea. The lakes may start as salt or brackish lagoons, becoming fresh by contributions from streams. Deltaic lakes are similar, formed by changes in river channels or by combinations of stream and coastal processes.

Coastal lakes are commonly shallow, and in some the waters may become partially restricted in circulation, giving rise to stagnant conditions. Bottom deposits range from clean sand to dark organic-rich mud. Coastal lakes are completely cut off from the sea and are tideless. They receive most of their sediment from associated streams.

Deflationary lakes. Lakes of deflation occur in arid regions, where wind work may scour shallow basins. The lakes are commonly shallow and subject to evaporation. The water may be saline, forming evaporitic deposits associated with sand, silt, and mud carried in by temporary streams. Deflationary lakes seldom have a true littoral zone, owing to the wide range in their expanding and shrinking areas.

Lakes of volcanic origin. Volcanic processes may produce lakes by damming of drainage lines by lava flows, or by development of calderas from volcanic explosions. Lake Tahoe is an example of the former, and Crater Lake, Oregon, is a type example of the latter. Volcanic lakes are small to moderate in size, and they may have steep sides, rugged outlines, and considerable depth. Associated deposits are re-worked volcanic debris.

Lakes of diastrophic origin. Earth movements are responsible for the formation of some lakes. Abrupt dislocation of rock strata (faults) during earthquakes may produce depressions or alter natural drainage. The lakes along the San Andreas fault south of San Francisco furnish examples. Slower downwarping of the earth's surface due to long-time isostatic adjustment may also develop lakes. The Great Lakes, although formed initially by combination of glacial scour and depositional disturbances of normal drainage, show evidence of basin tilting due to post-glacial elastic adjustments of the earth's surface. Basins of interior drainage, with deflation (playa) lakes, are commonly of diastrophic origin.

Lakes of diastrophic origin may range from large to small, with depths from shallow to great. Except for fault-produced lakes, many of them are among the larger lakes of the earth. The deposits in large lakes may not differ markedly from similar deposits in the oceans in terms of their physical attributes (texture, composition, and structure).

Artificial lakes. Here are included all man-made lakes, which range from small ponds to major bodies of water. Artificially dammed lakes are commonly located along valleys and are linear or branched in form, often with steep sides and moderate depth. Deposits in artificial lakes include sand and silt brought down by the original stream, which may form a delta at its mouth, and spread a blanket of finer material over the lake bottom. Deposits laid by density currents appear to be more common in these linear lakes with stream-bottom gradients than they are in more ovate, gentler-bottomed natural lakes of equivalent size.

LAKE PROCESSES

A number of lacustrine processes are sufficiently different from their oceanic counterparts to warrant mention.

Overturn. Seasonal changes in temperature in temperate regions causes an overturn of lake water. Cooling of the surface in late fall causes a sinking of the heavier water, with displacement of warmer water from below. This continues until the lake temperature is 4° C. throughout, whereupon the surface water remains at the surface until and after freezing.

In the spring the surface temperature is again raised to the point of minimum density, with another overturn. During the ensuing summer the surface water is further warmed and remains at the surface, whereas the lower cooler water may become oxygen-depleted. The main effects of overturn are a complete replenishing of oxygenated waters through the lake.

Overturn does not occur in tropical or polar regions. In the former the cooler water at the bottom is commonly stagnant. In polar regions the warmer stagnant water is at the bottom, with a layer of colder water at the top.

Ice shove. In temperate regions the work of ice may be very important in its effect on the shore. Small lakes display the effects of ice above, which may push and distort the shore deposits into irregular ridges.

Ice shove occurs where the lake surface is small enough to permit the surface ice to act as an essentially rigid mass. During extreme cold spells the ice contracts and develops cracks which fill with water and are refrozen. During a later temperature rise the ice expands and thrusts against the shore.

In larger lakes ice damage is mainly the result of ice floes moving against installations. In Lake Michigan broken ice floes frequently form extensive icefields which may be driven against shore by onshore winds. Such icefields serve as protection against severe wave action, but the ice exerts heavy pressures and abrasive forces against structures. Timber piles are particularly subject to such abrasive forces.

Life history of lakes. A characteristic of natural lakes is that they are relatively short-lived in a geological sense. Various processes tend toward the extinction of lakes, but the time required depends largely upon the size of the lake and the dominant process.

Three general processes which destroy lakes are recognized. The first is the lowering of the outlet by streams flowing from the lake. The lake level drops as the outlet lowers, until the entire lake basin may be drained. Diastrophic processes which tend to warp the lake basin may entirely eliminate a lake through slow tilting.

The third process of lake destruction involves filling the lake basin with vegetation or sediment. Sediments may be introduced by streams or by wind. Vegetation gains a foothold on the shallow borders of lakes, and gradually grows farther into the lake. Filling by vegetation is particularly common in glacial lakes, which become converted into peat bogs, muskegs, or marshes.

Artificial lakes are particularly subject to filling with sediment, as is evidenced by the numerous dammed lakes in which reservoir silting has become a serious problem.

FEATURES OF LARGE LAKES

Large lakes display the same processes as small lakes, but because of greater wave fetch, shore processes are much more pronounced, and locally or temporarily may attain the order of magnitude of average shore conditions on the oceans. Large lakes are also more important than small lakes in terms of harbor development, protective structures, beach maintenance, and other engineering aspects.

LAKE MICHIGAN

The writer is most familiar with Lake Michigan, which will be taken as an example of a large lake. The lake is about 320 miles long, and 80 miles maximum width. The surface area is 22,500 square miles. Its greatest depth is 870 ft., and its surface lies about 580 ft. above mean sea level at New York.

The western shore of the lake has been studied by the writer in more detail than the eastern. The stretch of greatest interest to the writer extends from Milwaukee to the southern end of the lake. Specifically, many of the observations on waves and currents mentioned below were made at Northwestern University, just north of Chicago, under research grants from the Graduate School.

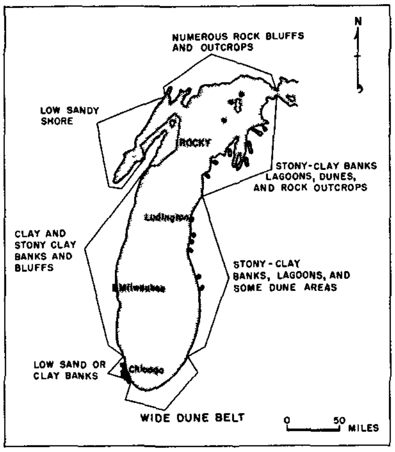

Fig. 1. Shore features of Lake Michigan

Shore features of Lake Michigan. Fig. 1 is a sketch map of Lake Michigan, showing a classification of its shores. The northern shores, including the peninsula along Green Bay, are typically rocky, with limestone bluffs and pocket beaches. The western shore is characterized by clay or stony-clay bluffs with relatively narrow beaches along most of its extent. The eastern shore is an alternation of stony-clay bluffs and sand spits with lagoons, and wider beaches on the average than the western shore. Some rocky areas occur along the northeast. The southern shore has a wide sand beach backed by an extensive dune area.

Beaches along the western shore are seldom more than 100 ft. wide. The slopes vary from 1 on 5 to 1 on 60, with an average slope of about 1 on 30. The beach composition ranges from pebbles to sand, with sand beaches more common.

The banks or bluffs along the western shore range from 10 or 15 ft. to more than 100 ft. high. The southern part of the western shore was low in its natural state, and is now almost wholly fronted by sea walls or bulkheads from Chicago to the Indiana state line.

Milwaukee, Waukegan, and Chicago have the most important harbors along the southern part of the western shore. Many parts of this stretch have also been improved with bulkheads and groins. This is especially true of the residential districts between Chicago and Waukegan, and adjacent to other cities along the lake.

Winds, waves, and currents. Along the southwestern part of Lake Michigan the winds blow from the north 17 percent of the time, from the northeast 7.5 percent, from the east 6.9 percent, and from the southeast 8.9 percent of the time. These winds control the waves which strike the western shore. From a four-year daily record at Evanston, it was found that the lake was calm or essentially so (waves less than 6 in. high) about 7 percent of the time. Waves from the northeast occurred about 47 percent of the time, from the east about 15 percent, and from the southeast 31 percent.

For the four-year period from summer, 1946 to summer, 1950, the average period of all waves, regardless of direction, was 3.6 sec. at Northwestern University. For the northeast and east waves the average was 4.4 sec., and from the southeast, 3.0 sec. Waves from the southeast were 5 sec. or less for 96 percent of the days. For northeast waves the periods were 5 sec. or less for 67 percent of the days, 7 sec. or less for 94 percent of the days; and the longest average period observed from the northeast was 10.5 sec.

For the same period, the average wave heights at the breaking point for waves from all directions was about 1.0 ft. For northeast and east waves the average was slightly larger, and from the southeast slightly smaller. The "significant wave", as an overall average, was 1.6 ft. from the southeast, and 2.3 ft. from the east and northeast. The highest average waves observed were from the east, with height 6.5 ft. The largest individual waves observed at the breaking point did not exceed 10 ft., and were in fact probably not larger than 8 ft. in height.

Other wave data, collected offshore at Milwaukee, during 1931 and 1932, showed that waves exceeded 3 ft. 39 percent of the time (in contrast with 10 percent at Northwestern). Waves more than 10 ft. in height occurred 1.1 percent of the time, in contrast with no average values that large at Northwestern.

In general, it appears that the southern half of the western shore of Lake Michigan has an expected average wave height at the breaking point of the order of 1.5 to 2.5 ft. during any given year. The maximum average wave height at the breaking point may be of the order of 8 ft., with individual waves at the breaking point not exceeding 10 ft.

Refraction plays an important part in wave heights at the breaking point. It is noticeable at Northwestern that storm waves from the east, which approach the shore head on, are larger than northeast waves, despite the much longer fetch of the latter.

Shore currents along the western shore of the lake flow southward about 50 percent of the days, and flow northward about 30 percent of the days. During calms or when the waves are from the east, no strong unidirectional currents occur. Data are sparse on currents, but it is observable that the southward-flowing currents are stronger than those flowing north, owing to the greater energy content of the northeast waves. The strongest current observed was 3.5 ft. per sec. to the south.

Changes in lake levels. Lake Michigan, in common with the other Great Lakes, displays seasonal and long-time fluctuations in level. The datum of the lake is 578.5 ft. Since 1900, the highest monthly mean level was 582 ft. in July, 1929. The lowest monthly mean in the same period was 577 ft. in January, 1926.

The major cycles of lake level have a period of 10 to 11 years, and an amplitude of the order 3 to 5 ft. Since 1900, peaks were attained in monthly average elevations during 1907-08, 1913, 1917-18, 1929, and 1943. The cycles are irregular, with secondary peaks and troughs. The cause of the cycles is not fully understood. Presumably they depend upon ground water and evaporation conditions, inasmuch as no major streams enter the lake.

Seasonal changes in lake level are shown by higher levels in the summer and lower in winter. The annual range in elevation is 0.5 to 2.5 ft. In 1949 the annual range was 1.7 ft.

The principal effect of changing lake levels is its control of shore erosion. During high stages of the major cycle, storm waves are able to undercut the bluffs, and the severity of the erosion is a function of combinations of high levels and larger-than-average storms.

Lake Michigan displays no visible tidal effects, and it is estimated that the tide is about 2 in. Irregular shorter changes in level, called seiches, occur due to variations in barometric pressure over the lake.

Sand movement. The net movement of sand along the western shore of Lake Michigan is southward. In the lake's natural state, sand derived from the bluffs in the stretch from the foot of the peninsula at Green Bay (see Fig. 1) to Chicago was slowly carried southward, and accumulated in the natural trap at the south end of the lake to form the large belt of Indiana dunes.

Seasonally there is a slight reverse in sand movement, owing to the prevalence of southeast waves during summers. This reverse movement is much less significant than the southward movement associated with fall, winter, and early spring currents moving southward.

Estimates of sand drift along the shores were made at several localities by the Beach Erosion Board in cooperation with local or state agencies. In general, it was found that the drift is lean compared with usual ocean standards. Maximum amounts are of the order of 40,000 cubic yards per year, with averages of the order of 5,000 to 10,000 cubic yards. Detailed studies show that the shore drift varies considerably along the western shore of the lake, depending upon configuration of the shore, nature of bluff material, presence of bulkheads or groins, and harbor structures.

An important feature affecting the amount of shore drift is the availability of unconsolidated materials for erosion. Surveys show that the average natural rate of erosion for the stony-clay bluffs near Milwaukee was about 2 ft. per year. It is estimated that this would feed about 35,000 cubic yards of debris into the lake per mile per year, of which 20 percent is sand and pebbles, and the remainder silt and clay. Along the bluffs farther south, the natural rate of erosion may have been 3 ft. per year, with local rates as high as 10 ft. per year along certain low sand banks.

Present-day protective structures along the lake have probably reduced the effective erosion to one-fourth or less of the natural rate. To a large degree the intervals of erosion are now confined to storm seasons during times of high lake level. The period 1943-47 was characterized by high lake levels, and erosion was markedly greater than during the preceding decade.

ENGINEERING STRUCTURES

Numerous typical shore structures, including breakwaters, sea walls, bulkheads, revetments, jetties, and groins have been constructed along the lake shore. Of these, the writer is most familiar with groins as structures for creating or maintaining beaches.

The permeable groin, developed by S. M. Wood, had some of its earliest installations in the general stretch from Chicago to Milwaukee, and numerous examples may be seen. The groins are constructed of pre-cast concrete, and have an increasing permeability lakeward.

The most common type of groin has been the short impermeable wooden type, made of piles or sheeting. Wooden cribs, filled with broken stone, are also commonly used as large groins or jetties. More recently, steel sheet piling groins have come into extensive use, some with openings to make them partially permeable.

In areas where the drift is very lean, or where the shore is protected by sea walls or bulkheads, as along the lake front in Chicago, beaches have been constructed with imported sand. The structures include a large impermeable hooked concrete jetty at the south end of the system, with shorter wooden or steel groins spaced along the beach north of the main jetty. The sand is placed in the system, and slowly migrates southward until trapped by the hooked jetty. Periodically sand may be carried or pumped to the north end of the system to renew the cycle.

In a recent study of the Illinois shore line of Lake Michigan, the Beach Erosion Board recommended similar systems for other localities with lean drift. For more normal shore conditions the Board recommended impermeable groins with a horizontal portion at about berm level, and a 1 on 25 slope under water to the low water datum. The width of the horizontal portion depends upon the width of the beach, and the slope of the lakeward portion may be adjusted to stable beach slopes for the exposure and sand size.

CONCLUDING REMARKS

The purpose of this paper is to present the general topic of lake processes to an engineering audience from a geological point of view. It is apparent that the shores of larger lakes present many problems in common with the sea coast, but the absence of tides, and of first-rank storms, means that geological processes are less marked, and structures may in general be smaller.

In contrast to many coastal areas, the Great Lakes probably have less consolidated materials in their banks and bluffs, inasmuch as the basins lie mainly in glacial deposits. Hence rates of erosion may be much greater than on harder coastal rocks. The effect of long-period changes in level also introduce problems of selecting distances above and below lake datum in structures, to allow for the more shoreward wave action during times of high levels.

The much leaner shore drift along lakes as compared to the oceans also means that problems of beach development and maintenance may be more difficult to solve. Greater reliance on imported sand in closed systems seems to be the trend in some larger communities where the demand for recreational beaches is great.

It is interesting to note that in some respects lakes may be considered as models of the ocean. For the southern part of the western shore of Lake Michigan, it is the writer's impression that the scale factor (based on wave period and height) is of the order of 1/9 for the length dimension, and 1/3 for time. Much more data are needed from systematic wave and current measurements, to obtain a better basis for comparison. Further data on the relative behavior of standard shore engineering structures under lake and ocean conditions would also be very useful.

REFERENCES

Beach Erosion Board (1946). Beach erosion study, Lake Michigan shore line of Milwaukee County, Wisconsin: House Doc. 526, 79th Cong., 1st Session.

Johnson, D.W. (1919). Shore processes and shoreline development: John Wiley and Sons, New York.

Krumbein, W.C. (1944). Shore processes and beach characteristics: Tech. Memorandum No. 3, Beach Erosion Board, Corps of Engineers, Washington, D.C.

Krumbein, W.C., and Griffith, J.W. (1938). Beach environment in Little Sister Bay, Wisconsin: Bull. of Geol. Soc. Amer., vol. 49, pp. 629-652.

Shepard, F.P. (1937). Revised classification of marine shorelines: Jour. of Geology, vol. 45, pp. 602-624.

Shepard, F.P. (1948). Submarine geology: Harper and Brother, New York, Chapter 4.

Worcester, P.G. (1938). A textbook of geomorphology: D. Van Nostrand Co., New York, Chapter 11.