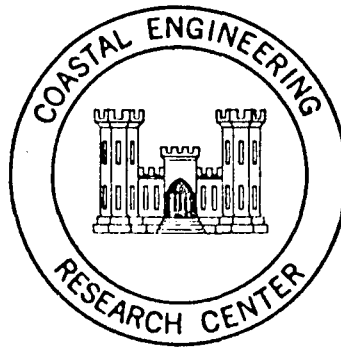# EFFECT OF PARTICLE SIZE AND DISTRIBUTION ON STABILITY OF ARTIFICIALLY FILLED BEACH PRESQUE ISLE PENINSULA PENNSYLVANIA

by

D. W. Berg and D. B. Duane

REPRINT 1– 69

APRIL 1968

U. S. ARMY, CORPS OF ENGINEERS

COASTAL ENGINEERING RESEARCH CENTER

U. S. ARMY

COASTAL ENGINEERING RESEARCH CENTER

June 1969

ERRATA SHEET

for

"Effect of Particle Size and Distribution on Stability of
Artificially Filled Beach, Presque Isle Peninsula, Pennsylvania"
by Dennis W. Berg and David B. Duane.

Page 162. Figure 1 - should read Borrow Area A and Borrow Area B.

Page 163, 168 and 169, Figures 2, 5 and 6. Legends should read
    "Coarse fill envelope"

Pages 170, 171, Figures 7 and 8. In each case the figure has been
    reversed from top to bottom; in each case, the (a) refers to the
    bottom figure, the (b) refers to the one on top.

Pages 175, 176, Figures 9, 10, and 11. The first two words in the
    last sentence of the captions should read "Juxtaposed is" instead
    of "Superposed in". This is also true for the same phrase in the
    first line of text on page 176.

Page 177. Third paragraph, third line, should read "spring-summer low
    values" instead of "high values".

EFFECT OF PARTICLE SIZE AND DISTRIBUTION ON STABILITY OF ARTIFICIALLY FILLED BEACH, PRESQUE ISLE PENINSULA, PENNSYLVANIA[1]

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Abstract. Presque Isle Peninsula, a sandy spit on the south shore of Lake Erie, has experienced continued erosion of its lakeside shoreline ever since first attempts to stabilize and halt its natural eastward migration. For nearly 150 years numerous structures have been built on the shoreline in attempts to slow down or halt the deterioration and migration of the Peninsula and consequent loss of valuable land.

In 1965, approximately 1.27×10^4 m^3 of sand fill, coarser than fill previously used as well as coarser than that which naturally existed on the Peninsula, was placed on a section of the beach; subsequently annual data collection surveys were made in the fill area and in or adjacent parts of the Peninsula.

Analysis of the data indicate the test area involving coarse sand fill has undergone minimal material loss and maintained a relatively stable profile. On the basis of this experiment it is judged that definite shore stabilization occurs, with attendant benefits such as substantially reduced nourishment requirements, from the utilization of sand fill that has size characteristics superior to that originally found on an eroding beach.

INTRODUCTION

Background. Presque Isle Peninsula, a compound, recurved sand spit located on the southern shore of Lake Erie at Erie, Pennsylvania (Fig. 1) projects approximately 4 km into the Lake and has a lakeward shoreline of nearly 10 km. Periodic surveys of the peninsula begun in 1819 show that it has migrated in an easterly direction in excess of 800 m. Since the peninsula acts as a natural breakwater for Erie Harbor, the preservation of peninsula in its present location has been the cause of many plans of erosion control, not all totally successful. In the late 1930's, the first comprehensive study of Presque Isle was initiated, resulting in a beach erosion control plan that was designed to alleviate the erosion of the narrow westerly section of the peninsula and halt its eastward migration. The resulting project, shown on Fig. 1, completed in 1956, was comprised of restored beaches on the lakeside shoreline and a system of groins to retard the expected erosion of the restored beach on the westerly section of the peninsula.

Prior to construction of the project, the estimated erosion rate of beaches in the critical western section of the peninsula was approximately 15,000 m³/year. After the project had been in operation for several years this estimate had been revised to roughly 115,000 m³/year. Later studies by the Coastal Engineering Research Center have indicated that the long-term average erosion rate of this westerly section of Presque Isle is probably more on the order of 138,000 to 153,000 m³/year. Furthermore, earlier studies indicated that the erosion rate varied as the yearly mean lake level of Lake Erie varied:
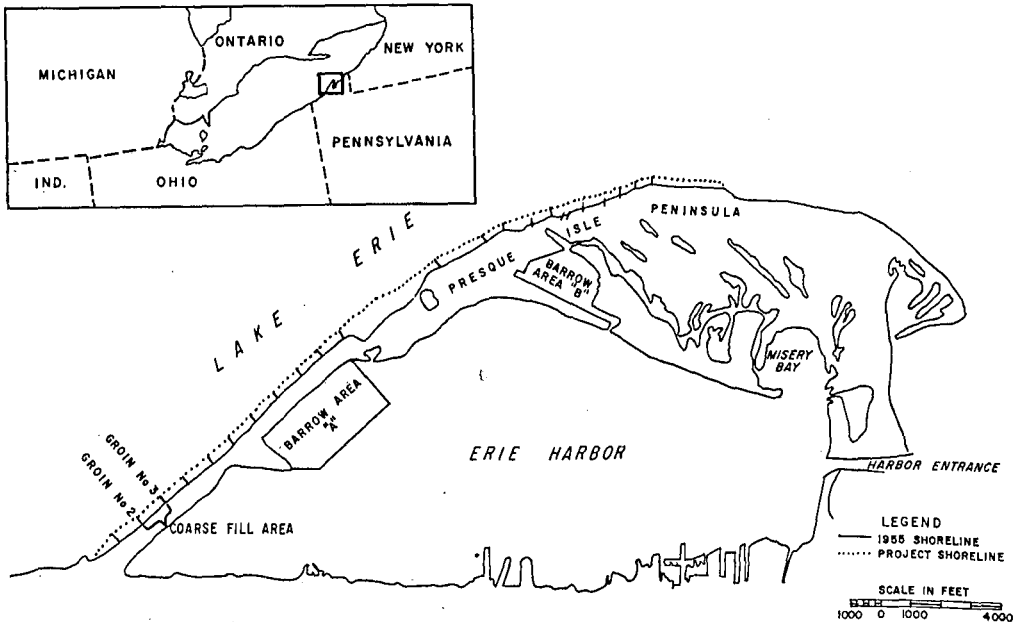

FIG. 1. Study area. Location of coarse fill area in relation to general plan of Presque Isle Peninsula, Erie, Penn.

increasing as the mean rises and falling as the mean annual lake level lowers (Berg, 1965).

Among many variables, stability of beaches depends upon the size distributional characteristics of the material that comprises the beach and nearshore underwater bottom topography. The beaches of Presque Isle prior to construction of the beach erosion control project exhibited median diameters of approximately 2.1 ϕ. Because of a readily available source of material in the harbor formed by the peninsula the material selected for original restoration of the beaches was somewhat finer with a median diameter of 2.32 ϕ (Berg, 1965). It is judged that the fine size of fill material, as reflected by the median diameter, explains in part the increased erosion rate of the westerly sections of the peninsula. Subsequent nourishment of the beaches in 1961 and 1965 utilized materials from 1955-56 borrow areas. Nourishment in 1965 was confined to the area east of the groin system with the exception of coarse fill which was placed between groins 2 and 3 (Fig. 1).

Experiment Design. Purpose of the coarse fill (mean particle diameter coarser than that for the fill previously used) was to test the thesis that coarser sediment would better withstand the erosive forces acting on the peninsula.

Fill material selected for this test, 12,700 m³ was supplied by a commercial aggregate company from an offshore source and was blended to meet size specifications of Pennsylvania Highway Department Type "A" concrete aggregate. This criteria, considered fine aggregate for concrete, is actually considerably coarser than fill material used in the original beach restoration and subsequent beach nourishment of 1961 (Fig. 2). The sediment represented by the coarse fill envelope is positively skewed with a mean diameter of approximately 0.4 ϕ and a standard deviation of approximately 1.5 ϕ. Particle
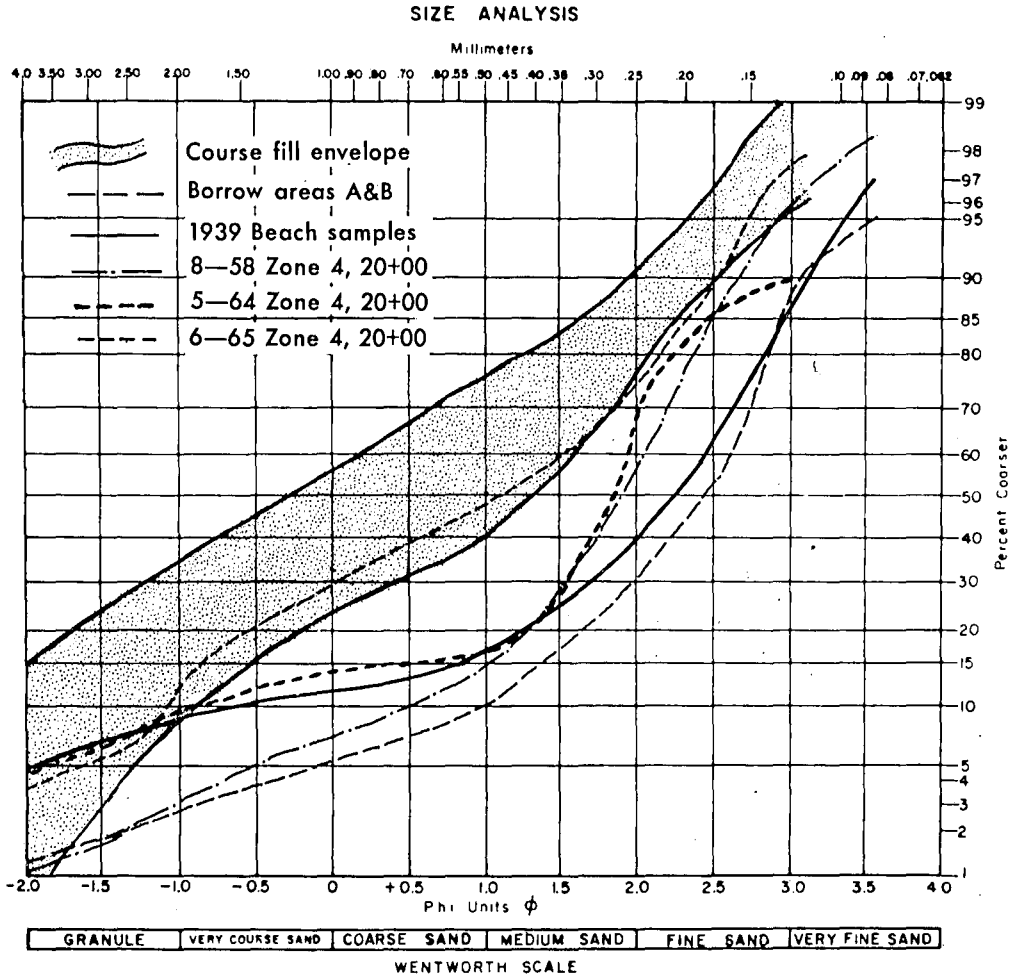
SIZE ANALYSIS

FIG. 2. Cumulative frequency curves. Characteristic curves of postfill sediment compared to specified coarse-fill envelope and original (1939) beach sand.

sizes present in the original beaches and nearshore are also present in the fill material.

The area selected for placement of the coarse material was in the groin embayment bounded by groins No. 2 and No. 3 (Fig. 1) as this area is within that zone on the peninsula which has experienced the greatest erosion.

In order to insure that the fill specified was actually placed on the beach, the material was tested by mechanical sieve analysis prior to its placement on trucks and after it was dumped on the shoreline. Of 127 samples tested only one point of one sample fell outside of the envelope curve shown in Fig. 2.

PROCEDURES

Field. Monitoring of the test area consisted of determination of the subaerial and subaqueous profiles along specified ranges and collection of sediment samples along selected profiles (Fig. 3). Determination of the subaerial profile was by standard surveying techniques; determination of the subaqueous profile was by standard sounding techniques.

BERG and DUANE

STA. 10+00 STA. 12+56 GROIN No. 2 STA. 13+06 STA. 13+56 STA. 15+00 STA. 17+50 STA. 20+00 STA. 22+62 GROIN No. 3 STA. 23+16 STA. 23+62 STA. 25+00

SURVEY BASELINE

LEGEND
—— — SURVEY BASELINE
— — PROFILE, NO SEDIMENT SAMPLES
—O— — PROFILE, WITH SEDIMENT SAMPLES
■■■■ GROIN
- - - - - - WATERLINE, JULY 1967

SCALE IN FEET
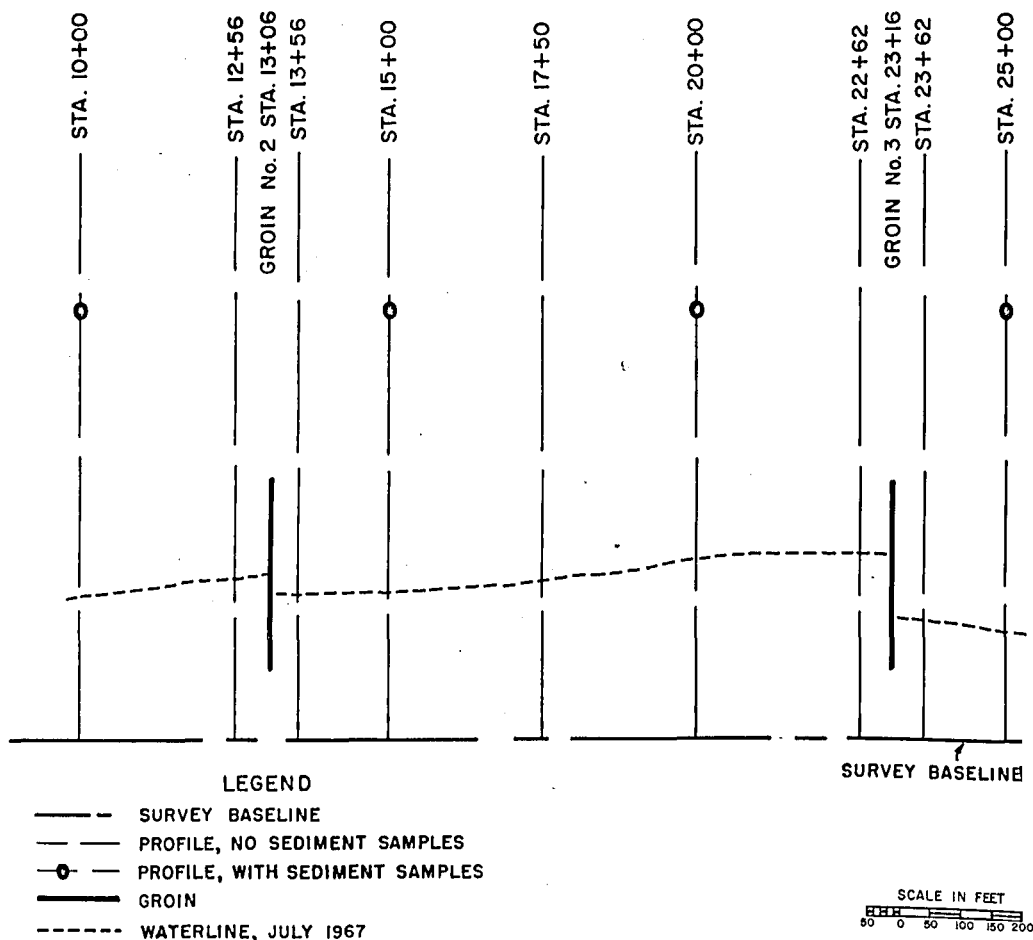50   0   50   100   150 200

FIG. 3. Detail plan of coarse fill area. Note the location of topographic and sediment sampling profiles to the groins.

A grab-sample of sediment was obtained from the back beach, bern crest, and water line as well as at a water depth of approximately 1, 2, 4, and 6 m. Profiles and sediment samples were obtained twice annually for a three-year period beginning June 1965. In regard to sediment and profile analysis, interpretation, and illustration, emphasis is placed upon Range 20+00 because some sediment samples had been obtained along this particular profile as far back as 1957. However, study and analysis were also made of sediment and topography obtained along profiles 10+00, 15+00, 25+00, and four ranges in the vicinity of groins 8 and 9 (Fig. 1).

Laboratory and Computer. Frequency distribution of sediment size classes was determined by Buffalo District, Corps of Engineers or a commercial testing firm utilizing standard sieving procedures. Sediment mean diameter $(\overline{X}_\phi)$ and standard deviation (σ_ϕ) were computed by moment measures utilizing CERC computer facilities and programs developed by CERC staff. Median diameter (Md_ϕ) was determined graphically or by computer.

For purposes of this study size frequency data from individual sediment

TABLE 1. Definition of zones. Depths refer to LWD (low water datum) of 568.6 feet above mean water level at Father Point, Quebec.

Zone	1		2		3		4
Depth							
Feet	≤ −20	< −12	≤ −12	< −4	≤ −4	< +4	≥ +4
Meters	≤ − 6	< − 3.7	≤ 3.7	< 1.2	≤ 1.2	< 1.2	≥ 1.2

TABLE 2. Changes in zonal sediment mean diameter with time.

△ = water line
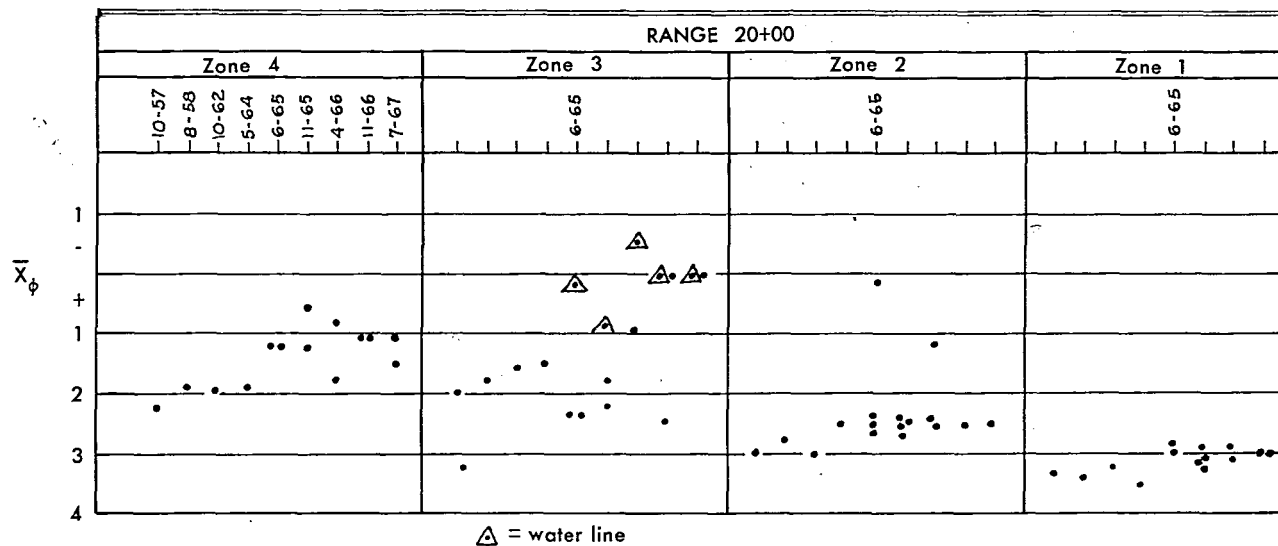
samples in depth zones were composited to produce a cumulative frequency
curve representative of each particular zone at each sampling period. The four
zones are defined in Table 1.

Drawing of "topographic" profiles and computations of the volume of sedi-
ment movement as revealed by profile changes were also done on CERC facili-
ties utilizing in-house computer programs. Techniques of volume computation
utilized the average end area method of earth calculations (Allen, 1931). The
CERC computer programs permit a detailed examination of different zones
along the profiles as well as the more usual computation of net material move-
ment utilizing the entire profile. The data in suitable format then becomes
available for any additional volumetric computations deemed necessary and ma-
chine drawing of the profiles in various combinations.

Following an initial analysis of topographic profiles it was determined
that four distinct zones of the beach and underwater hydrography would be ex-
amined in detail. These zones are defined in Table 1.

<div align="center">OBSERVATIONS</div>

Sediment Size Characteristics.

Pre 1965. Numerical values of $\overline{X}_\phi$, $\sigma\phi$, and skewness exhibited no clear
numerical values attributable to environment or depth zone, although some dis-
tinctive trends are noted. Water line samples are almost always coarser ($<\overline{X}_\phi$)
than samples from other environments. Deeper water samples, those from
water depths greater than 1.2 m are the finest with $\overline{X}_\phi$ approximating 3.
Values of median diameter of samples studied closely approximate values of
$\overline{X}_\phi$. Table 2, a plot of the value of $\overline{X}_\phi$ by zones versus time, clearly indi-
cates a zonal segregation. In a previous section it was stated that cumulative
frequency curves were plotted for composite samples within certain zones, the
same zones that were used in the computation and analysis of the volume of
erosion or deposition. The natural segregation of $\overline{X}_\phi$ values within the zones
reinforces the validity of the original basis of selection and indicates they ap-
proximate a truly natural zonation.

A generalized size distribution curve for all samples obtained from the
small beaches extant in 1939 is depicted on Fig. 2. Also illustrated are gen-
eralized curves for Zone 4 samples (backbeach and berm) along Range 20+00
obtained in August 1958, May 1964, and June 1965, the first sample obtained
from the emplaced coarse fill. A marked similarity exists for pre-1965 Zone
4 sediments, all of which exhibit an increase in particle size over sediment
comprising borrow areas A and B (Fig. 1). The increase in particle size can
be explained as the result of natural sorting processes although some fine ma-
terial also is lost during dredge and fill operations. Sediment samples were
not obtained from the profiles until nearly a year after 1956 and 1961 fill op-
erations making it impossible to determine exactly how similar or dissimilar
the emplaced material was to subsequent beach samples. However, based on
the character of curves in Fig. 2 and the plot of $\overline{X}_\phi$ in Table 2, little immedi-
ate modification occurred in Zone 4.

Post placement modification of Zone 3 samples is represented by a slow
and continued increase in $\overline{X}_\phi$ as illustrated in Table 2. Shape of these Zone 3
distribution curves is similar to that for the 1939 beach samples. However, as
expressed by the median diameter of the composite curve, the 1939 beach sam-
ples are finer than Zone 3 sediment created by the 1956 and 1961 fill opera-
tions (Fig. 4).

Sediment in Zones 2 and 1 does not seem to show much change through
time. In all instances sediment on the surface of the Lake bottom from Zone 1
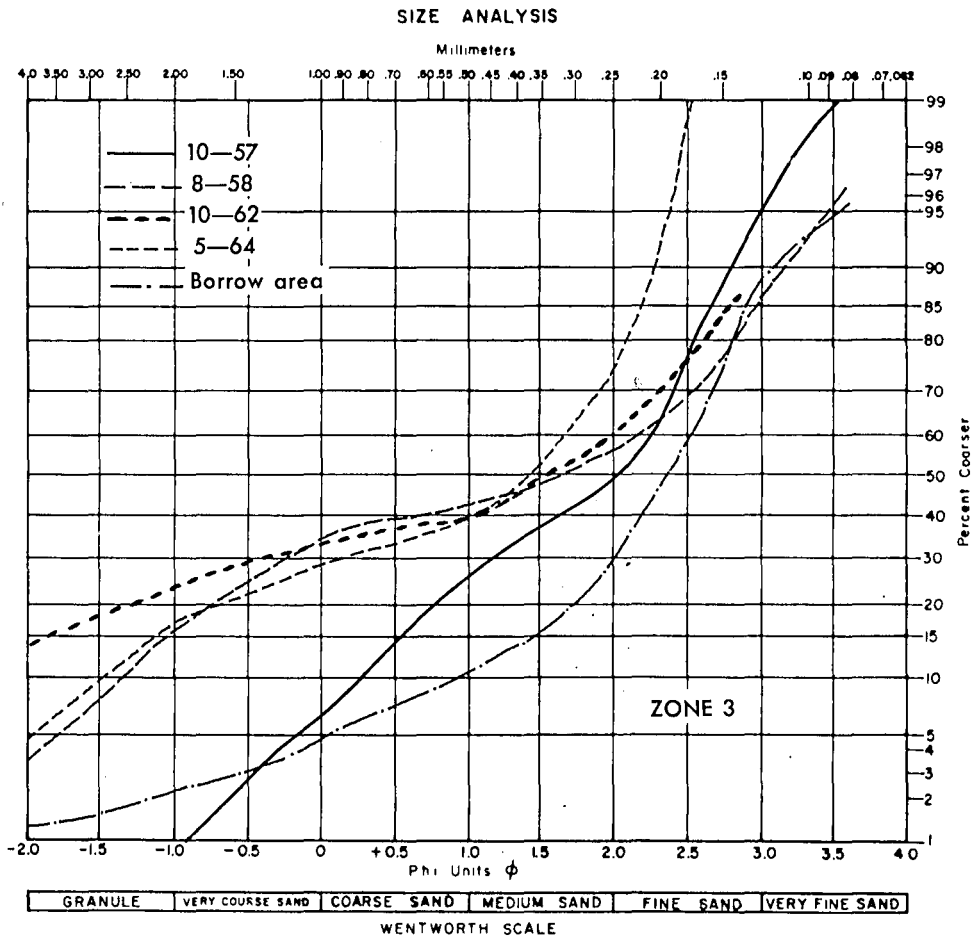
SIZE ANALYSIS

Millimeters

FIG. 4. Composite sediment cumulative frequency curves. Note contrast in shape of curves for sediment from Zone 3, Range 20+00 to curve describing sediment from original borrow areas A and B.

is finer than any other surface sediment in the study area.

Sorting (σ_ϕ) of Zone 4 sediments does not change significantly after the initial adjustment, but it is poorer than the original fill material. Zone 3 sediment undergoes a decrease in sorting with time and as $\overline{X}_\phi$ decreases (sediment becomes coarser). Because of the original analytical treatment of these samples it is not possible to determine sorting of Zone 2 and 1 samples.

Post 1964. As was true with pre-1965 samples, numerical values exhibit trends. Most clearly illustrated is a zonation of $\overline{X}_\phi$ versus water depth (Table 2). A marked contrast exists between pre-1965 beach and nearshore samples (Zones 4 and 3) and the coarse sediment specified in the 1965 groin fill operation. This contrast is well illustrated in Fig. 2 and Table 2. The decrease in the value of $\overline{X}_\phi$ following placement of the coarse fill is most noticeable in Zones 4 and 3, although a slight shift in values also occurs in Zones 2 and 1 (Table 2). Greatest fluctuation in mean diameter occurs in Zone 3, with water line samples being coarsest.

Degree of sorting of sediment in the coarse fill area fluctuates less through time than that for samples obtained from other profiles in the groin fields. Also, Zone 4 and 3 samples in the coarse fill area are generally better sorted than similarly analysed and analogous sediment from within unfilled groin bays.

Post placement modification of the coarse fill sediment as illustrated by the composited distribution curves definitely occurs in Zones 4 and 3, and seems to occur in Zone 2 also. Sediment in Zone 1 does not seem to show changes through time which can definitely be attributed to a single factor, such as an affect attributable to the deposition of fines being winnowed out of the fill on the beachface and nearshore zone.

Mean size of sediment in Zone 4 does not change appreciably after placement of the coarse fill (Table 2), although σ_ϕ does change. These factors are illustrated in the composited distribution curves (Fig. 5) which, pivoted about the mean, show a general decrease in slope with time. With time and consequent sorting of the sediment by storm waves and wind the cumulative frequency curves of the composited zone samples fall out of the specified fill envelope.
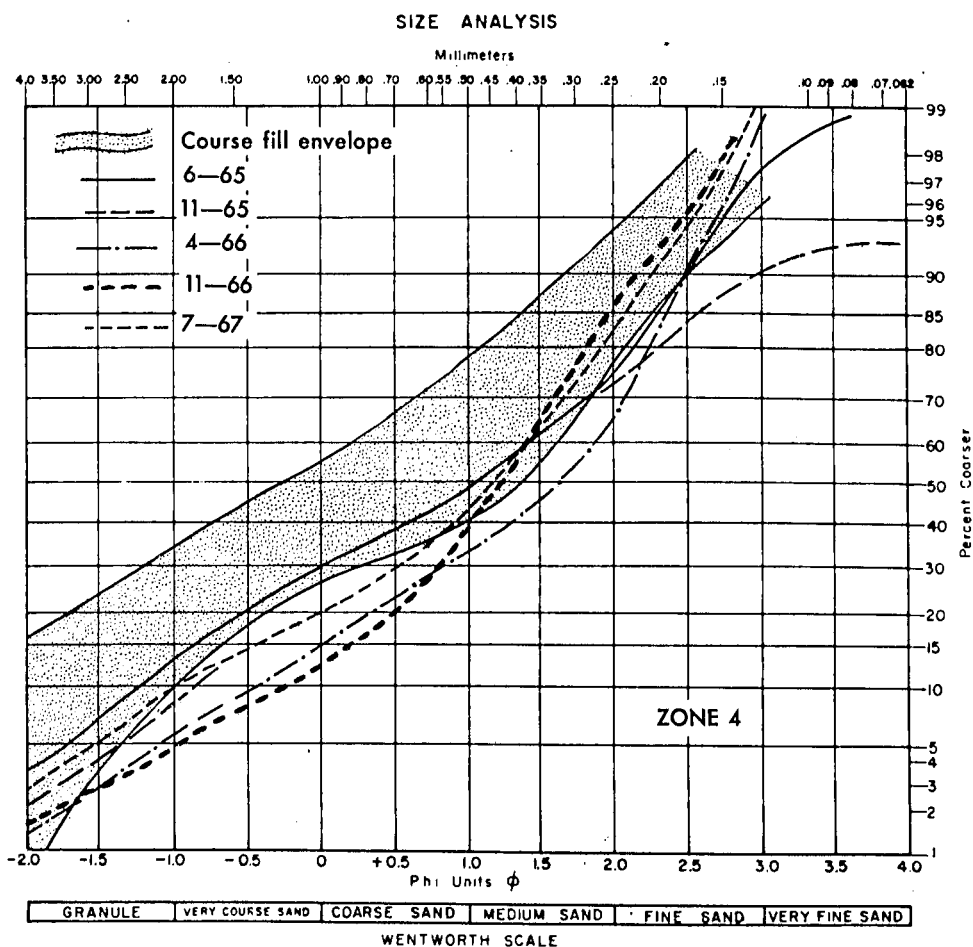

FIG. 5. Composite sediment cumulative frequency curves. Note relative stability (near uniform slope and position) and relationship to coarse fill envelope of sediment from Zone 4, Range 20+00.

However, in no instance following 1965 fill operations is there the contrast in
zonal samples and the coarse fill envelope as is illustrated in Fig. 2 for sam-
ples prior to the 1965 coarse fill.

Sediment in Zone 4 along other sampled ranges has about the same $\overline{X}_\phi$ as
sediment along Range 20+00, although σ_ϕ fluctuates more widely. This is true also
of Range 15+00 (which is in the updrift shadow of groin 2) but to a lesser degree.

Considerably more changes occur to sediment in Zone 3 (+1.2 to -1.2 m) as a
result of the coarse fill. Effect at the water line is immediate, but nearly 12 months
elapse before the coarse fill begins to appear in the nearshore-offshore area, i.e.,
approximately 1 m depth (Table 2). This delay is probably due to the manner of fill
placement; in this instance the fill being bulldozed to the water's edge with natural
processes responsible for offshore movement. Fluctuation in $\overline{X}_\phi$ for samples from
the water line corresponds with the rise and fall of lake levels, except for the July
1967 samples. These two samples are nearly identical to the November 1966 low
water samples. Mean diameters and σ_ϕ among the four samples involved are nearly
identical. Additional surveys are needed to substantiate or discredit implications of
these similarities and their effect on the stability of the topographic-bathymetric
profile. Modification can also be seen in the composited distribution curves of Fig. 6,
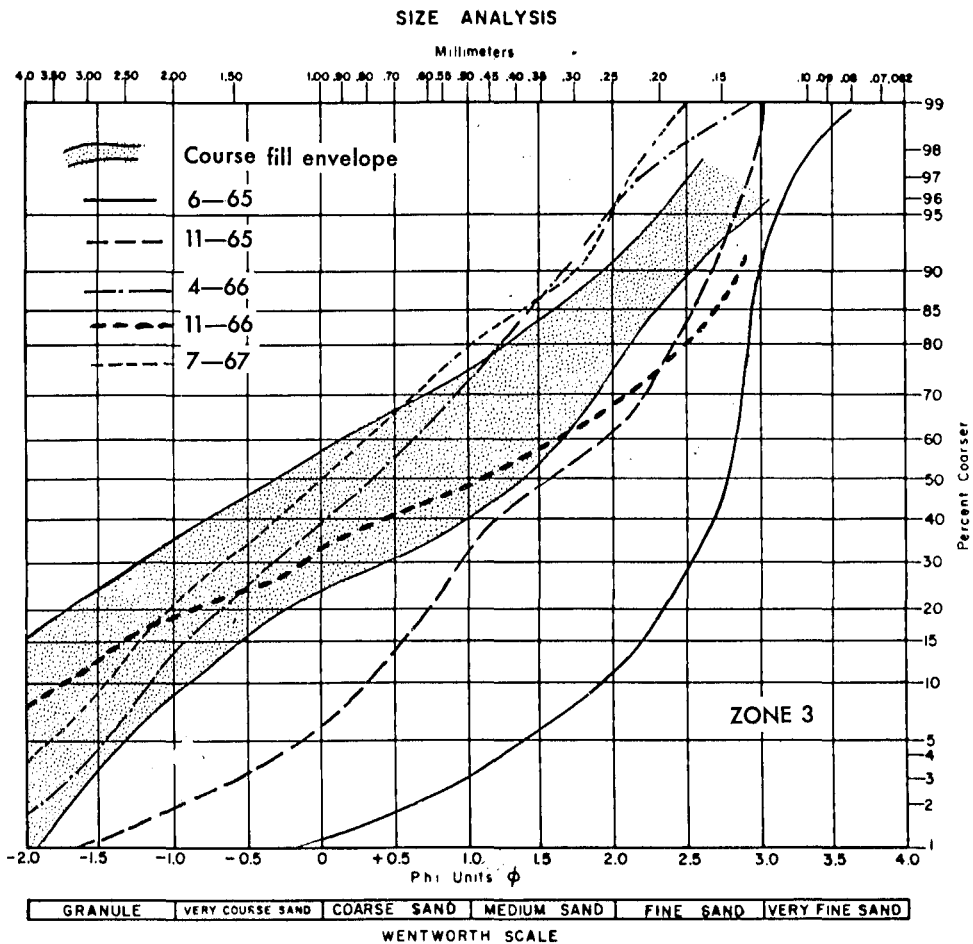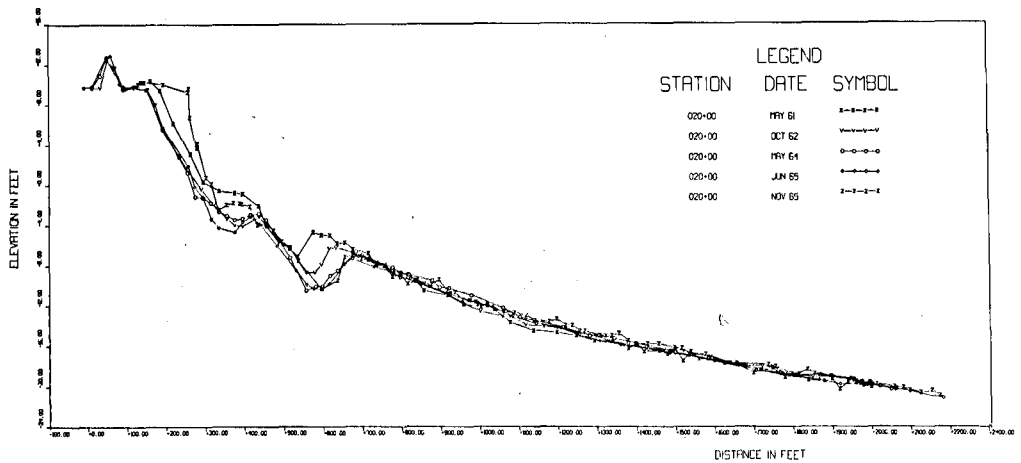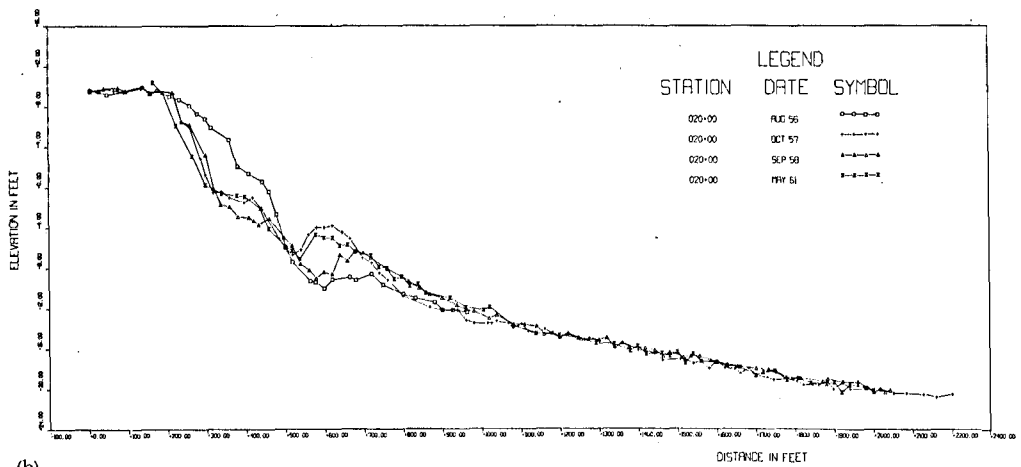

FIG. 6. Composite sediment cumulative frequency curves. Clearly visible is granulo-
metric modification of sediment from Zone 3, Range 20+00 through time and approach to
the specified coarse-fill envelope.

(a)

(b)

FIG. 7.   Comparative morphologic profiles for Range 20+00, (a) Original fill and adjust-
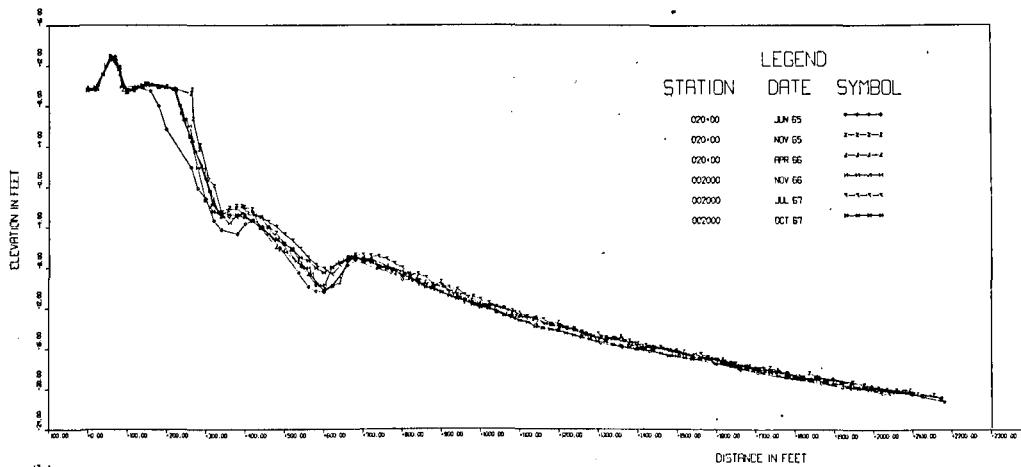ment; (b) first beach nourishment and adjustment.

where the effect through time of natural sorting processes is clearly demon-
strated. In effect, as the coarse fill is moved offshore the sediment here begins to
take on the characteristics of the fill material as described by the specification en-
velope.

The relationship described above does not exist outside the coarse fill area,
and is not as strong along Range 15+00 which is in the updrift shadow of groin 2
(Fig. 2). The effect of coarse fill along this range seems to be confined to sedi-
ment in Zone 4 and sediment at the water line. Samples from approximately 1 m
depth show little or no change in either $\overline{X}_\phi$ or σ_ϕ through the period of surveys.

Profile Changes. Artificial placement of material on a shoreline usually is
reflected in rapid adjustments of the material until an equilibrium profile is at-
tained. This equilibrium profile is characteristically dependent on the particle
size distributions of the material involved and the predominate wave climate. Some
methods of material placement tend to adjust to this equilibrium profile somewhat
faster than others.
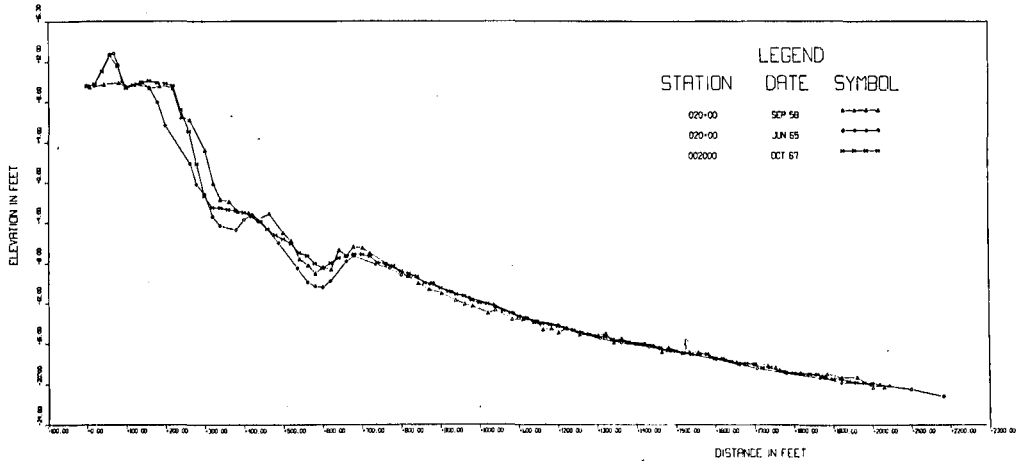
FIG. 8. Comparative morphologic profiles for Range 20+00. (a) Coarse fill and adjustment; (b) original fill, first nourishment, and coarse fill.

     The original restoration of the beaches on Presque Isle in 1955-56 and the nourishment of the beaches in 1960-61 was accomplished by hydraulic dredging methods. This method of material placement tends to provide a gradual slope to the beach and underwater hydrography as the material is placed becaused the highly fluid characteristics of the sand slurry as it is discharged on the shore. There also tends to be an initially high loss of fine material as these particles are put into suspension and carried lakeward, either to enter the alongshore littoral drift or to be carried offshore and there deposited. Examination of the profiles for the period 1956 to 1961 (Fig. 7a) and 1961 to 1965 (Fig. 7b) show this initial high loss rate from the beach foreshore slope and nearshore bottom. Monthly mean levels of Lake Erie for the months of surveys depicted in Figures 7 and 8 are summarized in Table 3.

     It can be seen by close examination of the profiles of Fig. 7 that the initial high loss rate of material is from Zones 4 and 3 with a corresponding increase in Zone 2 for the period following the original fill operation of 1955-56. Similar

TABLE 3. Mean lake levels for designated months.

Month & Year	Elevation (ft)	Referred to LWD
Aug 56	571.45	+2.89
Oct 57	570.12	+1.56
Sept 58	569.90	+1.34
May 61	571.57	+3.01
Oct 62	569.80	+1.24
May 64	569.72	+1.16
June 65	569.87	+1.31
Nov 65	569.07	+0.51
Apr 66	570.10	+2.05
Nov 66	569.36	+0.08
July 67	571.05	+2.49
Oct 67	570.30	+1.74

effects can be observed following the nourishment of 1960-61. However in thie latter case, the relative increase of material in Zone 2 is somewhat smaller due to previous accretion in this lower zone.

Coarse material in the area between groins 2 and 3 (Range 13+56 to Range 22+62) was placed during 1965 by trucks and mechanically distributed over the beach by bulldozers. This method tends to "perch" the material on the shore line and provides a steep foreshore slope. Adjustment of this slope by wave action causes the slope to slough off, eventually approaching an equilibrium profile.

Adjustment of the fill of 1965 is shown on Fig. 8a. For the period November 1965 through October 1967 there is an initial high loss rate from the higher zones and a corresponding increase of material in Zone 2 (Fig. 8a).

In order to make some general comparison of the relative movement of material, the profiles for Range 20+00 for the latest survey after a fill operation had taken place but prior to the succeeding fill (September 1958, June 1965 and October 1967) are shown in Fig. 8b. These data indicate that the dune on the back beach has become relatively stable (more by auxiliary protective measures such as fencing and vegetative plantings made by park personnel than by natural factors) and the offshore slope in Zone 1 has become relatively fixed. It is also apparent that maximum material movement occurs in Zone 4, (backshore and foreshore) and Zone 3, (area of maximum wave attack and nearshore bottom).

An interesting aspect of the offshore morphology illustrated by profiling in Figures 7 and 8, as well as by other profiles not illustrated, is the presence of multiple bars. Somewhat similar multiple bar aspects of offshore bottom topography have been described for Lake Michigan (Davis and McGeary, 1965) and Lake Superior (Bajorunas and Duane, 1967). The latter study noted three major bars, the third or deepwater bar occurring lakeward of the 8 m depth contour. Aerial photographs of eastern Lake Michigan often exhibit a third bar but it is unknown at this time in what depth of water that bar occurs. The deep water bar in Lake Superior has no analogue in the Presque Isle area.

Depth of water over the crest and trough of the lakeward bar off Presque Isle is very nearly the same as that for the analogous second bar of Davis and McGeary (1965) and intermediate bar of Bajournas and Duane (1967). A nearshore bar off Presque Isle is visible in Figures 7 and 8 and is also reported in the above referenced papers. Water depth over the crest of this shallow water bar and the relief of the feature are very nearly identical to the analogous features in the cited Lake Superior and Lake Michigan studies.

Davis and McGeary (1965) reported that the bars on eastern Lake Michigan were stable over a 10-year period, while Bajorunas and Duane (1967) documented shifting of all bars with rather rapid movement of the most shoreward bar. Surveys reported in this study also document movement of offshore bars (Figures 7 and 8). However, these surveys do not show very much movement of the nearshore bar in either an offshore or onshore direction. The frequency and period of surveying may account for the apparent lack of movement; possibly the presence of the groins accounts for the apparent lack of movement.

Volume of Sediment Movement.

In order to define material movement, analysis of the survey data previously described was made for the zonations shown in Table 1. A summary of the volumetric changes which occurred between surveys is shown in Table 4. In addition to the zones previously listed a total change for the whole profile is also shown. Examination of the data for the period August 1956 through June 1965 shows that in almost every case, excepting periods in which fill operations occurred, there is loss of material from Zones 4 and 3 (above -1.2 m). For the period after June 1965 the losses in these zones are modified by periods of accretion.

Also discernible is the fact that major accretion occurs in Zones 2 and 1 (below -1.2 m) in the limited area under consideration. This is in part a result of alongshore movement (the groins do not extend into these zones). However, it is judged also to reflect the offshore movement of material from the beach and nearshore bottom to these deeper water areas and represents the adjustment to an equilibrium profile.

Because the figures in this table are for specified periods of time dictated by the occurrence of aperiodic surveys the values are not truly comparable; rather they are trend indications of material movements. The values suitably reduced to monthly rates of movement and rearranged for periods of similar occurrences are shown in Table 4. It is apparent from the figures in this table that those portions of the profile above -1.2 m (Zones 4 and 3) experienced continued erosion for the period prior to the placement of coarse material in 1965. However, for the period after the coarse material had been placed, these zones experienced accretion.

INTERPRETATIONS

Stability of Beach and Modifications of Offshore Profiles

The most effective and efficient absorber of wave energy impinging upon a section of coastline is a wide sand beach from which recreational benefits may also be realized. In either instance a beach is effective only if it is stable; that is, only so long as its existence continues. Beach stability can be defined as the ability of a beach to withstand the wave forces acting upon it with little or no net loss of material to the littoral stream. A stable beach insures the permanence of a protective structure (the beach) for valuable backshore areas and recreational advantages for man.

In examining the movement of the material in the area under study, it is apparent that the material placed on the shoreline in 1955-56 and 1960-61 experienced rapid and prolonged erosion in the beach and nearshore hydrography. This erosion marked the instability of the beach and effectively reduced its intended uses. Examination of survey data for the particular groin embayment under study indicates that the dry beach area had been reduced by approximately 35% for the period August 1956 (following initial fill) to June 1965 (prior to coarse fill).

During the modifications in profile morphology (Fig. 7) which reflected the continued erosion and instability of the beach, only slight changes were detected in the granulometric characteristics of the sediment. Lack of profound changes in granulometric character is to be expected because of the gross similarities of fill material and the sand on the beaches existing in 1939.

When coarse material was placed on this area in 1965 and once initial adjustments had occurred, the beach and nearshore experienced an overall addition of sediment and an accompanying growth of the usable above-water area.

TABLE 4. Period volumetric changes in cumulative volumetric changes, Range 13+56 thru Range 22+62. Volumes in YDS³; M³=0.764 x Yds³. Values are positive (accretion) unless otherwise indicated.

Date of Survey		Total		Zone 4		Zone 3		Zone 2		Zone 1	
		Period	Cum.	Period	Cum.	Period	Cum.	Period	Cum.	Period	Cum.
Aug	1956	105799	105779	-19449	-19449	-25439	-25439	28305	28305	122362	122362
Oct	1957	534	106313	-3011	-22460	-4091	-29530	56	28361	7576	129938
Sept	1958	6945	113258	3928	-18532	4081	-25499	1131	29492	-2191	127747
May	1961	-13803	99455	-6671	-25203	-11155	-36604	-6212	23280	10236	137983
Oct	1962	-7943	91512	-1164	-26367	-7124	-43728	18	23298	324	138307
May	1964	-12509	79003	2246	-24121	-15	-43743	-3375	19923	-11362	126945
June	1965	44119	123122	14277	-0944	12011	-31732	4439	24262	13490	140435
Nov	1965	-7323	115799	-2766	-12610	-2631	-34363	494	24756	-2420	138015
Apr	1966	4868	120667	447	-12163	527	-33836	1538	26294	2356	140372
Nov	1966	9480	130147	-2384	-14557	-4388	-38224	10390	36684	5863	146235
July	1967	-39545	96602	356	-14191	-1355	-39579	14782	121892	-23756	122418
Oct	1967										

TABLE 5. Actual volumetric changes and monthly volumetric rate changes, Range 13+56 through Range 22+62 for three periods of fill and adjustment. Figures in YDS³; M³ = 0.764xYDS³.

Time Period	Total Profile	Zone 4	Zone 3	Zone 2	Zone 1
Aug 1956 thru Sept 1958	(+106313)* +4252*	(-22460) -898	(-29530) -1181	(+28361) +1134	(+129938) +5198
Sept 1958 thru June 1965	(-27310) -337	(-1661) -20	(-14213) -175	(-8438) -104	(-2993) -37
June 1965 thru Oct 1967	(+11599) +414	(-1661) -20	(+4164) +149	(+1969) +70	(-4464) -159

*Note: (+106313) = actual changes; +4252 = actual changes reduced to monthly rate.

Profile changes are depicted in Fig. 8a; the general stability of the coarse fill is demonstrated by a comparison of Figures 8a and 8b. In spring 1968 the dry beach area within groins 2 and 3 has increased 5% since June 1965.

The modification of the profile morphology after the coarse fill is coupled with a modification of sediment in Zones 4 and 3, the latter being clearly depicted in Table 2 and Figures 5 and 6. As stated previously, the granulometric effect of coarse fill on sediment in Zones 2 and 1 is obscure. Nevertheless the profile changes indicating accretion in these zones does follow the placement of coarse fill on the beach.

The multiple bar morphology persists through the addition of coarse fill. However, both bars noted by this program occur in Zones 2 and 1, where the effect of the 1965 beach fill on granulometric characteristics of the sediment is not clear or unequivocably attributable to the coarse fill. Size (mean $(\overline{X}_\phi)$ and median) of the sediment both on and off the bars off Presque Isle is very similar to that reported for analogous bars in Lake Michigan (Davis and Mc-Geary, 1965) and Lake Superior (Bajorunas and Duane, 1967). The similarity in the form of the bars and the gross size characteristics of the sediment comprising the bars, may be directly coupled to the wave climate. Saville (1953a) presented data for Erie, Pa. indicating the dominant wave was 1-2 ft high with a period of 2-3 sec. In a similar study on Lake Michigan, Saville (1953b) presented data for Muskegon, Mich. (north of the area of study reported by Davis and McGeary, 1965) showing dominant wave to be 1-2 ft high with a period of 2-3 sec. No equivalent statistics are known to be available for Lake Superior. Nevertheless, the similarities and apparent correlations among sediment granulometric characteristics, offshore morphology, and lake wave statistics (real and implied) indicate a similarity in active processes and responses of the several Great Lakes. Results of the coarse fill experiment at Presque Isle therefore may be directly applicable to the other Great Lakes.

Volumetric Changes

As previously indicated, the coarse fill material was probably one of several parameters that could vary and directly affect the movement of material. The effect of lake levels must be considered in any analysis of the long term trends in material movement and consequent volumetric changes, as well as the effect of groins and their location. In order to facilitate the analysis of the data, isometric block diagrams for the groin embayment were constructed showing cumulative volumetric changes within the groin embayment through time. Figure 9
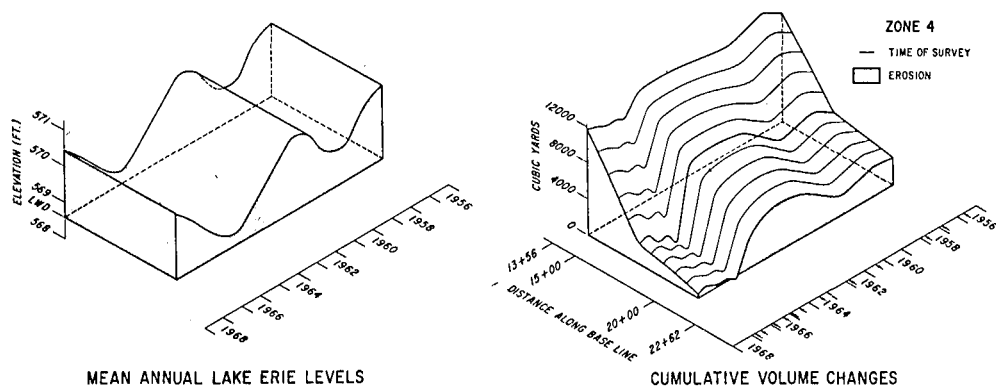

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FIG. 9. Isometric block diagram of cululative volumetric changes (YDS^3) in Zone 4 of coarse-fill area. Note effect of updrift groin on sediment movement. Superposed in block diagram illustrating correlation of annual lake level changes to volumetric changes.
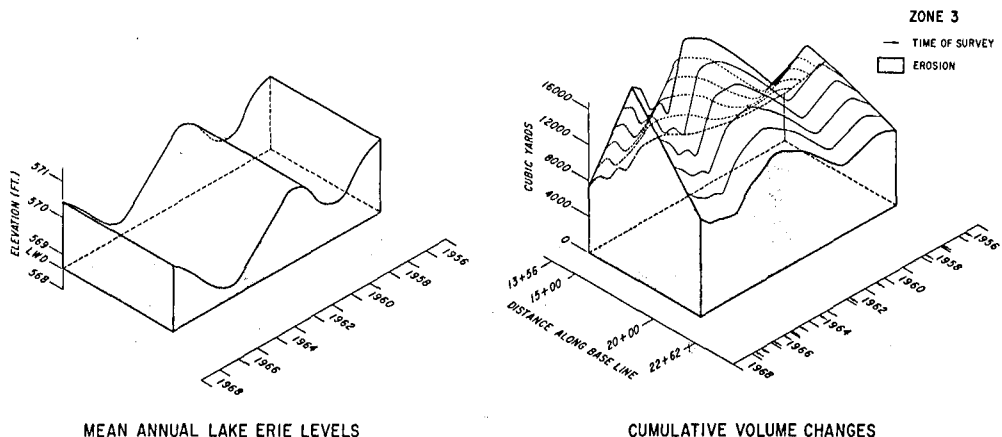
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FIG. 10. Isometric block diagram of cumulative volumetric changes (YDS^3) in Zone 3 of coarse fill area. Effect of updrift groin on sediment movement in this zone is less clear cut. Superposed in block diagram illustrating correlation of annual lake level changes to volumetric changes.

illustrates the changes for Zone 4; superposed in an isometric block diagram of the mean annual lake levels for Lake Erie, which facilitates the comparison of the changes in sediment movement with changes in lake levels. Cumulative volumetric changes are erosional for Zone 4. Note that the maximum period of erosion occurs at these times when the mean annual lake level is at its highest recorded values. Similarily when the lake levels recede, the rate of erosion is reduced in a corresponding manner but with a slight lag in time.

The rate of erosion is decreased following placement of the coarse fill in the summer of 1965. This effect of the coarse material fill is exhibited by a decrease in the slope of the surface of the block diagram in Fig. 9 in which groin effectiveness in retarding movement of material in Zone 4 is also shown. Greatest erosion occurs in the vicinity of groin 2, the westerly groin of this embayment, decreasing rather quickly towards groin 3, the easterly and downdrift groin.
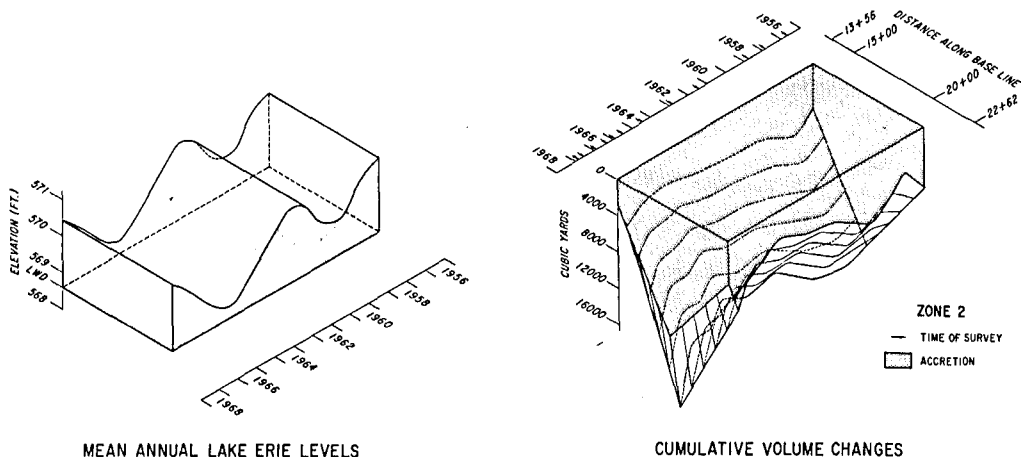

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FIG. 11. Isometric block diagram of cumulative volumetric changes (YDS^3) in Zone 2 of coarse fill area. This zone is essentially entirely lakeward of the ends of groins 2 and 3. Superposed in block diagram illustrating correlation of annual lake level changes to volumetric changes.

A similar illustration depicting changes for Zone 3 in Fig. 10. shows that the major area of erosion in Zone 3 within the groin embayment occurs more nearly in the center of the embayment and is modified by relative accretion in the vicinity of the groins. Effectiveness of the coarse material in stabilizing the beach and profile is shown by a decrease in erosion following its placement. Changes in erosion rates with changes in the surface of the mean annual lake level are again quite noticeable.

As depicted on the profiles, deeper water zones experienced the addition of sediment over the span of time represented by surveys. The three-dimensional aspect of cumulative accretion in Zone 2 is depicted on Fig. 11. In large part, this zone represents depth beyond the contour at the end of the groins. The major area of accretion is in the center of the groin embayment, one aspect that makes this zone appear as a mirror image of Zone 3 (Fig. 10). As was the case with the representative erosional surfaces of Zones 4 and 3, the crenulations of the representative accretion surface of Zone 2 follows the rise and fall of the mean annual lake levels.

Mean $(\overline{X}_\phi)$ and median diameters of samples at the water line fluctuate with a periodicity that is seasonal, sediment being coarser in the spring or early summer (Table 2). This occurrence of spring-summer high values of $\overline{X}_\phi$ also coincides with high mean annual lake levels and the concomitant increase erosion rates in Zone 3. Because the "environment" is constant, irrespective of the lake levels, the fluctuation in $\overline{X}_\phi$ as the lake levels fluctuate is judged to reflect the marked contrast of the original beach and nearshore sediment and fill. The coarse fill is essentially unimodal, although slightly skewed. Consequently, once placement of the coarse fill was affected and the material had migrated into the nearshore offshore area, the fluctuation of $\overline{X}_\phi$ in Zone 3 seems to nearly cease. As no concomitant decrease in the fluctuations of the value for $\overline{X}_\phi$ occurs in the groin fields east of the coarse fill area, it is judged that the coarse fill is more nearly in equilibrium with the "environment" than sediment resulting from previous fill operations. The tendency for constancy of the $\overline{X}_\phi$ value corresponds with the decrease in erosion rates and stability of the profiles. More surveys need be made to further evaluate the significance of the apparent constancy of $\overline{X}_\phi$ with stability of the profile.

CONCLUSIONS

On the basis of the data collected in connection with the study herein reported, certain conclusions are made:

1) beaches and nearshore zones composed of coarse sediment are more stable than those beaches and nearshore zones composed of finer grained sediment for a given set of environmental conditions therefore producing a decrease in erosion rate, frequency of required nourishment, and increase in direct protective and recreational benefits;

2) where construction or restoration of beaches are a proposed plan of improvement, utilization of sediment coarser $(<\overline{X}_\phi)$ than that comprising the original beach should be considered;

3) the coarse sediment to be used as fill material should be relatively well sorted with a distribution of particle sizes to cover all grain sizes present in the original environment;

4) direct correlation of changes in erosion-accretion rates with the rise and fall of lake levels earlier suggested (Berg, 1965) is strongly supported;

5) a definite offshore decrease in mean grain size $(>\overline{X}_\phi)$ occurs and within the groin embayment studied on offshore transport of beach material occurs; and

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6) the similarities in active processes and responses along portions of the coastline of several of the Great Lakes to those processes and responses occurring at Presque Isle indicate results of this coarse fill experiment may be directly applicable to the solution of erosion problems on other Great Lakes.

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