A METHOD OF TRACING SEDIMENT MOVEMENT ON THE TEXAS GULF COAST

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ABSTRACT

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PREFACE

Research described in this report was conducted as part of the research program in Coastal Engineering at Texas A&M University.

This report was primarily written by the senior author in partial fulfillment of the Master of Science degree requirements under the supervision of the junior author who was his major advisor.

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INTRODUCTION

Vast sums of money have been expended on coastal structures by almost every country with a coastline. But, when such structures have interfered with littoral processes, the costs of the original construction have sometimes been overshadowed by the costs of repairing, removing, or altering the structures in order to adjust to the environmental realities of the site. In 1951 Eaton (9)[1] stated that

> . . . knowledge of the littoral characteristics of the area in which engineering works are being considered is of vital importance to the coastal engineer. Any coastal structure which extends into the sea will both affect, and be affected by, the littoral processes. Failure to understand and evaluate these effects properly is likely to materially alter the economic value of the completed work. (p. 145)

Taken at face value, Eaton's remark appears to be a truism which could be dismissed as being not only

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The scholarly journal used as a pattern for format and style of this thesis is the _Journal of the Waterways, Harbors and Coastal Engineering Division_, _American Society of Civil Engineers_.

[1]Numerals in parentheses without the abbreviation "p." refer to corresponding items in Appendix I--References.

trite, but as pointless as saying that one must know what loads a planned building will be subjected to in order to design safe from failure, yet for reasonable safety and for avoidance of overbuilding. Certainly, warning an engineer to understand his environment before designing a structure which may significantly alter the environment, or which may be seriously affected by that environment, cannot be considered a novel admonition. However, civic and commercial pressures sometimes require that a structure be designed and built even if the nature of the surroundings at the building site are not clearly understood. This is particularly true in the case of coastal structures, where the environment is constantly being shaped and changed by the dynamic processes of sea and wind.

The lack of understanding of littoral processes has not precluded man's attempts to improve on or protect his coastlines. Man-made barriers such as jetties, groins, and breakwaters have been used extensively on coastlines of the world to counteract the destructive forces of the sea. However, it is ironical that in many cases structures built to provide protection to coastlines have actually had the effect of exposing adjacent shorelines to even greater damages than those suffered in the natural state. Such classic engineering mistakes in the battle of protecting shorelines are well illustrated by man-made barriers reaching into the sea off California (48) and off the coast of New Jersey (47). In both of these examples, the structures built have significantly affected littoral processes. In California, unwanted accretion occurred at the Santa Barbara Harbor where building of a jetty to protect the harbor entrance resulted in sand deposition across the harbor mouth and simultaneous erosion of the down-drift shoreline. At Ocean City, New Jersey, groins constructed to advance the beach seaward actually resulted in natural increase in erosion rates and the removal of artificial fill material offshore. These two selected examples illustrate what can happen if structures are built on a shoreline without the designer having proper understanding of how a structure will affect natural sediment movement processes.

Engineers and scientists have long attempted to investigate and explain the phenomena associated with shoreline processes. The first truly comprehensive work, which summarized the knowledge up to the time, was by D. W. Johnson (17) in 1919. However, the information Johnson could compile then was largely descriptive. Since 1919 a number of books (e.g., Johnson, 1951 (19);

King, 1959 (24); Bascom, 1964 (2); Ippen, 1966 (16); Ingle, 1966 (12)] and many reports have been written which have dealt with coastline processes. Still, much remains unknown about the mechanics of littoral processes even though a great deal of knowledge has been compiled about the forces which cause littoral drift.

The experimental procedures used to study the mechanics of littoral processes should be considered in light of this knowledge. The characteristics usually selected in the description of a beach are average grain size, the range of grain sizes, and the topographic characteristics of the slope of foreshore and nearshore zones (see Fig. 1 for a diagram of the beach profile and generally accepted terminology). Bascom (1), in his studies on California beaches in 1951, found that the steepness of a beach slope depends upon the size of the beach material making up the slope. The larger sand sizes are associated with steep slopes, and the smaller sand sizes make up gently sloping foreshores.

The beach characteristics themselves are largely determined by the physical forces to which the beach is exposed and by the type and quantity of material made available to the beach. Beach sediments come from five principal sources: streams and rivers, which transport sand directly to the ocean; seaward blowing winds

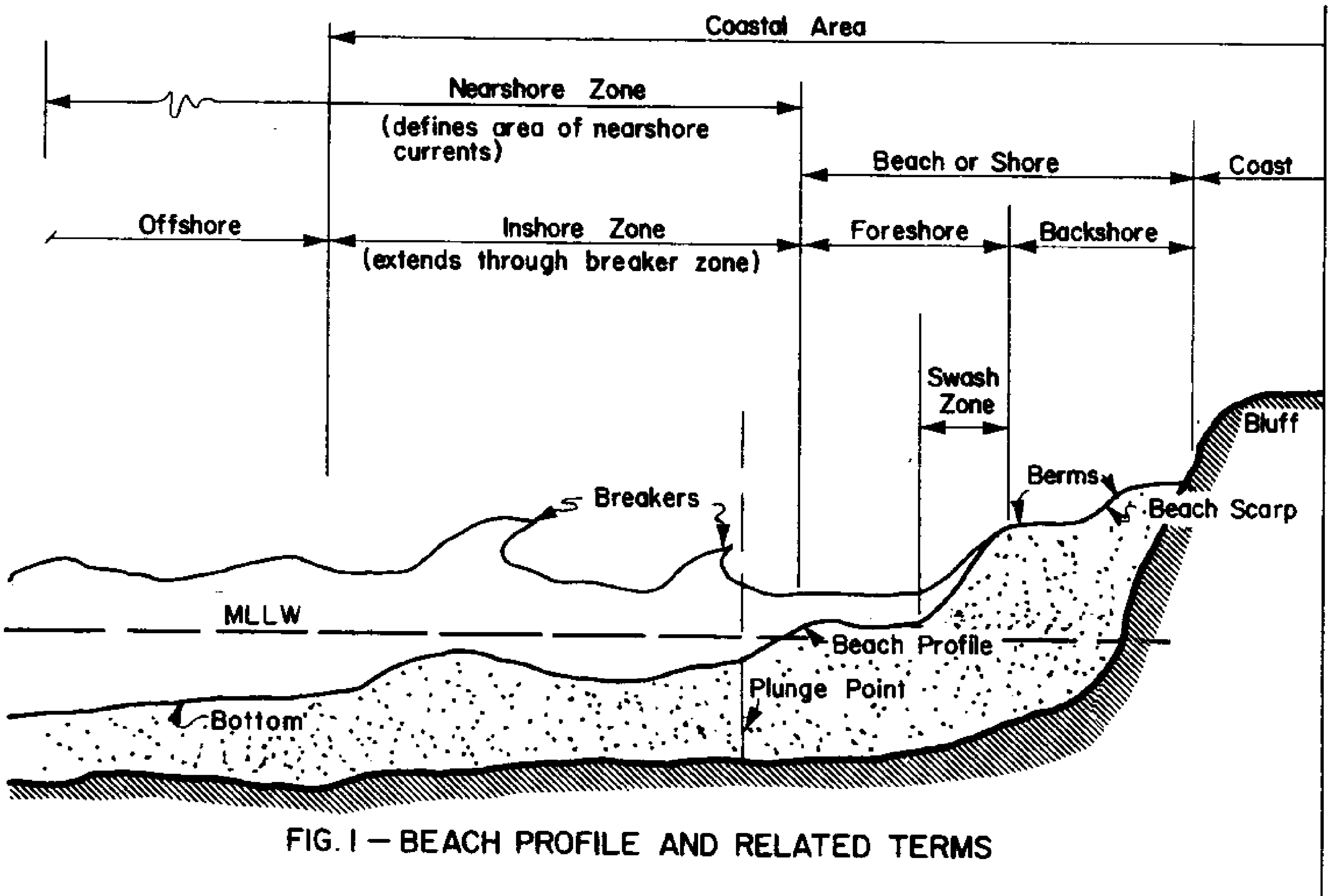


FIG. 1 — BEACH PROFILE AND RELATED TERMS

Modified after U. S. Army, Corps of Engineers, "Land Against the Sea" (43), p. 16.

which transport sand from land dunes; erosion of cliffs; offshore deposits; and material of biogenetic origin (14). Beaches may be prevented from receiving material by natural barriers, such as headlands, or by man-made barriers, such as jetties, groins, or breakwaters, which interfere with the flow of littoral transport. Material is lost, or taken out of the mechanism of littoral transport, either through the process of wind transport inland or by sediment flowing into the heads of submarine canyons (37).

Wind waves are the primary sources of energy which cause the shaping of beaches. Wind waves affect beaches in two major ways. First, steep waves tend to erode beaches by taking material from the foreshore zone and depositing it offshore, whereas waves of low steepness bring material from the nearshore zone and deposit it in the foreshore zone (Fig. 2). Another effect results from waves breaking at an angle to the beach. When this occurs, a longshore current, or littoral current, is set up parallel to the shore in shallow water (26). It is this current which causes longshore drift, the transport of sand, in the surf zone.

Other phenomena which cause sand movement are rip currents which transport sand seaward, and the zig-zag

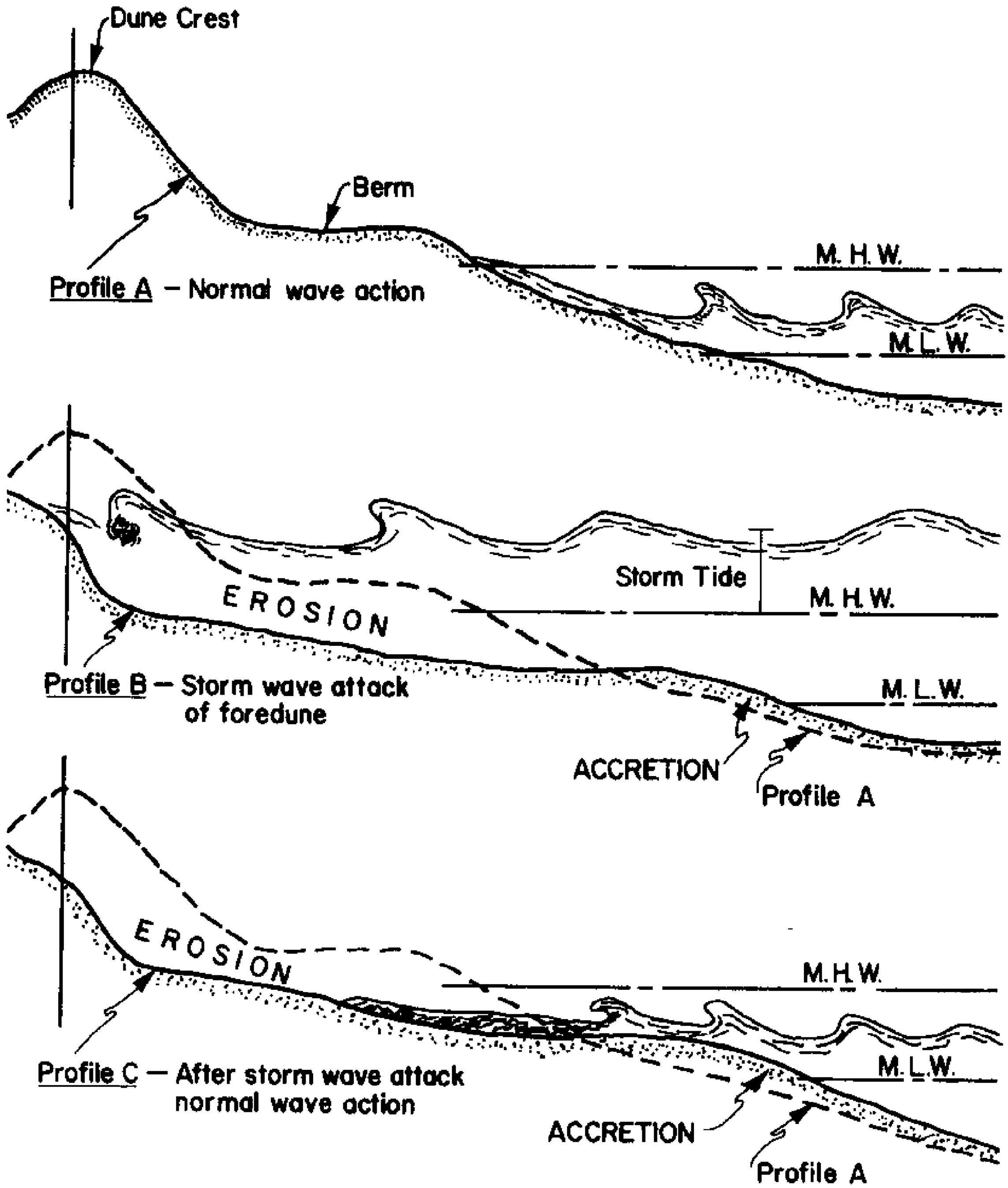


FIG. 2 — DIAGRAM OF STORM WAVE ATTACK

Modified after U. S. Army, Corps of Engineers, "Land Against the Sea" (43), p. 16.

movement of water (upslope-downslope) in the swash zone. This zig-zag motion of water results in sand movement called beach drift. The longshore drift and the zig-zag beach drift together constitute littoral drift. Fig. 3 portrays the nearshore circulation and the general directions of sand movement. It can be seen from the effects of circulation that sand transport is due to wave action in the breaker zone, seaward transport by rip currents, longshore transport in the direction of the littoral current, and movement in the swash zone by beach drifting.

Since the mid 1950's, a large amount of research has been conducted in the field of sediment transport along coastlines, particularly along the California coast, by American investigators. As a result of the development of sediment tracing techniques, as well as better methods of physically describing shoreline processes, a great deal of information has also begun to accumulate specifically pertaining to littoral transport, especially as it pertains to specific areas of interest. Studies of littoral transport have taken place in the laboratory as well as in the field. In the laboratory, mathematical models and wave basins have been utilized to attempt determination and prediction of both direction and rate of sand transport.

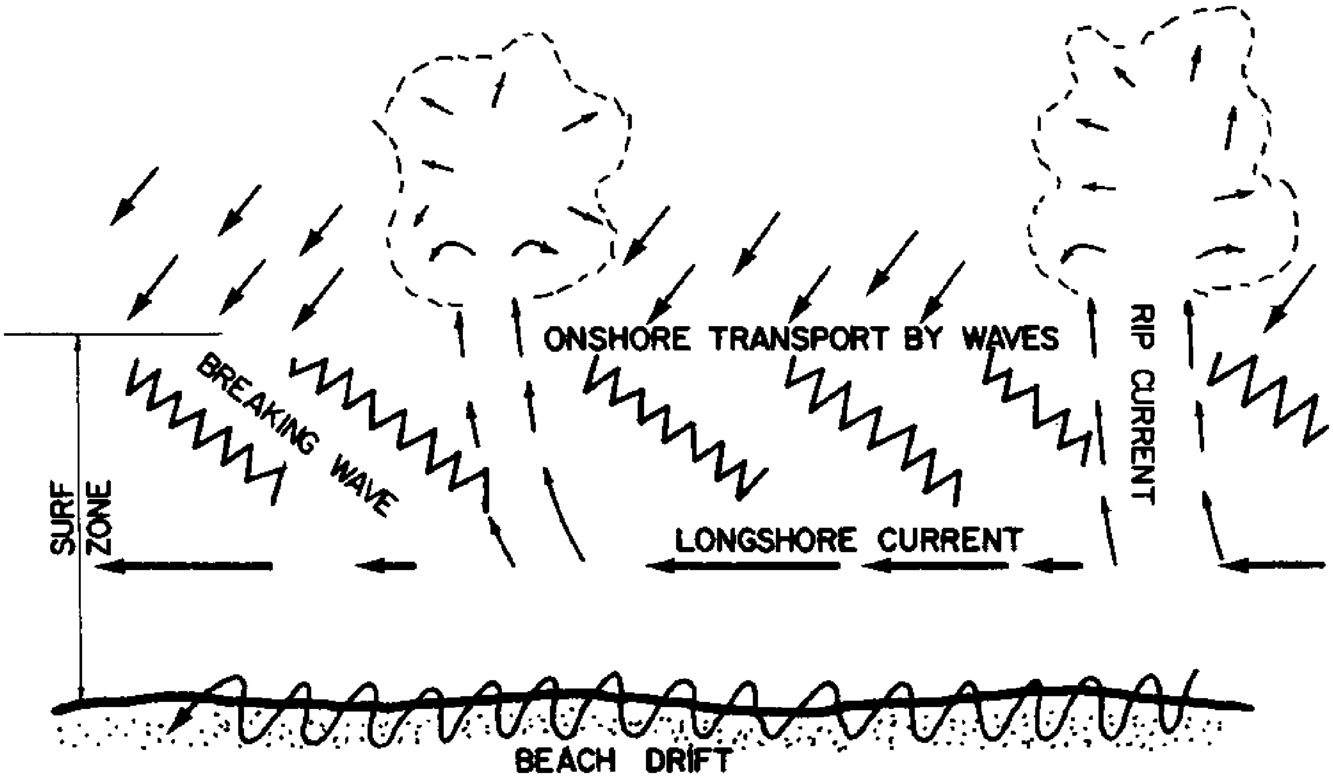


FIG. 3 – NEARSHORE CIRCULATION SYSTEM

Modified after Inman and Frautschy (14), p. 516.

In the field the tracing of identifiable particles has been used to study the mechanics of littoral transport, while studies using observable accretion or erosion to measure transport rates have also been conducted.

In the United States, sediment transport studies have been conducted on the east and west coasts, particularly at or near harbors and inlets. Only one such investigation, a limited study by Malone (28) using radioisotope tracers near Galveston, has been carried out on the Texas Gulf Coast. A simple glance at a map of the Texas coast is enough to raise the question of why so little work has been done on the tracing of littoral drift. A knowledge of the littoral characteristics of any coastline is an invaluable tool of the coastal engineer, sedimentologist, beach developer, or state planner. With its long coastline and expanding population, it is logical to assume that in the future the Texas coast will undergo great development, both industrial and recreational. When this time comes, errors in coastal structure design and planning can be avoided in Texas. However, such errors can only be prevented if a study of the sediment movement on the Texas coast is first undertaken.

In this paper, the writer will review some of the various techniques used by investigators to trace beach sand movement. These techniques will then be analyzed in order to justify the writer's selection of the method employed in the experiments. The technique of tracing beach sand coated with fluorescent paint will be shown to be the most feasible method available in terms of cost, effort, safety, and time. It was necessary to verify by field tests on a Texas beach the technique used since the environmental characteristics where the east and west coast studies were conducted are significantly different from the characteristics of Texas beaches. The California beaches on which Ingle conducted his studies are typically steep and have an average median sand size greater than the very fine sand found on the gently sloping Texas beaches. The difference in grain size also applies to east coast beaches. In addition, wave heights are usually considerably greater on the Pacific and Atlantic coasts than on the Gulf beaches.

In the experiments no attempt was made to obtain quantitative information concerning beach movement, but rather simply to develop a method which can easily and inexpensively be applied by future investigators in what is hoped will be a comprehensive study of littoral drift along the Texas Gulf Coast. In addition to a review of previously used techniques of beach tracing, and a detailed description of the experiments, a brief history of the test site and justification for the selection of this site as a test location will be given. Based upon the results obtained from the experiments, recommendations for future experiments will also be made.

CHAPTER II

AVAILABLE METHODS FOR INVESTIGATION OF BEACH SAND MOVEMENT

Both laboratory and field studies of beach sand movement have limitations which need to be identified and understood. As a result, it is important to review some of the major work done in order to place these limitations in proper perspective.

Methods Based on Laboratory Investigation.--In the past 25 years, many attempts have been made to duplicate beach processes with models. The first important work was by Krumbein in 1944 (26). Later, Saville (35) used model studies to relate the littoral transport of sand by wave action to wave characteristics. Although these studies provided some information about the processes of littoral transport in the model wave basin, verification of rates of transport or correlation with actual field data was not satisfactorily achieved. Recently, Russell (34) used fluorescent coated pebbles in the laboratory to trace beach shingle movement and to obtain data for the measurement of transport rate. He then applied his laboratory-derived relationships to actual conditions in the field in England at three beaches about which quantitative information concerning actual erosion and accretion was known. Russell's comparison between the theoretical and the actual total amount of sand transported differed by over 60 per cent. However, this study by Russell is significant in that it was the first effort to obtain quantitative relationships for littoral transport through the use of model tracing employing fluorescent coated material.

The main deficiency of using model studies to determine what will occur on beaches is that to date model technology is not adequate to accurately duplicate all natural coastline processes simultaneously. In 1960, at the conclusion of an extensive study of littoral processes off an inlet on the west coast of Denmark, Reinalda (33) stated,

> The most important conclusion is that in small-scale models in which problems concerning littoral drift are studied, a considerable scale effect may occur in the transport distribution in a line perpendicular to the coast. At the same time it appears that this may result in phenomena in the model which greatly deviate from the prototype. (p. 324)

Some investigators, having sufficient knowledge of past changes in bottom configuration, and using artificial material in place of sand, have been able to construct workable models. Noda (32) used vinyl pellets to simulate the sand in the prototype and claimed satisfactory similarity. However, he admitted that "it is almost impossible to verify the quantitative characteristics in the model experiment" (p. 567).

Consequently, it is evident that the mechanisms of sediment movement due to wave action and current are not sufficiently understood to obtain reliable working models in the laboratory. Most reliable work in the study of littoral transport has therefore been conducted in the field.

Methods Based on Field Investigation.--In the field, attempts to determine sediment transport both quantitatively and qualitatively have been tried. The most reliable quantitative investigations are those associated with measuring amounts of material trapped by natural or artificial barriers along the shoreline. Qualitative studies include tracing of radioactive sediments, tracing of natural heavy minerals, and tracing of fluorescent and radioactive coated sediment particles.

Although there are problems associated with field tracer studies, the results obtained do not involve the discrepancies evident in model studies. The tracer particles used must fulfill the requirement of having identical hydraulic characteristics with the sediment of the study area, but still must be readily identifiable when mixed with surrounding natural sediment.

This means that size, shape, density, distribution, and strength of the tracer must be the same as the surrounding sediment and that the tracer must have a physical characteristic by which it can be identified (10). The physical properties used so far to distinguish tracers are those of radioactivity, composition, or color.

Quantitative Field Studies.--A prominent work in the quantitative study of littoral drift was conducted by Johnson (20) along the coast of California. Studies of this nature are continually in progress. Quantitative information obtained in these studies is valuable in areas contiguous with natural or artificial barriers. If there is no intervening topography which adds or detracts from the littoral drift between a site in question and an existing barrier, then quantitative measurement of accretion or erosion against the barrier should give a reliable estimate of the rate of littoral drift at the site in question. However, quantitative information on littoral drift gained by this type of observation must be applied with care in evaluating littoral drift at areas very far from where the quantitative measurement has been made.

Radioactive Tracers.--Since 1954, when Japan and England first carried out tracer studies using radioactive tracers, there have been many experiments with radioactive labeling material or naturally radioactive sediment. Table 1 lists selected experiments that have thus far been undertaken. It is interesting to note that the bulk of radioactive tracer work has been done in Europe and Japan, although Inman and Chamberlain (13) and others have used radioactive tracers in the United States. The radioactive tracer technique, when compared with other techniques of tracing beach sediment, has two primary advantages: (a) the method is applicable to all sizes of material, and (b) it is possible to detect the tracers in any sea state even when the tracer material has been buried. However, there are a number of disadvantages in the use of radioactive materials. The paucity of radioactive sediment tracing in the United States may be explained on the basis of these disadvantages, which Ingle lists:

> (1) In many instances the level of radioactivity is hazardous or at best presents legal complications if used on public beaches, (2) artificial materials (glass, etc.) containing isotopes are seldom hydrodynamically equivalent to natural sand grains in the environment under study, (3) if surface absorption or plating is not used, the naturally occurring grains must contain an isotope readily activated upon bombardment, (4) the use of naturally occurring sand requires a lengthy preparation before and cooling period after bombardment in an atomic pile, (5) the cost of radioactive techniques is relatively high. (p. 10)

Table 1.--RADIOACTIVE ISOTOPES USED FOR MARKING BEACH MATERIAL

Beach Fraction	Nature of Labelling				Date of Experiment	Site
	Labelling Remarks	Isotope	Ray	Half-Life Days		
M A	Mass labelling after grinding of soda glass				1954,1955	Thames Estuary
M N	Applied as solution					
S A	Mass labelling after grinding of soda glass	Sc^{46}	γ	85	1954-1957	Poole, England Great Yarmouth, England, Adour, France
S A	Applied to Zeolite "green-sand"				1958-9	Netherlands Delta Project
S A	Isotope added to soda glass	Zn^{65}	γ	245	1954,1955	Hokkaido, Japan
S A	Glass beads	Na^{24}	γ	0.6	1956	Netherlands
S N	Surface labelling				1957	Baltic, Sweden
S A	Crushing of soda glass subsequent to labelling	Cr^{51}	γ	28	1955	La Bocca, France
M N	Applied as solution	Au^{198}	γ	2.7	1958-59	San Francisco, U.S.A.
S A	Mass labelling in soda glass	Ru^{86}	β,γ	18.6	1955	France
S N	Agar-agar film labelling	Fe^{59}	γ	45.1	1956	U.S.S.R.
S N	Radiation of phosphorus impurity in quartz sand	Ph^{32}	β	14.3	1955 onwards	California, U.S.A.
S N	Reduction of silver nitrate solution	Ag^{110}	β	270	1957	Cape Mondego, Portugal
S A	Incorporated into Soda glass	Ta^{182}	γ	111	1957	Adour, France

M = silt, S = Sand, P = Shingle, A = Artificial, N = Natural.

Modified after Kidson and Carr (22), pp. 48-49.

Several methods of preparing radioactive tracers have been used by different investigators. In tracing silt and sands, one method employs ground glass, which is labeled by incorporating a radioactive isotope. The glass tracer is then reduced to the size range of the sediment under study and placed in a reactor for irradiation. Another method, though not widely used, is the labeling of natural sediment particles through absorption of chemical solutions containing isotopes. Large amounts of material can be labeled in this manner, but too many procedural problems for easy use are generally caused by the variations in absorption rates between grains composed of different materials and the necessity of increasing absorption by annealing (23). Surface plating has also been used by investigators (29), as well as insertion of a radioisotope into drilled holes in large size natural sediment particles (38).

Where natural beach material, containing a radioisotope, is present, the tracing of the dispersion of the source material is readily accomplished by taking samples and then irradiating the natural isotopes contained in each sample. By this method beach tracing off the coast of California has been accomplished by Inman and Chamberlain (13) who obtained samples of quartz sand containing phosphorus. The samples were then subjected to irradiation and returned to the test site. At arbitrary periods shortly after the reintroduction of the irradiated quartz to the beach sand, surface and subsurface samples were taken from designated points in the test area and analyzed for their irradiated particle content. The concentration of tracer in each sample was determined by exposing the samples to x-ray film, and the black dots made on the film were counted. A pattern of dispersion from the point of injection was ascertained, and the direction of transport was determined. The greatest disadvantages of this method, other than the inherent problems of radioactive tracing, are that direct detection is not possible since only short beta rays are emitted, and that the isotopes occurring in natural sand have short period half-lives, usually less than 30 hours.

Kamel and Johnson (21) also studied sediment transport along the California coast, using naturally radioactive thorium as a means of detecting the direction of littoral drift. Of the three natural sources of gamma radiation in rock, K^{40}, U^{238}, and Th^{232}, they determined that Pb^{212}, a daughter in the Th^{232} series, would best fulfill the needs of detection of thorium and discrimination from uranium. In their study, sand samples were collected at mid-tide from many different places on the beach from the Russian River south to Point San Pedro. Source areas for radioactive thorium were identified in the region, and the decrease from the source area in concentration of thorium or heavy minerals was used to indicate the longshore drift. To determine the effects of progressive sorting (due to transport by longshore currents) and to eliminate local sorting (due to oscillatory motion of the waves), analysis of thorium and heavy mineral concentrations were made only for the 74 to 177 microns size fraction. Results of the study were arrived at by analyzing the distribution of beach samples, with their thorium and heavy mineral concentrations, along with wave diffraction diagrams.

Natural Tracers.--In the past 40 years geologists have used heavy minerals to trace the source of sedimentary deposits. Properties inherent in these natural tracers include high density, color, and radioactive or magnetic characteristics. Since heavy minerals have a tendency to remain in the foreshore-inshore zones rather than to be transported offshore, they can, in some cases, be used effectively to trace the direction of littoral drift after many years of sediment transport have taken place. That is, a decrease in the heavy to light mineral ratio concentration may indicate direction of littoral transport. The basic requirement, in order for a study of heavy mineral concentration to be meaningful in terms of littoral transport, is that an identifiable source which contributes sediment to the littoral current must be present. There is some disagreement among investigators of littoral transport as to just how effective the use of natural tracers really is. Galvin (10) claims that,

> Because of their untypical size distribution and density, and because they can rarely be referred to a unique source, natural tracers are less satisfactory than fluorescent or artificially radioactive tracers in studying sediment motion. (p. 6)

Opposing this view, Byrne and Kulm (6) have stated,

> Radioactively tagged and fluorescent dyed sands have proved extremely valuable as indicators of short-term (days or months) sediment movement. However, for long-term (centuries) sediment transport, natural indicators, where they can be properly interpreted, are still the best. (p. 181)

McMaster (30) compared the mineral heavy fractions and light fractions of samples collected on the beaches of Rhode Island to determine the trend in littoral transport direction. On the Pacific coast, Trask (42) used mineral grain analysis to determine the source of sand accretion at Santa Barbara. In his study, relative percentages of the various minerals on the

Santa Barbara beaches were used and compared with percentages of samples collected along the coast as far as 250 miles north. The decreasing percentage of augite, making up a large portion of the sand at Santa Barbara, and coming from an augite source 100 miles north of Santa Barbara, gave Trask the idea that this northern source was the primary supplier of sand being deposited in Santa Barbara Harbor. In 1965 Cherry (7) studied the long-term beach and offshore sand movement on the coast of California between Drakes Bay and the Russian River by tracing relative concentrations of heavy minerals from their sources in the area of study. From his analysis of hindcast swell data, refraction diagrams, availability of sand, and knowledge of stable coastline slopes, he concluded that the beaches in the study area were in equilibrium, with negligible net gain or loss of sand.

Fluorescent Tracers.--Teleki (40) defines fluorescent tracers as:

> . . . clastic particles coated with selected organic or inorganic substances, which upon excitation of 3650A or 2537A wave lengths ultraviolet light emit fluorescence of variable wave length and intensity in the visible region of the spectrum. The term luminophore (primarily in Russian literature), although it also encompasses phosphorescent tracers, is interchangeable with fluorescent tracers. (p. 249)

Although attempts to impregnate or coat sand particles were made as early as 1938 in Germany, the first publication pertaining to fluorescent coating of tracers was in 1956 by Medvedev and Aibulatov (31) of the Soviet Union. Since that time studies in beach tracing through use of fluorescent tracers have been conducted in Britain, Germany, India, and the United States. Probably the reasons for such a surge in littoral transport investigations, using fluorescent tracer techniques as compared with studies using radioactive methods, are evident in the advantages of fluorescent tracer techniques. As stated by Ingle, they are:

> (1) naturally occurring coarse silt, sand, or cobbles from a study site can be readily marked, (2) the majority of dyes employed present no legal or health hazards, (3) different fluorescent hues can be used to differentiate between successive tests at one locality or to trace the movement of different size fractions, (4) solubility of binding media may in some cases be adjusted so that dye will adhere to grains for a period of from several days to several years, (5) cost of dyeing is relatively cheap, (6) dyeing can be accomplished anywhere and can in fact be carried out at the study site, (7) the time required for dyeing sand is short, often entailing only minutes, (8) the sand to be dyed in most instances does not require special preparation prior to dyeing other than drying, (9) sensitivity of the fluorescent technique is at least one grain in $1 \cdot 10^6$ grains, which is equivalent to radioactive techniques, and (10) dyes do not affect the hydraulic character of the labeled sand grains. (p. 11)

However, there are some disadvantages inherent in this technique. In its early stages of development, care had to be taken in choice of fluorescent substance, since some dyes were toxic or attacked the skin and were also susceptable to deterioration by sun and salt water. Another major disadvantage compared with radioactive tracers is that for accurate analysis it is necessary to collect samples. The first two disadvantages have largely been overcome with continual development and testing of existing and newly marketed materials. There are several methods of tracer preparation now available which achieve a multiple color possibility, variable tracer durability and longevity, minimum thickness of coating, retention of the original volume or specific gravity, and preservation of the original shape of the particle. Table 2 shows a selected list of possible dyestuffs and colors which can be used in coating fluorescent tracer material.

As noted previously, sediments dyed with fluorescent substances have been effectively used to trace the movement of natural beach sediments. Among many investigations conducted outside the United States, R. C. H. Russell's work (34) stands out as an attempt to obtain quantitative as well as qualitative results using fluorescent tracers. Russell attempted to

Table 2.--SELECTIVE LIST OF FLUORESCENT DYESTUFFS FOR USE WITH COATING RESINS

Color Index No.	Chemical Classification		Color of Fluorescence
	Name	Empirical Formula	
45170	Rhodamine B	$C_{28}H_{31}N_2O_3Cl$	Orange-red
766	Uranine	$C_{20}H_{10}O_5Na_2$	Greenish-yellow
45400	Eosin B	$C_{20}H_6N_2O_9Br_2Na_2$	Yellow
45410	Phloxine B	$C_{20}H_2O_5Cl_4Br_4Na_2$	Brick red
41000	Auramine O	$C_{17}H_{22}N_3Cl \cdot H_2O$	Green
49000	Primuline	$C_{21}H_{14}Al_3O_3S_3Na$	Milky blue
49005	Thioflavin TCN	$C_{17}H_{19}N_2SCl$	Yellow
46045	Phosphine	$C_{19}H_{16}N_4O_3$	Vivid green
50240	Safranine	$C_{20}H_{19}N_4Cl+C_{21}H_{21}N_4Cl$	Yellowish red

Modified after Teleki (40), p. 472.

construct a method of quantitatively measuring littoral drift along a beach. The experimentation was developed in the laboratory of the Hydraulics Research Station, Wallingford, England, and then carried out on three different beaches on the English coast. Long-life fluorescent tracers were used, and only littoral drift along shingle beaches was investigated.

The laboratory method by Russell was the so-called dilution method in which tracer is injected at a known steady rate into a channel of unidirectional flow, followed by sampling downdrift from the injection point. Sediment transport rate is then calculated by $Q = q/c$; where Q is the sediment transport rate, q is the rate at which tracer is injected, and c is the concentration of tracer in the sediment. In Russell's laboratory model, small variation waves were generated cyclically at a shingle beach having individual grain size variations from 1 to 10 mm. Tracer material taken from traps on the beach was coated with fluorescent dye and replaced casually on the beach at the rate of 1/400 liter every three minutes for two hours. The degree of concentration was determined by obtaining the count of fluorescent particles visible per square foot of surface and applying the count against a concentration calibration. The value of Q was then obtained and checked against a value of Q obtained by mechanically trapping material as it drifted along the beach. The differences between these two values of Q were explained by Russell to be the result of two main errors, one involving the counting of randomly distributed particles, and one resulting from the moving layer of shingle and tracer being undesirably thin. It was also found from the experiment that the size of the moving sediment was coarser than the material of which the beach was composed.

Russell found that under the more complicated conditions of littoral drift in two directions, caused by the change in direction of incoming waves, the dilution method can be used to predict transport rate only if it is assumed that the drift pattern for a short time (a few days) is the same as the general pattern over a long period (years). Russell also developed the mathematics to relate the movement of tracer to littoral drift under conditions of movement in opposite directions by using an analysis of bins dumping into each other a specified amount p to the right an q to the left, while the central bin continuously receives material. Distribution curves of concentration versus distance units from the injection point (central bin) can then be plotted for various values of p and q. Accordingly, if the tracer is added to the beach at a rate m/t, where m is volume and t is time, and if the concentration at a point x is N_x, and if the concentration C_x of tracer is measured, then the net rate of transport may be found from:

$$Q = \frac{(p - q)}{t} \cdot \frac{mN_x}{C_x}$$

Curves derived from the above relationship were then used to obtain Q from field tests on the beaches of Rye, Dungeness, and Deal. Tests were confined to shingle beaches since Russell felt that sand tracer lost offshore could not be estimated, whereas shingle is generally assumed to remain on the beaches. Crushed concrete was used as tracer material, dumped at the rate of 700 pounds per week at Rye and Dungeness. The distribution was surveyed after 22 weeks and 52 weeks for calculation of Q. At Deal the tracer was dumped at the rate of 100 pounds per day for 21 days and then surveyed. At all sites samples were surveyed at 200 feet, 500 feet, 1000 feet, 2000 feet, and 3000 feet on either side of the injection point. The area in which the pebbles were counted was initially 36 square feet at Deal and 100 square feet at Dungeness and Rye. For Rye, the calculations could be compared with a known volume of accretion. A comparison of this known volume with the calculated volume for one year of transport revealed a disparity between the 53,000 tons of shingle actually moved by littoral processes and the 31,000 tons estimated by calculation. The calculated drift at other locations was consistent in that the smallest drift was found to be at the beach which was least exposed to big waves, whereas the largest amount of drift was at the most exposed beach.

In the United States, pioneer work in beach tracing using fluorescent tracer material has been largely carried out by Ingle, Wright (50), and Yasso (51). Ingle's work on the California coast represents the most extensive study of littoral transport using fluorescent tracers conducted in the United States. From pilot tests conducted in 1959 (12), Ingle established the feasibility of using fluorescent dyed sand grains to trace the movement of sand in the foreshore zone. In 1962 he initiated a full-time program of research which lasted one and one-half years and was performed on five test beaches along the southern California coast. Surveys at the test beaches were performed at month or month and one-half intervals during the study's duration. From each of the five beaches Ingle collected a 100 pound sample of sand, which was dried and sacked, then sent to a commercial firm for dyeing. Ingle does not describe the dyeing procedure used since the commercial company requested that this information be withheld for competitive reasons. Nor does he state whether or not the dyeing procedure used can be duplicated in the laboratory, although he does say that the dyes employed were fluorescein and rhodamine-B. After dyeing and redrying, the sand was placed in vinyl bags, holding 5 to 10 pounds of dyed sand each. The sand was then taken back to the test sites and released on the beach. Ingle reports:

> At the time of release the plastic bags containing the dyed sand were carried into the surf and broken simultaneously on the bottom at predetermined release points. Release points were located at the up-current end of a sample grid, allowing the majority of samples to be taken in the area of greatest tracer transport. (p. 19)

The sample grid was established on the test beaches (each sample grid was about 500 feet long) after the direction and relative strength of movement of the littoral currents had been determined. A quick sampling method was developed by trial and error. This consisted of taking a surface sample by pressing a vaseline coated card onto the beach bottom, causing the top layer of sand particles to adhere to the card. Ingle describes this collection procedure:

> This first collection of quick samples was usually begun 5 min [sic] after release of tracer sand although this period was lengthened if weak conditions prevailed to allow movement of the tracer. After collection of one round of samples, a second collection was initiated almost immediately. However, up to 60 min. was again allowed to elapse if weak surf prevailed. As many as four sample collections were completed at increasing elapsed times after tracer release.

During the duration of each test measurements of wave height and period, current velocity, and wind velocity were made several times. Profiles were measured during each test along the line of tracer release perpendicular to the shoreline. Ingle reports the next step:

> Upon return to the laboratory the grease and sand coated sample cards were examined under a short-wave ultraviolet lamp. . . . Numbers of fluorescent grains adhering to each sample card were tabulated and the area of the cards covered by sand also noted. In this manner the number of fluorescent grains per square inch of surface area was obtained for each sample station and interval sampled.
>
> . . . .
>
> [The values obtained per] card were corrected to compensate for the elapsed time between release of the tracer and the last sample collected in each sample round. . . .
>
> . . . .
>
> Corrected tracer concentrations were then plotted at their respective stations and contoured with isopleths representing equal concentrations of fluorescent grains per square inch of surface area. (pp. 42-44)

Contour maps, from which directional tendencies of the littoral transport could be ascertained, were constructed for each sample series. These contour maps depict fluorescent concentration within the sample grid at increasing time intervals after tracer release.

Wright's (50) work consisted primarily of developing a simple inexpensive technique for marking sediment particles with a fluorescent coating and devising appropriate analysis procedures. The site of the field work was the beach at Horseshoe Spit, Sandy Hook, New Jersey. The beach consists of medium to coarse, well-sorted quartz sand having an average median diameter in the test area of about 0.6 mm. Wright tested 8 different dye substances before choosing an anthracene and chloroform solution for sand labeling. Wright's definitive statement of the characteristics of the anthracene coating is quoted below in its entirety for later reference in Chapter IV.

> Anthracene is a colorless, very brilliantly fluorescent (when slightly impure) material which is readily soluble in various organic solvents but insoluble in water. . . . It is quite stable under all conditions to be found on beaches; it lends itself readily to a variety of marking techniques; its bright yellow-green color under ultraviolet light is unlike the color of any of the naturally fluorescent materials (mostly kelp fragments and small arthropods) found in the beach sand. (p. 4)
>
> . . . It was found that the material [anthracene] would adhere quite satisfactorily to the surface of grains . . . and although obviously brittle, was able to survive 24 hours of constant agitation in a ball mill with a negligible loss of weight (0-023%). The coating actually increased average particle

> weight by slightly less than 0.1%, and the thickness was so slight that it could not be measured by mechanical means. It seems likely that the resistance of the anthracene coating to abrasion is a result of the gentleness of impact between particles of this size (median diameter between 0.5 and 0.7 mm.) in the presence of a cushioning layer of water. In the field it was noted that the film on particles of pebble size (m.d. 4 - 6 mm.) persisted over two weeks under moderate conditions, and marked sand particles remained identifiable three or four weeks. Despite these occurrences, the effective life of particles marked in this manner is believed to be approximately two weeks; certainly sufficient time for dispersal to have ended the usefulness of any but a very large run for quantitative sampling. (p. 4)

Wright's marking procedures were developed in the laboratory but were readily adaptable for field marking. First Wright collected a small amount of sand (50 - 80 pounds) from the proposed test site, washed it in water to remove extraneous materials, then drained and rewashed the sand in denatured alcohol to remove pollutants adhering to the particles, afterward immersing it in the anthracene and chloroform solution. After thorough mixing to ensure that all particles had been coated, the sample was drained again and spread in a well-ventilated place to dry. As in Ingle's procedures, a sample grid was laid out at the test site. However, Wright's grid was much smaller since the wave climate on his site was much calmer than at Ingle's sites. A total of four tests were run, with the largest grid being 24 by 32 feet, and the smallest 20 by 20 feet. In general all four grids were placed so that the depth of each ran from the limit of high tide to the low tide mark. Sampling locations within the grid were spaced at 2 foot or 4 foot intervals. All sampling after injection of coated material was accomplished when the beach was uncovered at low tide. The injection method consisted of spreading the coated sand along a measured line so that a ribbon of marked material, 6 - 8 cm. in width, was obtained. Collection times at the sampling locations within the grid varied from half a tidal cycle to two complete diurnal tidal cycles. Samples were taken with a cookie cutter which had a depth of penetration of two centimeters.

Marked particle concentration in the samples was analysed by splitting the collected sample from each sample point and then recording the number of the last split in which marked particles could be seen under an ultraviolet lamp. Assuming that the number of marked particles in a given sample is a power function to the base two of the number of subdivisions required to yield a fraction containing no marked material, the tracer concentration in the total sample could then be determined.

Yasso's (51) method of beach tracing differed from Wright's and Ingle's both in the coating technique and in the technique for obtaining samples after injection of the coated material. In his study, which was also conducted on the beach at Sandy Hook, Yasso employed one of the dyeing techniques he had previously investigated. Particles in four size classes ranging from 1.397 mm. to 0.589 mm. were selected for marking as tracer particles. Each size class of particles was coated with a different color mixture of Switzer Day-Glo acrylic lacquer and American Cyanamid Beetle resin.

At the test site a sampling line was established 100 feet downdrift of the coated sand injection point. A single point injection procedure was used, the test sample being injected in one lump at a point located at mid-swash level. Collection of samples on the sampling line began 20 minutes after injection of the marked particles. Yasso used a tin can bent to scrape a channel 0.18 foot wide and 0.10 foot deep along the sampling line. The dug channel began at the backwash limit and extended about 10 feet upslope towards the swash limit. The center one-third of each length of sample was used for analysis of tracer concentration. Concentration was determined by exposing the sample to an ultraviolet light and then extracting the tracer particles. In this manner Yasso compared tracer concentration along his sampling line with time from injection of the tracer sand.

Comparative Analysis of Tracer Methods.--Although all of the available methods described above for beach tracing accomplish more or less the desired result of determining littoral drift patterns, each method has inherent disadvantages and advantages over the other methods. After making a comparative study of the available methods, the writer decided to select one or a combination of them which could be modified to trace beach movement along the Texas Gulf Coast. The criteria for selection were that the coating material must have more than a few hours of effective life and that the tracer could be followed equally well in areas such as inlets as well as along straight shorelines. In addition, the method selected would have to be adaptable to the distinct characteristics of the Texas coast. That is, it must work for very fine-grained sand, gentle beach slopes, narrow foreshore zone, and generally mild surf conditions. Also, since future studies are envisioned to take place upon beaches used for recreation, the tracer material must not be hazardous.

Although a model study, employing some type of traceable material, was considered as a possible tool for studying beach movement, any results obtained from the model study would need field verification before more extensive model studies could be undertaken. And, in view of the difficulties experienced in trying to duplicate the complex changes which occur along a real beach, it was thought that only a field test could realistically test any method selected. The correlated study and field test performed by Russell had the limitation of being conducted with pebble and cobble sized material. Since his test attempted a quantitative analyses, it bears close scrutiny as a possible means of prediction for the littoral drift along the Texas coast, with its well-sorted sand distribution. Unfortunately the differences in the mechanics of cobble and sand transport are too great for use of Russell's curves or his methods. Pebbles and cobbles move along a path which can be more precisely determined than the movement of fine sand grains. And, when dealing with grains having a median diameter of approximately 0.15 mm., as is the case on the Texas coast, concentration of tracer particles are more significantly affected by burial of the sand or by grains being put into suspension. In the surf zone, sand grains travel in three dimensions, whereas pebbles move primarily with the bed load in the direction of littoral currents.

Unlike pebble concentrations, which can be easily measured because of pebble size and movement along the bottom, sand concentrations must be deduced from only a few points in time and space. And, since the concentration gradient of the sand movement is asymmetrical from the injection point, quantitative measurement is at best a guessing game with the present methods available.

Tracing through use of natural heavy minerals was patently unsuitable, since too general a qualitative finding is inherent to this method. Although radioactive tracing has certain advantages, and has been shown by Malone (28) to be suitable for application on Texas beaches, there appear to be too many major disadvantages which cannot be minimized and which provide formidable obstacles to an extensive study. The method which appears most suitable is the method of fluorescent tracers.

CHAPTER III

THE STUDY SITE

In order that the writer's field experiments might provide the groundwork for future studies, as well as give future investigators a reliable method of sediment tracing, the field test site had to satisfy three major requirements. First, the site had to be easily accessible for logistic purposes; second, the area should be one at which future development (for recreation or industry) would be likely to occur; and third, the site should be at or near an area worthy of future study, for example, an inlet, harbor, or breakwater. A test site which could fulfill all of the above requirements is located only 160 miles south of Texas A&M University. This site is at the mouth of the Colorado River near Matagorda on the central Texas Coast (Fig. 4).

A more precise map of the study area is given by United States Coast and Geodetic Survey on chart No. 1284. The river mouth itself is located about 94 miles southwest of Galveston, 47 miles southwest of Freeport Harbor, and 32 miles northeast of Pass Cavallo. The nearest town to the river mouth is Matagorda, six and one-half miles up the Colorado River.

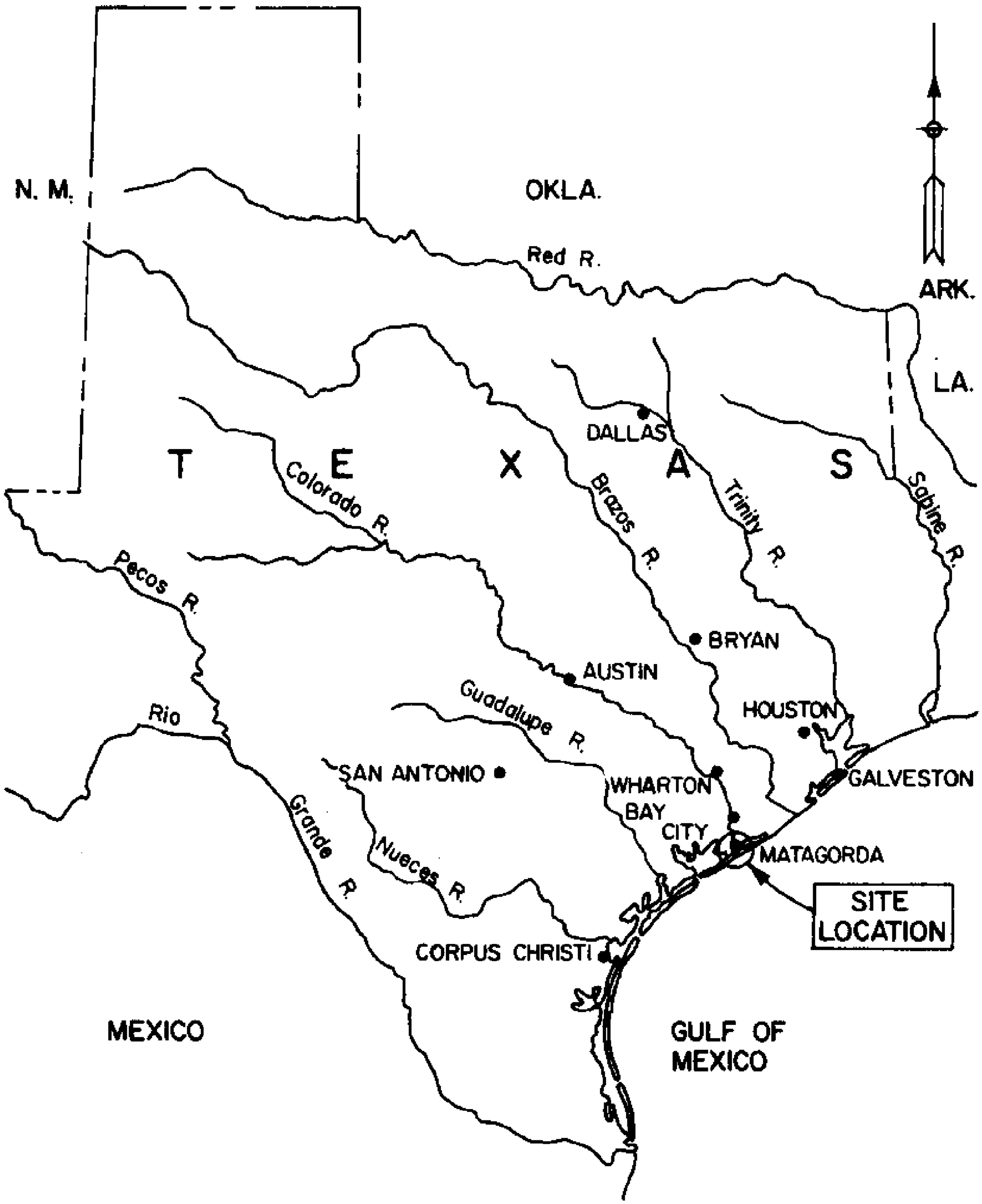


FIG. 4 — VICINITY MAP

<u>General Characteristics</u>.--As seen in Fig. 5, one access road, which runs parallel with the river from the mouth to the town of Matagorda, leads directly to the beach. Although the photograph in Fig. 5 presents the beach area in 1957, the road shown is still in existence. The importance of having access directly to the study site is primary since the amount of equipment required (transit, test sand, survey level, etc.) was too much to hand carry any great distance.

The physiographic and hydrographic features of the test site are typical of the Texas shoreline. At the mouth of the Colorado, the mean diurnal tidal range is about 1.0 foot. In the winter, prolonged north winds may depress the water surface several feet below mean low tide, whereas south and southeast winds in the summer raise the water surface as much as 3 feet above mean low tide. Inland, at Matagorda, the water level in the river has been recorded at as much as 14 feet above mean low tide during a hurricane. The mouth of the river is usually obstructed by both an offshore bar and a spit on the northeast side, making the controlling depth in the mouth of about one to two feet at mean low tide. The depths over the bar change frequently as a result of floods on the river and storms in the Gulf. Also, the configuration of the spit is

FIG. 5—MOUTH OF THE COLORADO RIVER AT HIGH TIDE
OCTOBER 17, 1957

Dotted line outlines present day spit exposed at low tide constantly being changed by littoral drift, which has a predominant direction to the southwest. This littoral drift tends to build up the spit, whereas gulf storms tend to erode it. In the absence of storms, and from the prevalence of mild wave conditions, the spit enlarges to the southwest, at times almost closing the channel entrance, because the river velocities at the mouth are insufficient to keep the channel scoured of sediment deposits.(Fig. 5).

The test site lies in a region with warm summers, mild winters, and high relative humidity. The lack of marked topographic relief features, the prevalence of southerly winds (except for short periods of northerly winds brought by high pressure air masses moving down from the north), and the site's position on the Gulf of Mexico all contribute to the mild climate. The mean average annual temperature is about 70°F, with January being the coldest month and August the warmest month. Mean annual precipitation, based on records for Houston, is about 45 inches. The area is subject to intense short-period thunderstorms, rainfall associated with general storms which may last several days, and heavy rain from hurricanes or tropical storms. Although floods may occur any time during the year, the broad, marshy characteristics of the lower flood plain produce slow-moving floods which do not significantly alter the configuration of the river mouth (43).

There are a number of indications (46) that steps will be taken soon to overcome the natural shortcomings of the site for commerce and recreation. Local interests have tried for many years to have the federal government improve the mouth of the Colorado to promote greater commerce and add to the recreational attraction of the area. At present the only commerce consists of shrimp and fish caught in the Gulf and adjacent bays. However, the shallow depths and the shifting bar and spit make the channel prohibitive to boats having drafts greater than the controlling depth in the inlet. It is claimed that if the mouth were deepened and protected by jetties, shrimp commerce landing at Matagorda would increase by five million pounds (46), and that the opening of a channel sufficient to take larger boats would greatly enhance the area's sport fishing.

Since the early nineteen fifties the U.S. Army Corps of Engineers has considered the mouth of the Colorado as a possible site of coastal improvement. In 1955 a report on the feasibility of either improving the existing channel or building a new channel at the mouth of the Colorado was forwarded to the Chief of Engineers (43). However, the report also included feasibility studies of other possible sites on the Gulf for a deep-draft navigation channel, and it was decided that improvement at a site other than the Colorado was more feasible at the time. In 1967 another report concerning the advisability of such improvement for the mouth of the Colorado in the interests of commerce and flood control was submitted to the Chief of Engineers (46). The conclusions reached in this latter report were favorable towards improving the river inlet. The report stated:

> Economic analysis of the selected plan for providing an entrance channel shows an immediate need for construction of this project for timely development of the water resources of the area. In addition, an emergency entrance from the shrimping and oil and gas production areas of the mouth of the Colorado River is needed. The economic savings which would result from reducing travel distance for fish and oil company service craft and development of the recreation potential would improve the general welfare of the people in the area. (p. 28)

The proposed project plan provides for a jettied entrance channel at the mouth of the Colorado, with a minimum channel depth of 12 feet. This proposed project has been approved by Congress, and at present several alternative jetty and channel designs are being studied for implementation of the project.

The above cited Corps of Engineer reports, together with a report prepared by Drs. Arnold H.

Bouma and William R. Bryant, geological oceanographers at Texas A&M University (3), provided the writer with a great deal of specific information about the site relative to his experiments. Moreover, the documentation available pertaining to the lower Colorado River shows that the experiment site is worthy of study not only for its future commercial and recreational prospects, but also for the unique way in which the channel entrance into the Gulf was formed. In order to show how the river inlet affects littoral drift, a brief history of the river is given below.

Site History.--Until a few centuries ago, the Colorado River flowed to the Gulf over an alluvial plain southwest of Wharton (Fig. 6). Then, as a result of both stream piracy and the uplifting of a dome sometime in the recent geologic past, the river channel was shifted west of Wharton, causing the river to flow into Matagorda Bay at what was to become the town site of Matagorda (Fig. 7). In its new channel, the river meandered back and forth, cutting away at its banks and slowly building a delta into Matagorda Bay. The continuous undermining of the banks resulted in a large number of trees and a great amount of brush falling into the river. Eventually this material caused many natural dams to be formed in the river channel between

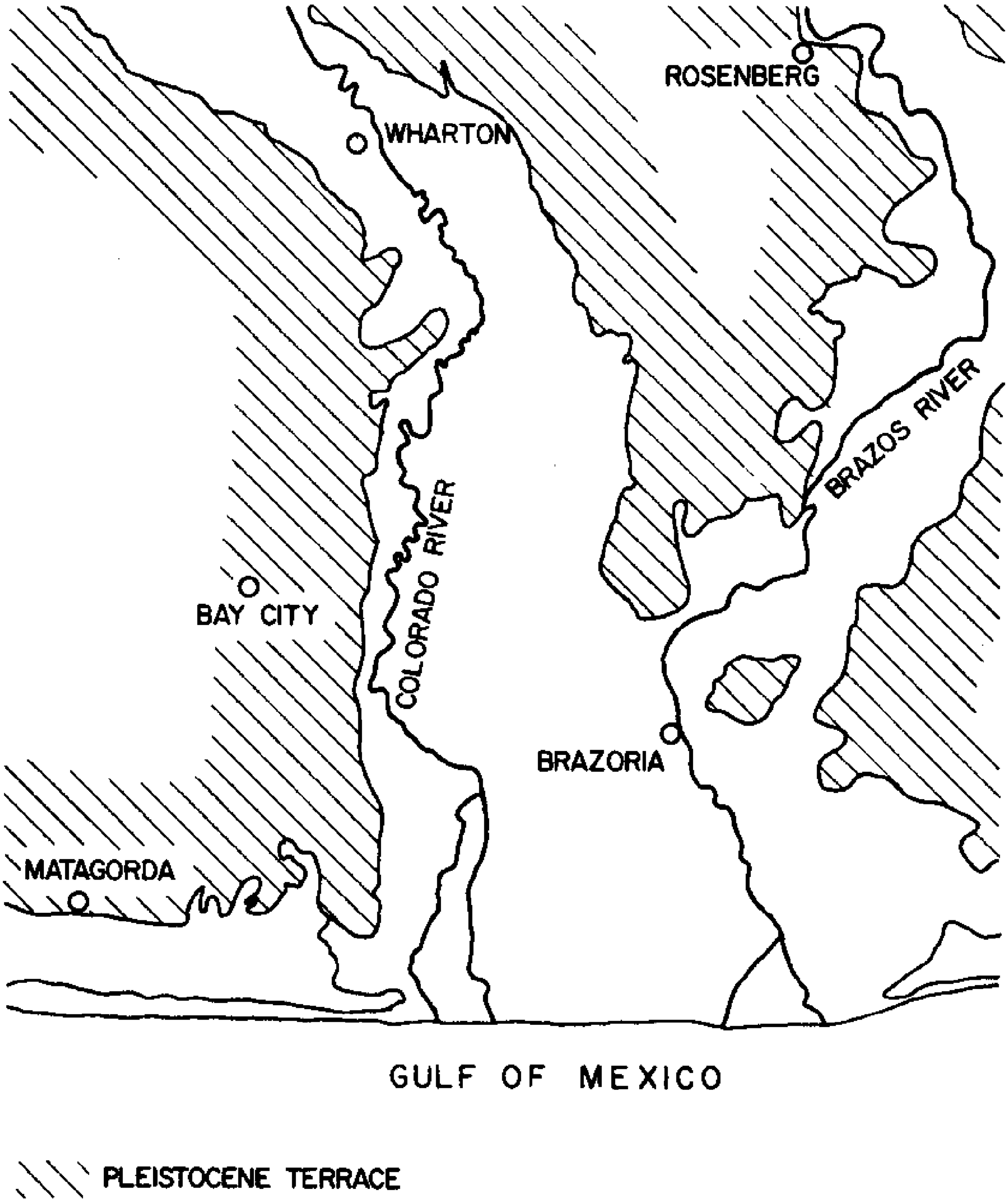


FIG. 6 — COURSE OF THE COLORADO RIVER A FEW CENTURIES AGO

After Bouma and Bryant (3), p. 21.

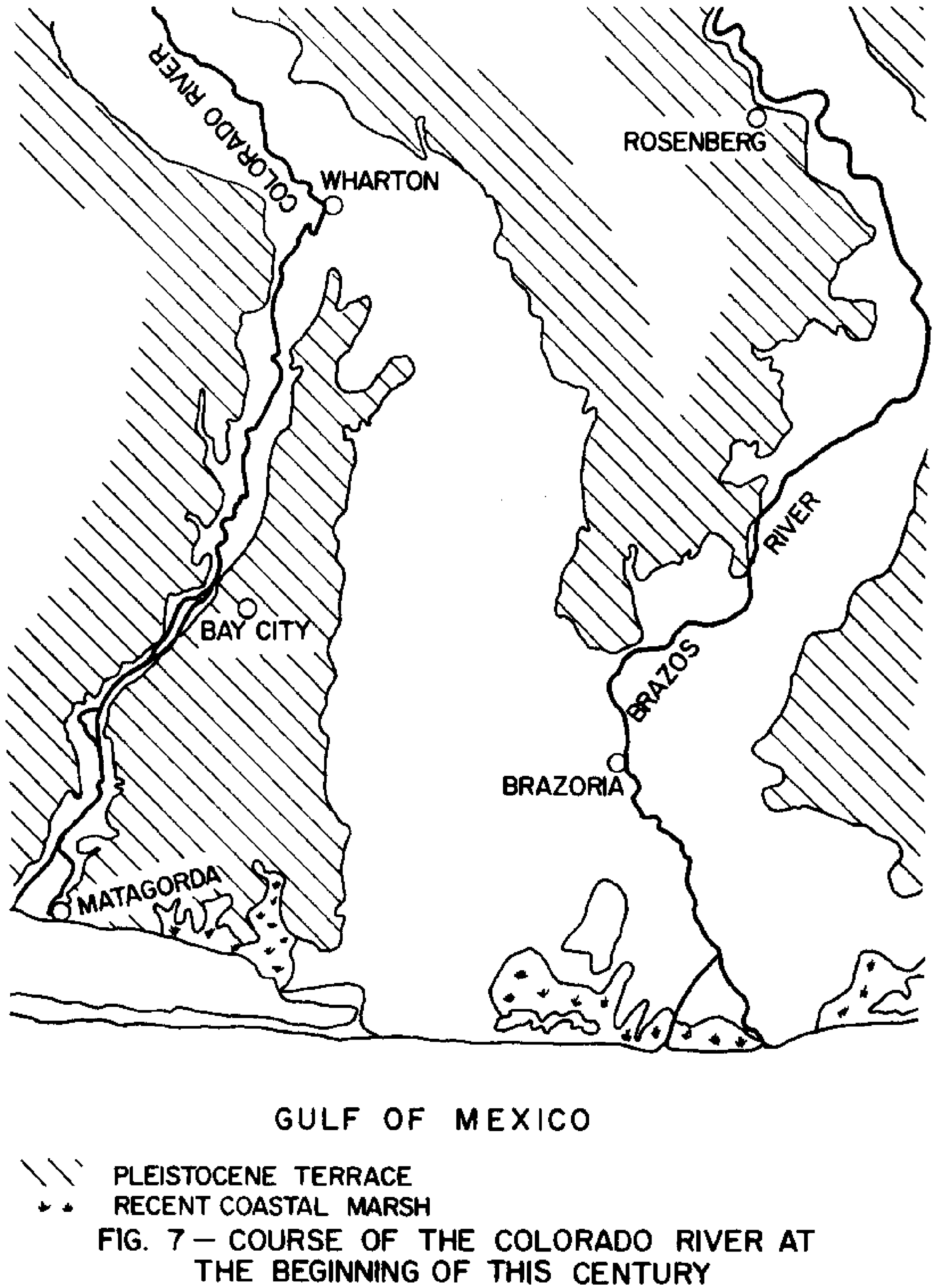


FIG. 7 — COURSE OF THE COLORADO RIVER AT THE BEGINNING OF THIS CENTURY

After Bouma and Bryant (3), p. 22.

21 and 45 miles above the mouth. These dams impeded the flow of flood waters, stopped debris and silt from being carried to the mouth, and retarded the growth of the delta. In 1929 local interests at Wharton successfully caused the dams, which had formed a large "raft," to be broken up, and the growth of the delta in Matagorda Bay was thereby greatly accelerated. Although removal of the raft alleviated flooding of lowlands near Wharton, it caused greater flooding of the lowlands near the mouth of the river. To relieve this condition, in 1934 local flood control agencies dredged a channel along one of the former river outlets, through the river delta, across Matagorda Bay, and through the offshore barrier beach to the Gulf of Mexico. Since 1934, continued deposition of silt and debris carried by the river has resulted in an extension of the delta flats entirely across Matagorda Bay (Fig. 8).

Once the channel was dredged across the barrier beach, river sediment which had previously been deposited in the bay was now available for insertion into the littoral current. Considering that the Colorado River ranks third in silt load among Texas rivers, carrying approximately 9 million tons annually (46), one would expect a marked build-up of the beaches southwest of the river mouth since 1934. However, an

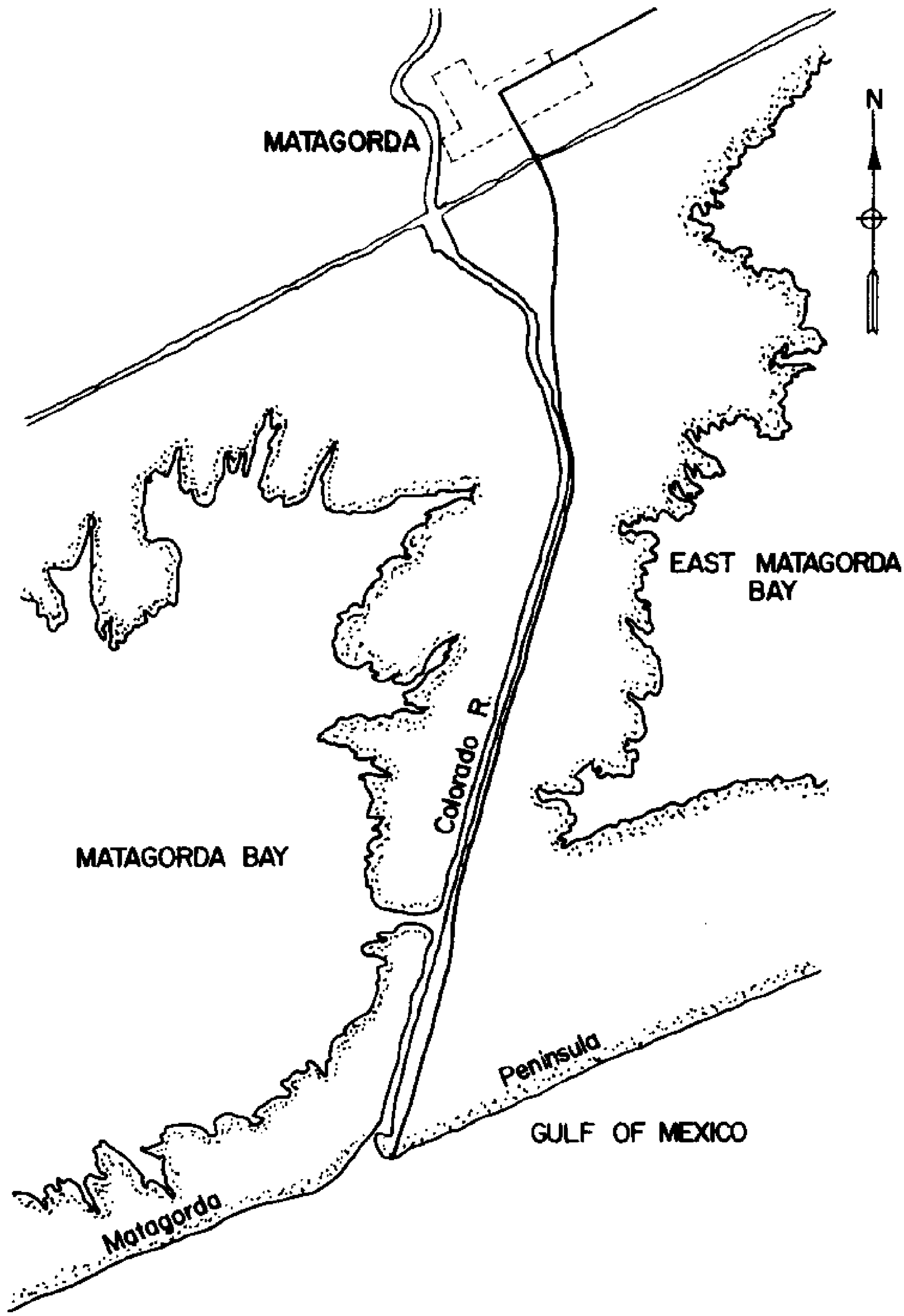


FIG. 8 – COLORADO RIVER DELTA

examination of photos of Greens Bayou, located about 17 miles southwest of the Colorado River mouth, shows that although the numerous washovers through the barrier beach have been silted up and closed, the shoreline itself has been steadily eroded. In fact, since 1934 there has been no discernible increase in the rate of accretion on any beach downdrift of the river mouth.

Need for Littoral Drift Studies.--Both the 1955 and 1967 Corps of Engineer reports on the mouth of the Colorado River state that construction of the proposed jetties would interfere with normal shore processes by stopping or impeding littoral drift. The reports also imply that there is insufficient data to predict accurately what shoreline changes might occur. Yet it may well be that construction of the jetties would cost much more in annual maintenance than the estimated figure if in fact a disturbed littoral drift would severely erode the downdrift side of the jetties or cause a substantial bar to be built at the entrance of the channel. A better knowledge of the site, which may be afforded by the methods of study investigated in this paper, could be instrumental in avoiding unreasonable maintenance costs.

Apparently in 1967 the Corps did not consider that possible drastic changes in the shoreline, resulting from the jetties' interference with the natural littoral drift, would cause significant problems. There are practical reasons taken into account by the Corps which appear to make detailed study of the littoral drift unnecessary. First, the proposed jetties at the mouth of the Colorado and the shoreline in the immediate vicinity are similar to the existing Matagorda Ship Channel. Therefore, it was assumed that the shore processes and the effects of the jetties would be approximately the same for both locations. And, from aerial photographs of the Matagorda Ship Channel, no significant recession of the downdrift shoreline can be detected. Second, the land area west of the mouth of the Colorado is unpopulated, inaccessible, and low in value. Thus, even if recession of the shoreline did occur, artificial replenishment of the beach there would not seem to be necessary. Last, the Corps predicts that shoreline advance on the updrift side of the proposed jetty system would take fifty years before there would be a danger of the shoreline building out to the end of the east jetty.

All these reasons are valid, yet they may well be considered in relation to additional points. It is true that at the present state of development in the area, the beach west of the mouth of the river has little value. But, one of the expected benefits of the project will be the increased attraction of the area to sport fishermen. It is possible that the west shoreline may in the future become as populated as the east shoreline. If this should happen, it would be worthwhile to ascertain beforehand whether or not the construction of the jetties would in fact cause severe erosion. Another question not yet answered is how much the Colorado River contributes to the littoral drift. In 1964, the Committee on Tidal Hydraulics recommended a number of studies of survey scope which should be made to determine a practicable plan for making the mouth of the Colorado River navigable (46). One of the recommendations was for the sampling and analysis of materials in the bar formation and the river to determine whether composition is wholly of littoral sediments or partly of fluvial sediments. Apparently this study has not yet been undertaken. In addition, an investigation of the nature of sand movement in the spit area might give valuable information concerning the rate of accretion on the east side of the mouth. If the processes of spit building were known, this information could be used to aid in the prediction of sand deposition on the east jetty of the proposed project.

The advances made in techniques developed to study littoral drift can now be taken full advantage of in any major coastal structure design, such as that being planned at the mouth of the Colorado River. Use of the writer's tested sand tracing procedures could be of help in ascertaining answers to the questions posed above. At the least, use of the methods could inexpensively provide qualitative information which might be valuable in design and could possibly result in savings on the cost of construction and maintenance of inlet projects.

CHAPTER IV

DEVELOPMENT OF PROCEDURES

After consideration of the several dyeing techniques available, the writer chose the method and material used by Wright (50) as being probably the most suitable for use in the proposed tests. Of primary importance in the selection of a dyeing method was the requirement that the fluorescent coating must not significantly alter the hydrodynamic characteristics of the natural sand grains. Since the particle size of sand grains found on Texas beaches is normally very small, coating thickness of the fluorescent material must be very thin. Wright has stated that the coating of anthracene on sand was so thin that thickness of coating could not be measured. And, as claimed by Wright, the hydrodynamic properties exhibited by anthracene coated sand had no significant difference from uncoated sand. In addition, Wright's method of dyeing has the added advantages of being inexpensive, easy to apply, and adaptable for use both in the field and in the laboratory. According to Wright, the method does not require sieving of the sand once the dye is applied, since after drying the individual sand particles separate from each other and retain the same size distribution as the sand before dyeing. Also, anthracene and chloroform, the two ingredients used in Wright's coating process, are readily available. Under an ultraviolet lamp, anthracene fluoresces a brilliant yellow-green making it useful as a tracer material.

Once the method of coating the sand particles was decided upon, a procedure to recover and analyze samples had to be determined. Most of the beach tracing done previously on the east coast took place over small areas and shoreward of the breaker zone. On the west coast, Ingle's tests included tracing over several hundred feet of beach. Ingle also was able to obtain a large number of samples in a very short time by taking samples from the sand surface rather than by scraping up a portion of a sample area. Since the wave heights found at the test site at the mouth of the Colorado seldom exceed three feet, the writer felt that the surface sampling methods of Ingle would be satisfactory. In addition, the writer planned to take samples over time periods of up to three hours after the tracer was to be released. These intervals dictated that a long grid system would be needed. Therefore, the sampling procedures used by Ingle seemed to be the most applicable.

Fluorescent Coating Procedures.--Wright's anthracene dyeing procedure was tested both in the field and in the laboratory for its suitability as a tracer coating on the fine sand dealt with at the test site. After evaluating the results of these tests, an alternative method of dyeing was investigated and used for a test run which produced positive results.

Test Dyeing of Sand Using Wright's Method.--In the field two buckets of beach sand were taken from the beach at a point just above the swash line where the seeding line would be located. Each bucket, when filled, contained approximately 35 pounds of sand. The sand was then taken to a work spot near the dunes, and prepared for dyeing. First, a two-gallon wide-mouth jar was half filled with denatured alcohol. Approximately five pounds of sand from the sample buckets were added to the jar containing the alcohol and the mixture was agitated by hand for about fifteen seconds. The alcohol was then drained through a muslin filter placed over a second two-gallon jar. After draining, the sand was placed on a six foot by eight foot plastic tarpaulin. This procedure was repeated until all the sand obtained for coating had been washed with the denatured alcohol. The reason for washing the sand in denatured alcohol was to remove pollutant material from the sand sample, since during the period of the experiments, June through July, the Gulf waters had been polluted by offshore oil spills. In fact, during the early tests in June, clumps of crude oil as large as silver dollars were encountered frequently both in the surf and on the beach. Although the washed sand was put on a tarpaulin spread out in the sun, no attempt was made to completely dry the sand before the next step, coating the sand with fluorescent material.

Next, 16.7 grams of the anthracene dye were added to one quart of chloroform and mixed until all of the dye was placed into solution. The solution was poured into a two-gallon jar, a measured amount of the washed sand was added, and the mixture was agitated by hand. The sand had been measured in a number ten tin can having graduated weight markings applied on its inside walls. After this mixing, the excess anthracene and chloroform solution was drained off and the coated sand was again spread out on the plastic tarpaulin to dry in the sun. Drying time at the beach was dependent upon the weather conditions. Usually, when a slight wind was blowing and the temperature was in the low 90's, drying time took from 75 to 90 minutes. Using the above procedure, two people could dye 35 pounds of sand in about 30 minutes. Although Wright claimed that 35 pounds of sand could be dyed with only one quart of dye solution, the writer found that it actually took two quarts of the dye solution to coat this amount of very fine grained sand.

<u>Evaluation of Anthracene as a Coating Material</u>.--Several field tests were conducted using sand which had been coated with anthracene. When sand samples from the first test were placed under ultraviolet light, there was no evidence of any dyed particles. After the first test, it was assumed that the coated sand must have been buried, placed into suspension in the surf, or moved out of the test area before samples could be collected. At this time the effectiveness of the dye procedure was not questioned. On the next test the sampling area was reduced from an area several hundred feet long to one only 100 feet long. This was done so that rounds of sample collection could be completed in a very few minutes, thus increasing the chances of picking up tracer material within the test area before it could be transported away by the littoral current. A total of 32 pounds of tracer sand was released at the updrift end of the test area. Samples were collected in three rounds, at two minutes, five minutes, and 15 minutes after tracer release. In addition, subsurface samples were taken at three different points along a line 25 feet downdrift of the sample release points. Suspended samples were obtained in the surf 15 feet

downdrift of the release point eight minutes after sample release. The subsurface samples were taken with a scoop device which collected sand to a depth of two centimeters below the beach surface. The suspended sample was obtained by simply holding an empty two-gallon jar beneath the water surface and letting it fill up. On placing all the samples under ultraviolet light 16 hours after the samples were taken, only a few spots of fluorescence showed up on the sample cards. Even more unexpected was the fact that none of the dyed sand was evident either on the subsurface samples or in the suspended sample. At this point the ability of the anthracene to remain coated on the sand tracer placed in the surf became slightly suspect.

A 35 pound sample of natural sand was taken from the beach and mixed in a rotary mixer in the laboratory at Texas A&M University. This was done to ensure that the negative results which were being obtained were not the result of inadequate coating when hand mixing the sand with the anthracene solution. Three quarts of the anthracene and chloroform solution were placed in the mixer along with the 35 pounds of sand. The additional solution was used to ensure complete saturation. The sand was mixed for two hours in the mixer, then placed in a 140° F. oven to dry. Once the coated sand dried, several samples taken at random were placed under an ultraviolet lamp and examined for thoroughness of coating. It was seen that all the sand particles were completely coated with the anthracene dye. However, in the field test using this dyed sand, again no fluorescent particles were visible on the sample cards collected. It thus appeared that the anthracene was washing off the sand. To check whether or not the dye was in fact washing off the sand tracer, the writer's coating procedure was rechecked in detail with the procedures described by Wright (50). No deviation was evident in the writer's application of Wright's method.

In an effort to double-check the processes inherent within Wright's method, a half pound sample of coated sand was placed in a two-gallon jar filled with water. After having been agitated in the jar, the sand was allowed to settle to the bottom. This was repeated four times over half an hour. Then the jar was placed under an ultraviolet light. The water in the jar showed up highly fluorescent with the yellow-green glow characteristic of the anthracene. Also small bits of material remained in suspension, refusing to settle out even after two hours. An examination of the particles under a microscope showed that they were not sand but rather platelets of material believed to be anthracene dye particles. After the sand was removed from the bottle by straining out the water, it was found that over 70% of the sand had lost its fluorescence. An additional test was performed on the coated sand by placing the sand in a one inch deep, 18 by 24 inch pan, and putting it in the bottom of the wave tank located at the Hydromechanics Laboratory, Texas A&M University. Water depth in the tank was 14 inches. Eight inch high waves having a wave length of 10 feet were generated over the pan containing the sand for one hour and 30 minutes. At the end of this period the pan was removed from the tank and placed under an ultraviolet light. Exposed to this light, the sand evidenced no fluorescence.

Thus the anthracene coating developed by Wright, did not have adequate durability under the tests conducted by the writer. Even though the grain size of the sand used by the writer was much smaller than the sand used by Wright, the writer could find no physical reason why the anthracene coating worked for Wright but did not work for Texas beach sand. Even when the sand was put in a jar filled with water and allowed to sit without any agitation, it was apparent that some of the anthracene coating washed off.

Selection of an Alternative Dyeing Procedure.--Three alternative coating techniques immediately appeared to offer the best possibilities for an alternative dyeing method: those described by Ingle (12), using a commercial firm to coat the sand; those used by Yasso (51), using a fluorescent paint and resin binder; and those described by Teleki (40), using some fluorescent dye material and ureaformaldehyde resin as a binding media. After an exhaustive search for a commercial firm in the central Texas area which could commercially dye sand with fluorescent material, one Houston company was found which had a process that was suitable. However, the cost ($125.00 for a minimum order of 1000 pounds of sand) was considered to be excessive. Moreover, the manager of the company was not willing to impart the dyeing technique, ruling out that the process could be duplicated in the laboratory. A review of the methods used by Teleki showed that his dyeing procedures involved long tracer preparation and required crushing machines to break up the sand clumps once dyed. In contrast, Yasso's description of his dyeing procedures indicated that no special equipment was needed and that the dye procedure could be accomplished relatively fast. Therefore the Yasso method was tried. The dye solution used by Yasso consisted of four parts Day-Glo acrylic lacquer 209 line (Switzer Bros., Inc.) to five parts Beetle Resin 227-8 (American Cyanamid Co.) cut to 10% solids by weight using methal ethyl keytone and toluene solvents in equal weight proportion. Unfortunately, the writer could locate no paint firm dealing with Switzer Bros., Inc. in the Central Texas area. Also, Beetle Resin is a patented product made only by American Cyanamid Co., and after conversations with several Houston plastic companies, no readily available equivalent substitute could be found. In Texas, Beetle Resin can only be obtained through the plastic division of American Cyanamid Corporation located in Dallas. The writer was able to purchase enough Beetle Resin from that source in order to conduct a test of the Yasso dyeing procedure. The acrylic paint used, Daylight Fluorescent Red-Orange, was purchased from the Preserv O Paint Manufacturing Company, the only paint firm in the Houston area which handles acrylic lacquer.

Test Dyeing of Sand Using Yasso's Methods.--Since the sand used in these experiments is considerably finer than that used in Yasso's experiments, the writer decided to cut the Beetle Resin to 8% solids by weight. The coating procedure was basically the same as used earlier in coating sand with anthracene. However, for the test of Yasso's method, the sand was dyed at the Hydromechanics Laboratory at Texas A&M University. The sand used in the dyeing process was obtained from the beach test site.

First, a weighed amount of acrylic lacquer and Beetle Resin cut by solvents was put into a two-gallon jar. Five pounds of sand were added and the mixture was shaken by hand until all of the dye solution had been absorbed by the sand. By trial the writer found that five pounds is most easily handled when mixed manually. Hand shaking the mixture becomes too tiresome when large amounts of tracer (over 30 pounds) are made up, and dyeing with more than five pounds makes it unlikely that all the sand is coated. Once the solution had thoroughly coated all the sand grains, the dyed sand was spread out on a plastic tarpaulin to dry in the sun. Care must be taken that the mixing is done in a ventilated room since the toluene fumes are toxic. For these experiments two men dyed 60 pounds of sand in one hour and 20 minutes, including set up time and calculations of ingredients to obtain the proper ratios of sand, acrylic lacquer, Beetle Resin, and solvents. Actual mixing time took 53 minutes. Drying time for the 60 pounds of sand took two hours and 15 minutes. Although drying ovens can be used, they must be equipped with a blower to safely dispose of the toxic fumes given off by the toluene. Air drying time can be reduced considerably if the sand is spread out over a large area, and dried under a mid-day sun. The excessive length of time required to dry the sample was probably due to the fact that the sand was dried in the early morning and was spread about two or three inches deep over a four by eight foot tarpaulin. In addition to a shorter drying time, spreading the sand out to a thin layer would also have speeded up the next process, breaking the sand clumps down into individual grains.

Yasso stated that the coated sand, having individual grains adhering to each other because of the binding action of the Beetle Resin, could be broken up by rolling a typewriter platen over the clumps. This method of breaking up the clumps was found satisfactory, but too time consuming. A mixer equipped with a crushing roller was used instead. Once crushed, the sand was put through a series of sieves in order to obtain the same size distribution as the natural sand, then run through a Visual Accumulation Tube (8) to check fall velocity changes. The results of this test showed the distribution for the dyed sand to be almost identical to that of the natural sand (Fig. 9). The crushing and sieving procedure took three hours for the 60 pound

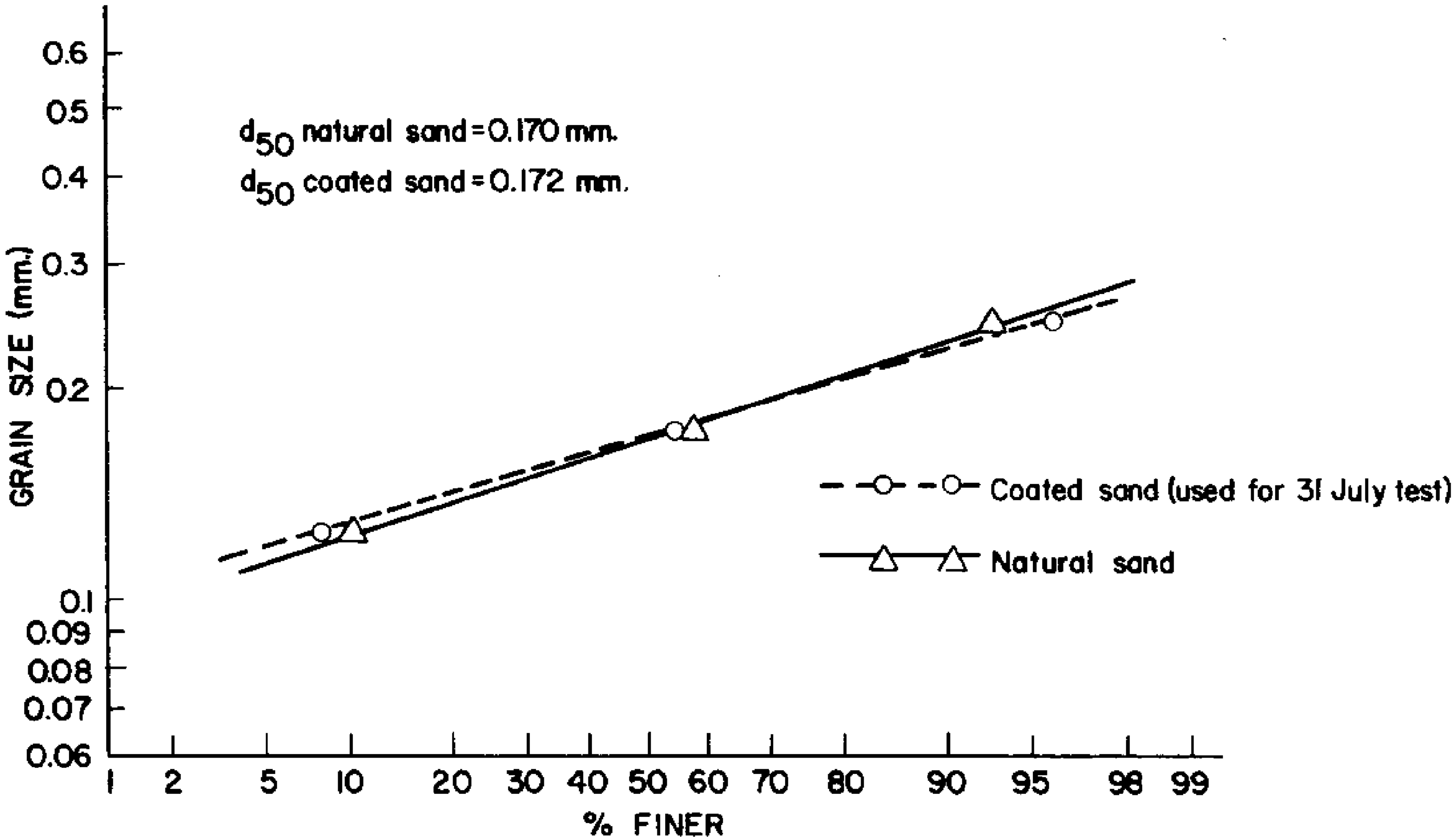


FIG. 9 — SIZE DISTRIBUTION OF NATURAL AND DYED SAND

sample. Although the procedures of dyeing, drying, crushing, and sieving took several hours from start to finish, it is apparent that the sequence can be carried out in the field since the sand clumps after dyeing can be broken up with a typewriter platen or other similar device.

Before using the dyed sand in a field test, it was checked for its hydrodynamic properties and the durability of its coating. In addition to the Visual Accumulation Tube Test, the sand was tested in the wave tank. One pound of the coated sand was mixed with five pounds of natural sand, put in a shallow pan and placed on the floor of the wave tank. The water depth and wave height were 14 inches and eight inches, respectively. The wave length was 10 feet. Since the dyed sand was brightly colored it could be visually observed in relation to the natural sand. It appeared that the coated sand movement was the same as the natural sand. After one hour and 30 minutes in the tank, the pan was removed and placed under a fluorescent light. It was observed that no congregating of the coated particles had taken place and that the dyed sand remained distributed throughout the natural sand, indicating that it had acted hydrodynamically the same as the natural sand. A sample of the coated sand was also subjected to the bottle-shaking test. From this test it could be seen that no discernible washing off of the fluorescent paint had occurred.

Field Tracer Tests.--On June 16, 1970, a field test was conducted at the beach near the mouth of the Colorado. An area of study was chosen approximately 1500 feet upcoast of where the spit began at the mouth of the river (Fig. 10). At this location the beach is straight, and the littoral drift would not be affected by river currents. A survey control datum was established on the beach about 200 feet shoreward of the high water line. All plane table surveys and profiles were referenced to this control.

Surface Current Observations.--Surface current velocities were measured at the beginning and end of each test using fluorescein dye. After a 100 foot line had been staked out onshore and parallel to the line of the beach at the waterline, a cup of fluorescein dye mixed with sea water was carried into the surf to a point perpendicular to one end of the 100 foot line. On signal from a timer stationed at that end of the line, the dye was released into the surf. The releaser then moved with the dye marker till he came opposite the other end stake of the 100 foot line. The timer meanwhile had also moved to the end stake and recorded the

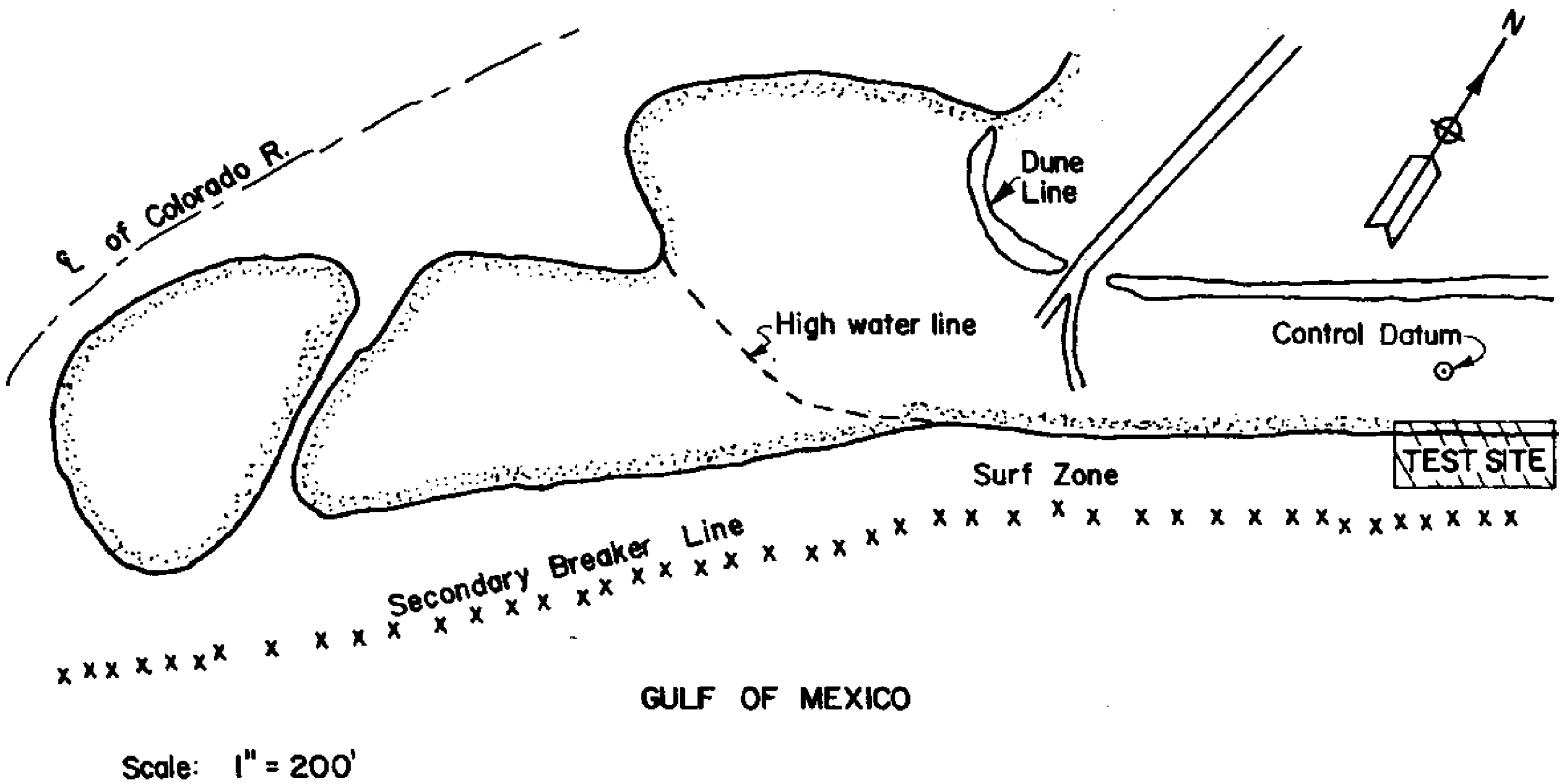


FIG. 10 – LOCATION OF TEST SITE

East Side of Colorado River Mouth Spit at Low Tide 31 July 1970 time of dye movement traveling the 100 feet. Velocity was then calculated in feet per second. General direction of movement was also noted. To get an average current velocity over the sample area, the foreshore zone was divided into back surf, mid surf, and foresurf areas. Three separate readings were made, with the dye being released in each of these three areas. The average velocity was then taken as the average of the three readings.

Grid Layout.--The grid layout could be established only after the speed and direction of the littoral current had been ascertained. Once the general direction and speed of the littoral current was determined, a grid layout was designed so as to obtain the best representative tracer dispersion pattern. On days when a relatively strong littoral current was present, the grid was designed several hundred feet long to ensure that tracer would be recovered inside the grid even after a period of two or three hours had elapsed since tracer release. On days when the fluorescein marker did not move significantly up or down the beach but appeared to be either stationary or moving perpendicular to the shore, the grid was laid out with only two or three hundred feet of width.

The sample pick-up points and seeding points were plotted on paper and a base line was surveyed using a transit and level rod. First, a line was established perpendicular to the water line and running through the base point. Then the base line for the grid was surveyed. This base line was parallel to the line of the beach and perpendicular to the line established through the base point. The base line was placed 25 feet inshore from the water line. Every 25 feet along the base line a chaining pin was placed over the first 100 feet of base line. The next two hundred feet was marked with chaining pins in intervals of 50 feet. Any further extension of the base line was marked in 100 foot intervals. At each marking point along the base line a six foot aluminum rod, one inch in diameter and painted with comet red paint on the top foot was driven into the sand to a depth of about two feet. Another line of rods, parallel with the base line and with each rod directly opposite a rod along the base line, was placed along the water line. Then in lines located perpendicular to the base line, rods were placed at 25 foot intervals out to the breaker line. Points at which the rods placed in the surf zone were driven were located by lining up the rod to be driven with the rods placed along shore. Distances from the base line were measured by means of a rope on which knots were tied every 25 feet. A staked out grid is shown in Fig. 11.

For purposes of marking samples taken after tracer release, points parallel to the base line were designated as rows, which were numbered. Each line of stakes perpendicular to the base line was called a column and designated by a letter. Column A was the column at the updrift end of the grid, column B the next column proceeding downdrift of the littoral current, and so forth. A sketch of the grid system used in the final test is shown in Fig. 12.

Tracer Seeding.--After the grid had been set up, a measured amount of tracer sand was placed in two-gallon capacity plastic freezer bags. The amount of sand placed in each bag depended on the characteristics of the littoral current at the time of the test. Larger amounts of tracer (from a basic weight of five pounds) were used when the current was strong. For the final test four bags were made up, each bag containing eight pounds of dyed sand. Although for this test the fluorescein dye marker indicated a weak littoral current, it was the only test to be made using tracer sand coated with acrylic lacquer and the writer wanted to ensure that the tracer would cover the entire test area heavily. About a quart of sea water was added to each bag along

FIG. 11-LAYING OUT THE SAMPLE GRID

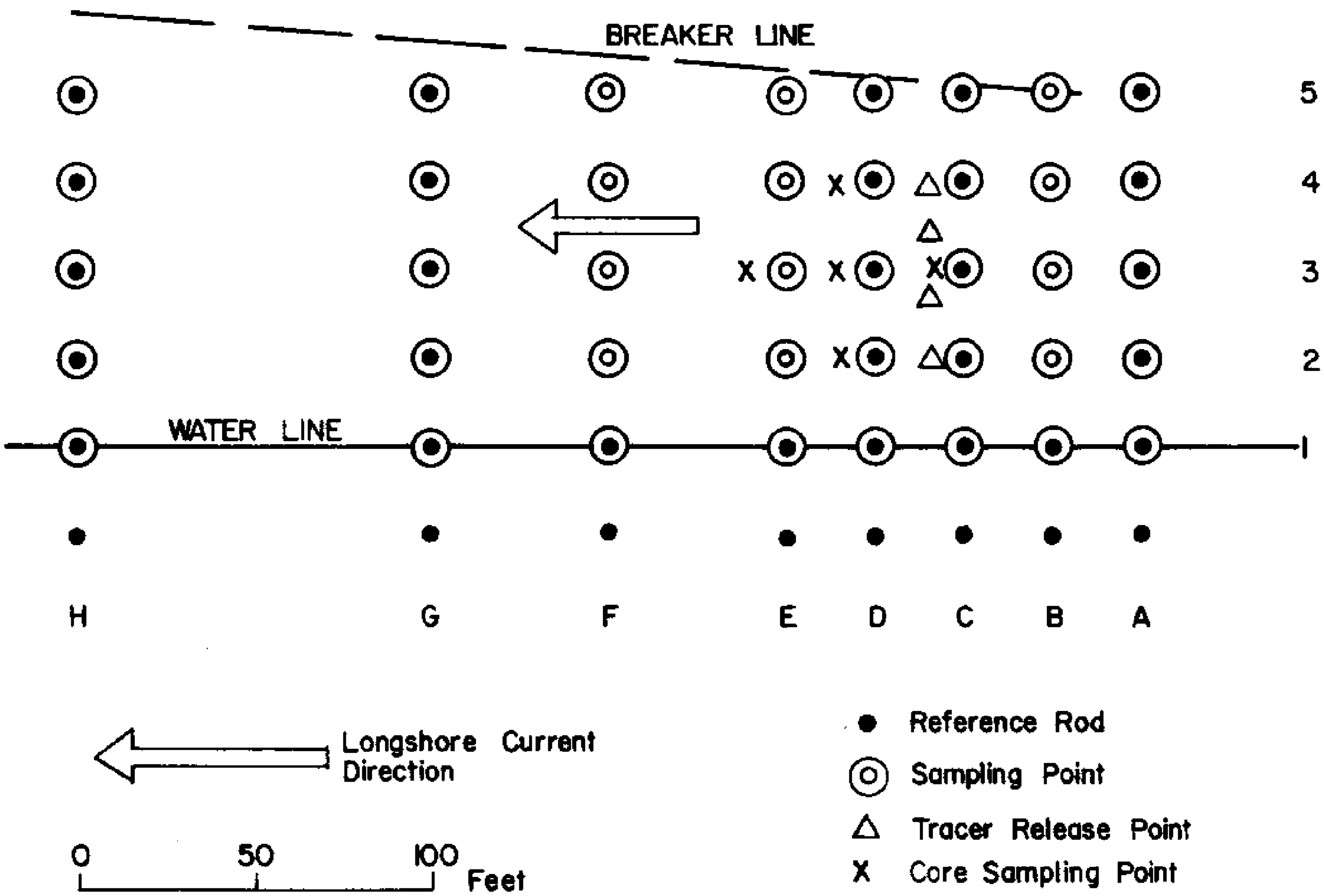


FIG. 12 — DIAGRAM OF SAMPLE GRID

with two squirts of liquid detergent, which was added as a wetting agent. The sand was then gently kneaded until it became thoroughly saturated with sea water. The seeding bags were tied off at the top and carried into the surf to the designated positions for release. On signal, all the coated sand was released simultaneously by holding the seeding bags on the foreshore bottom and then ripping open the bottom of the plastic bags.

Before using this method of releasing the coated sand, which was adopted from Ingle, a laboratory test had been performed in the wave tank to determine if a significant amount of the released sand would be placed immediately into suspension. Again, with a water depth of 14 inches, a wave having a height of eight inches and length of 10 feet was generated. An observer was stationed outside the tank so that whatever dispersion and suspension of sand which occurred could be seen through the transparent walls of the tank. A seeding bag, made up in the same manner as those prepared for the field tests, was released in the tank as the waves were being generated. In this instance a seeding bag containing five pounds of sand was used. As soon as the seeding bag was ripped open against the bottom of the wave tank, a cloud of fine sediment was placed into suspension. However, this suspended sediment settled out within 30 seconds of release. The pattern formed by the settling of the suspended material was roughly in the shape of an ellipse having a major axis of three feet eight inches along the direction of wave travel. The results of this test showed that whatever sand was placed into suspension in the surf as a result of the seeding method would not be a significant factor in the tracer dispersion, since the sand in the wave tank test settled out so quickly. Although a quantitative measurement of the amount of sand immediately placed into suspension was not made, it could be seen that this was only a very small percentage, estimated at less than five per cent.

Tracer Collection.--Posterboard cards, cut to three by three inches in size, were marked with a waterproof ink to designate point of sampling. The sample cards were then coated with vaseline on one side and attached to the end of a four foot pole by means of rubber bands. At each sampling point, the coated side of a card was pressed against the sand surface. With the sand grains pressed into the vaseline, a fairly uniform thickness of sand adhered to each card. Sampling cards were conveniently carried into the surf by means of a sampling board on which 30 sample cards were attached by spring clips. Sample collecting poles and a sampling board are shown in Fig. 13.

This method of sample collection proved fast and reliable. However, problems were encountered which were overcome through experience in sample taking. First, it was found that a too thin coating of vaseline on the sample cards resulted in spotty collection of sand. On the other hand, too thick a coating produced a thickness of sand cover which was difficult to analyze. Also, stamping the card straight down on the sand surface and pulling it straight up was not sufficient to thoroughly embed sand over the entire area of the card. It was finally found that the best results of obtaining a sample were achieved by gently rocking the sample card back and forth on the sand surface.

Sampling was conducted by three-man teams, two sample collectors and one man who carried the sample board on which the cards were attached (Fig. 14). The first sample collection began two minutes after the tracer material was released. Immediately after completing one round of collection, another round was started. Thereafter collections were made at time intervals which varied according to the strength of the littoral current. For tests when a weak current existed, the collection rounds were timed from one-half hour to one hour apart after the first two collections.

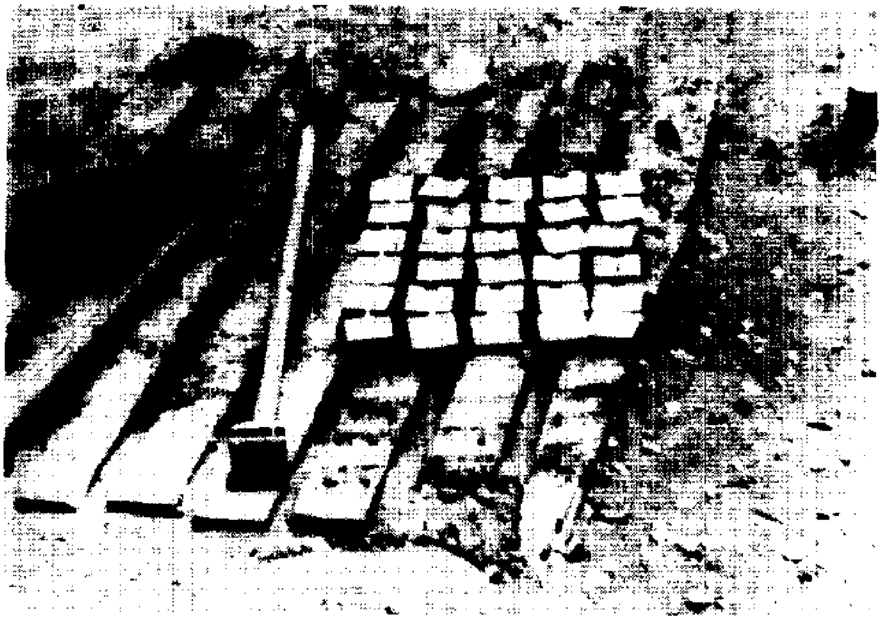


FIG. 13–SAMPLE BOARD AND COLLECTING POLES

FIG. 14–SAMPLE COLLECTION IN THE SURF

In contrast, when strong currents were present, intervals between collection rounds were shortened to allow for the faster sand movement. In the last field test, sample collection rounds were conducted 2, 15, 45, and 108 minutes after tracer release. Under normal surf conditions, about 8 to 10 minutes were required to complete a round of collection of 30 samples.

During the first tests, sampling positions at which no rods had been driven were located by stretching the knotted rope between the base line and the desired position. This method proved extremely time consuming. In subsequent tests the sample collectors were able to quickly find their sample points in the surf by lining themselves up with the two rows of rods placed on the shore and the columns of rods positioned in the surf. This final method of positioning was considered accurate enough for the test's purpose since the rods in place were positioned carefully.

Related Data Measurement.--Although it was beyond the scope of this study to attempt to relate the tracer dispersion to oceanographic, meteorological, topographic, or sedimentologic factors, it is realized that future studies using the methods developed must take into account all factors influencing sand movement. Accordingly, beach profiles, current measurements, breaker height and period, wind velocity, sediment size distribution, angle of breakers with shoreline, and general observation of the surf conditions were taken during each test. Most of these data were taken more for the purpose of developing a fast and easy procedure for obtaining a valid experiment method rather than to make use of the data in any sort of analysis which would relate the data to tracer dispersion.

Sand Size Analysis.--Visual Accumulation Tube analyses were made on sand samples taken from the site on each of the field tests made on June 7, 16, and 26. Results of these analyses showed that over this period of time the sand on the test beach retained approximately the same distribution (Fig. 15). When these distributions were compared with samples taken on the test beach in October 1969 and in April 1970 by graduate students in Coastal and Ocean Engineering at Texas A&M University, it was found that the median grain size varied by less than 10% (Fig. 16). Although these samples were not taken over a long enough period of time to state conclusively that the sand distribution at the test site remains consistent throughout the year, they did provide enough evidence to assume that over the summer months any variation of size distribution at the test site would be insignificant, barring radical

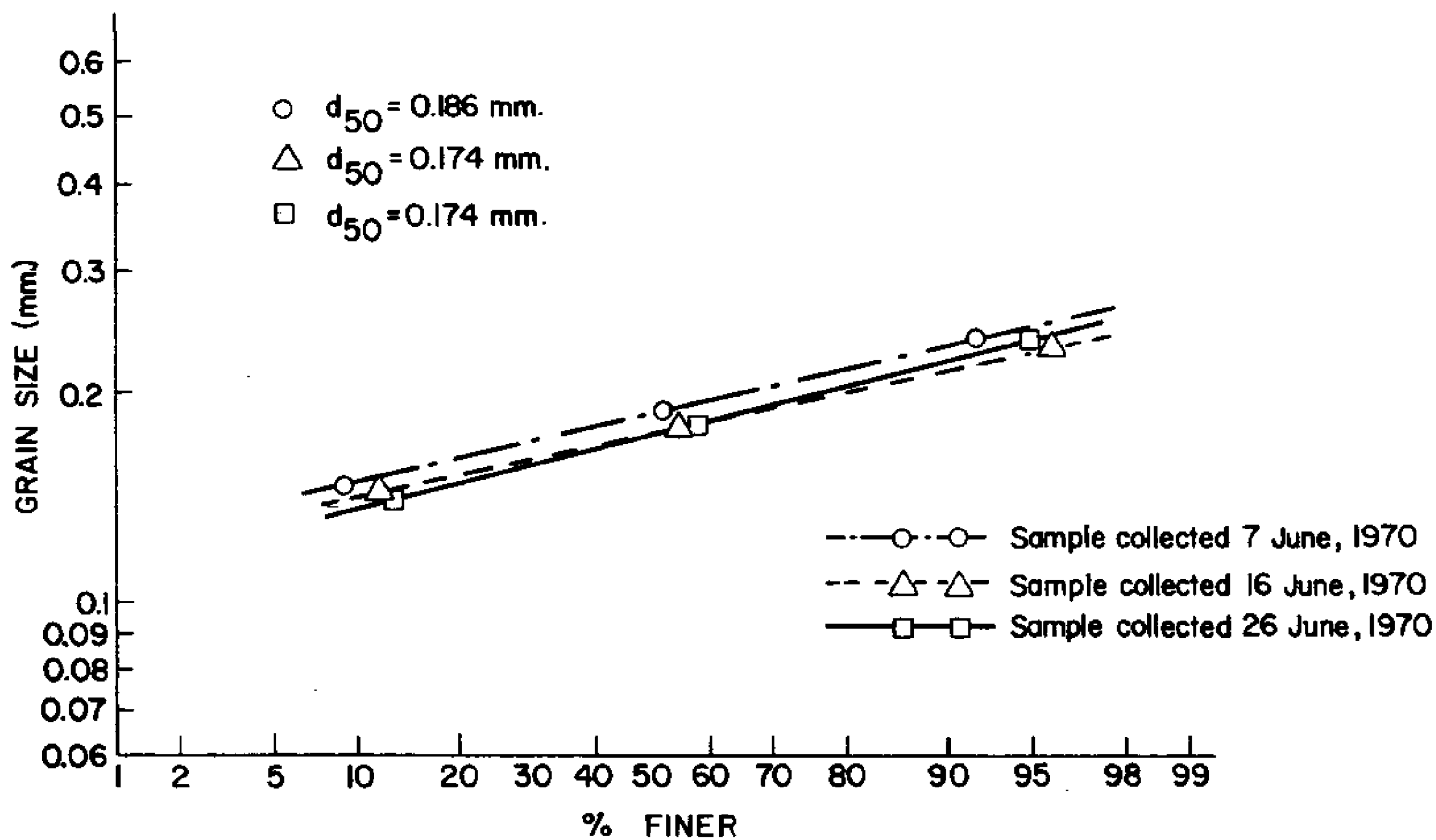


FIG. 15 — TEST BEACH SAND SIZE DISTRIBUTION
Summer 1970

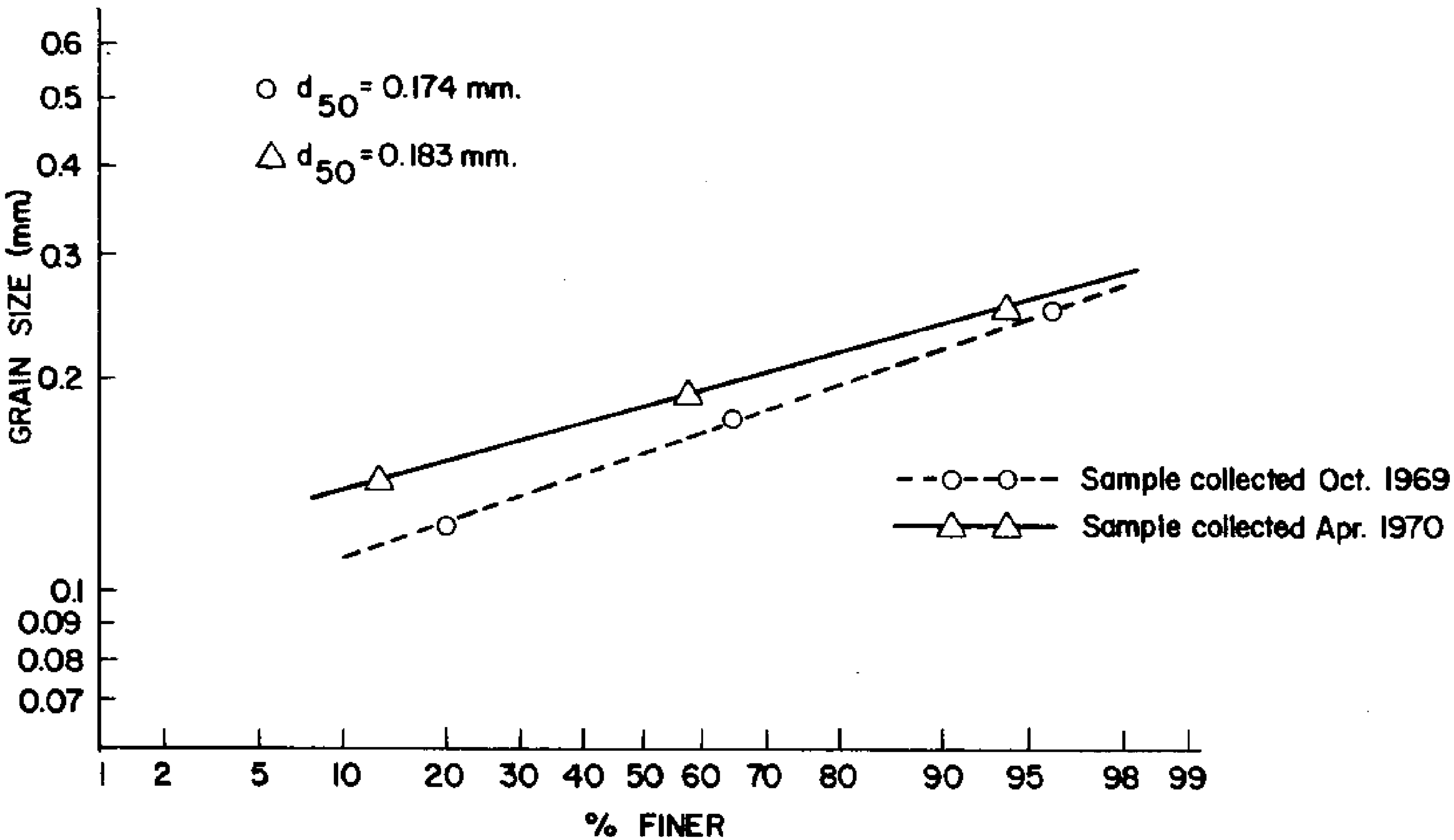


FIG. 16 — TEST BEACH SAND SIZE DISTRIBUTION
Fall 1969 and Spring 1970

changes of the beach caused by hurricanes. This assumption was important in that it allowed dyeing of the sand in the laboratories at Texas A&M University. Providing that this assumption is valid, it is not critical that the sand to be used as tracer material be taken from the test beach on the same day on which it is to be used in order to be confident that the tracer material will have the same size distribution as the surrounding natural sand. This leeway was important in the experiments, since the dyeing process using Yasso's method is most easily accomplished in the laboratory where mixing machines and mechanical sieve shakers are available.

Beach Profiles.--A profile of the beach was taken every day a tracer test was conducted. These profiles were run along a line perpendicular to the line of the beach and through the control datum. They were obtained with level and rod, and the distances along the profiles were measured by use of stadia. The profiles were taken from the top of the dunes to a point as far out in the surf as the rod man could go. Comparison of the profiles shows a typical pattern of build-up for a summer beach (Fig. 17). In early June a small offshore bar existed at the study site. It may be seen that as the summer progressed the bar was gradually worn down and a summer berm was formed.

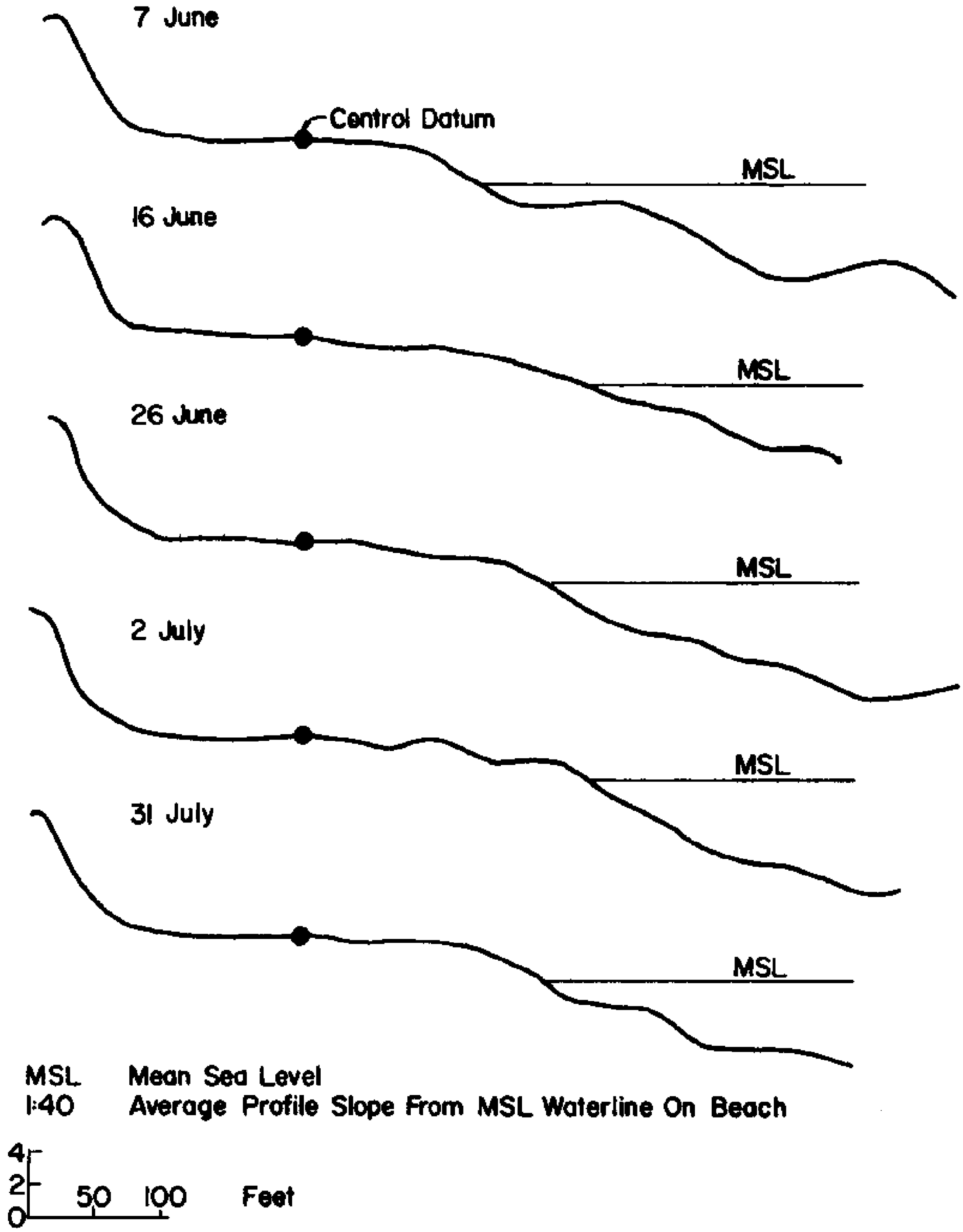


FIG. 17 - BEACH PROFILES

Surface Currents.--Several methods were tried in determining what method could best show the speed and direction of the littoral current. The first method used was simply the placement of a block of wood just shoreward of the breaker line and the timing of its movement down the beach until it reached shore. After only a few attempts it became obvious that this method was unsatisfactory. In every attempt the block of wood was carried ashore before it had traversed even one hundred feet. It appeared that the wood block simply had too much bulk, since the surging wave motion and wind were able to catch it and move it directly shoreward without much lateral motion.

The next test of a method was made with a one-gallon plastic Clorox jug, which was filled with sand so that only two inches of the jug was visible above the water surface when the jug was floated. But here again the floating object was too swiftly carried directly shoreward by the wind and wave motion. It was finally found that the most satisfactory method was to place fluorescein dye solution directly into the water, as previously described, and measure its rate of travel over a given distance parallel with the beach. For this method it was found that one tablespoon of fluorescein placed into a pint cup and mixed with sea water produced the best results. Once in the surf the fluorescein dye solution immediately disperses to form a readily observable green slick which moves with the surface current. During tests when the surf was not abnormally rough, the fluorescein formed a slick roughly four by eight feet, which, although elongated by the current, remained as a continuous sheet over the surface of the sea.

The most significant information obtained from the current velocity readings, aside from their use in determining grid layout, was that on three of the five test days, the dye marker indicated a net littoral current in a northeast direction. This showed that even though there is a predominant southwest drift, the littoral current does reverse itself. There was no significant difference in velocities between the two current directions. That is, on days when current direction was from the southwest, the velocity was just as strong as on days when the current was from the northeast.

Wind Speed and Direction.--Wind speed was measured with a hand held anemometer. Wind direction was ascertained by holding a two foot cloth streamer up to the wind and sighting along the line of the streamer through a vertical sight on a Brunton compass. Wind speed and direction measurements were made at least hourly during the tracer tests.

Wave Height, Period, and Angle with the Beach.--Wave heights were measured at the breaker line using a graduated stake held level with the still water level. Period was measured with a wrist watch having a second hand. Several methods were attempted in finding the angle of waves with shoreline using a transit and level rod. However, it was found that the best method was to sight down a breaking wave with a Brunton compass, obtaining an azimuth for the wave, then subtracting this azimuth from the azimuth of the shoreline taken along the waterline. Wave height, period, and angle were measured hourly.

General Observations.--The foreshore and inshore zones at the test site are almost always heavily laden with suspended sand and debris. Only once during the two months of the experiments was the water clear enough to see the bottom in over six inches of water. Winds were predominately from the south. The maximum wave height measured was three feet. The most usual condition of the surf in the test area was gentle. Sand on the beaches was dirty and contained a great deal of shell fragments.

<u>Analysis of Test Results</u>.--Using the sand coated by procedures adapted from Yasso, a final test was conducted at the test site on July 31, 1970. On this day the surf was calm, with wave heights of one to one and one-half feet. Wave period was six seconds, and the angle of waves with the beach was five degrees. The waves approached the beach from the southwest. The wind was at four miles per hour from the southeast. The dye marker for current velocities moved only 15 feet in 120 seconds in a northeast direction. A grid system was established, and four bags of tracer, each containing eight pounds of sand, were released simultaneously along column C. Samples were collected at two minutes, 15 minutes, 45 minutes, and 108 minutes after tracer release. A total of 90 samples were collected.

Five hours after the last sample was taken, and upon return to the laboratory at Texas A&M University, the grease and sand coated cards were placed under an ultraviolet light and examined for tracer concentration. The fluorescent coated grains were highly visible and countable, attesting to the suitability of the dye procedure. The number of fluorescent grains per card were then counted. Taking into account any areas of a card not covered by sand, the writer ascertained the number of fluorescent grains per square inch of surface area covered by sand. According to Ingle, the sensitivity of this method is at least 1 in $1 \cdot 10^5$ grains. Counting was made easier through use of a hand counter and an overlay grid of one inch squares made of thin black thread stiffened with fixative. An average of six minutes per card was required in counting. It should be noted here that safety glasses should be worn any time an ultraviolet light is used to detect fluorescent sand grains. In examining the sample cards under the ultraviolet light a black square of poster board was used to provide a dark background for the cards and to minimize reflection of ultraviolet rays.

In order to get a more accurate picture of tracer concentration, the number of grains per square inch for each sample station was adjusted for the differences in time between start of collection and actual time of collection for each sample station. From Ingle, the relationship

$$\frac{T_s}{T_a} G_a = G_c$$

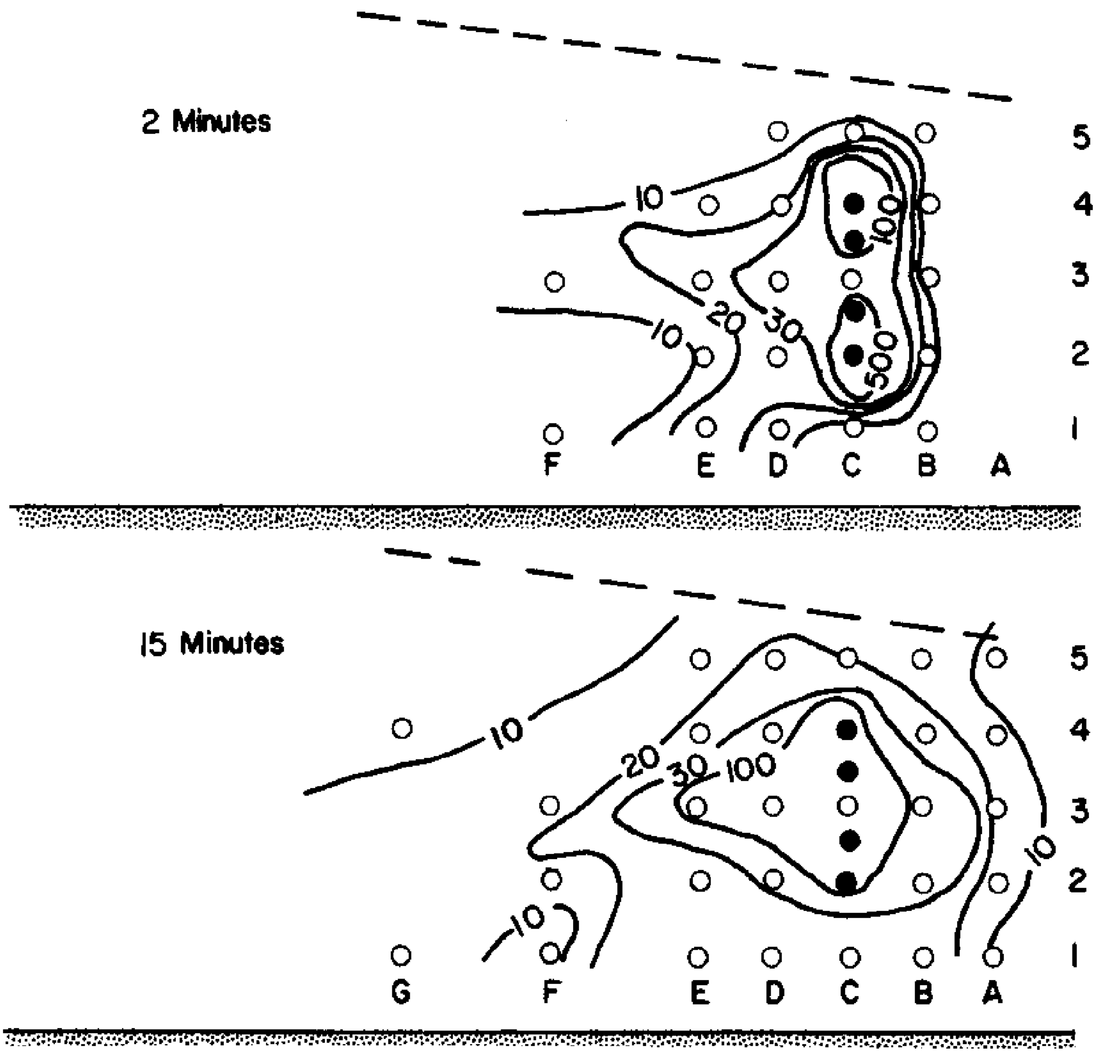
where T_s is the arbitrarily chosen standard elapsed time, T_a is the elapsed time at moment of sample collection, G_a is the counted fluroescent grains per square inch, and G_c is the corrected tracer concentration, was used. Thus for a given collection round, each concentration was corrected to a value that represented the tracer concentration at a single moment after tracer release. Tabulation of corrected tracer concentrations for the third round of collection is shown in Table 3.

For each collection round, the corrected concentrations were plotted at their respective positions on the grid, and contours representing equal concentrations were drawn to show tracer dispersion. Contour patterns for the four rounds of collection are shown in Figs. 18 and 19. From the patterns it can be seen that the predominant movement of sand is in a northeast direction. However, there is considerable movement in an onshore-offshore direction. This can be expected since the fluorescein dye marker used at the beginning of the test to obtain current velocity indicated a weak longshore current.

In addition to the tracer concentrations obtained, seven cores were taken downdrift of the tracer release points. The cores were made with six inch clear plastic tubing having an inside diameter of 7/8 inch. On return to the laboratory the tubes, with the sand still in place, were examined under the ultraviolet

Table 3.--TRACER CONCENTRATION CORRECTION FOR THIRD ROUND OF COLLECTION, 31 JULY

Sampling Point	G_a	$\frac{T_s}{T_a}$	G_c
3A1	4	45/45.05	4.0
3A3	7	45/45.50	6.9
3A5	6	45/45.75	5.9
3B1	10	45/46.00	9.7
3B2	13	45/46.25	12.6
3B4	12	45/46.50	11.6
3B5	8	45/46.75	7.7
3C1	22	45/47.00	21.0
3C2	120	45/47.25	114.0
3C3	10	45/47.50	9.5
3C4	120	45/47.75	113.0
3C5	11	45/48.0	10.3
3D1	18	45/48.25	16.8
3D2	21	45/48.50	19.4
3D4	11	45/48.75	10.2
3D5	4	45/49.00	13.9
3E1	4	45/49.25	3.7
3E2	10	45/49.50	9.1
3E3	21	45/49.75	19.0
3E4	12	45/50.00	10.8



○ Sampling point

● Tracer release point (8 lbs. of fluorescent sand)

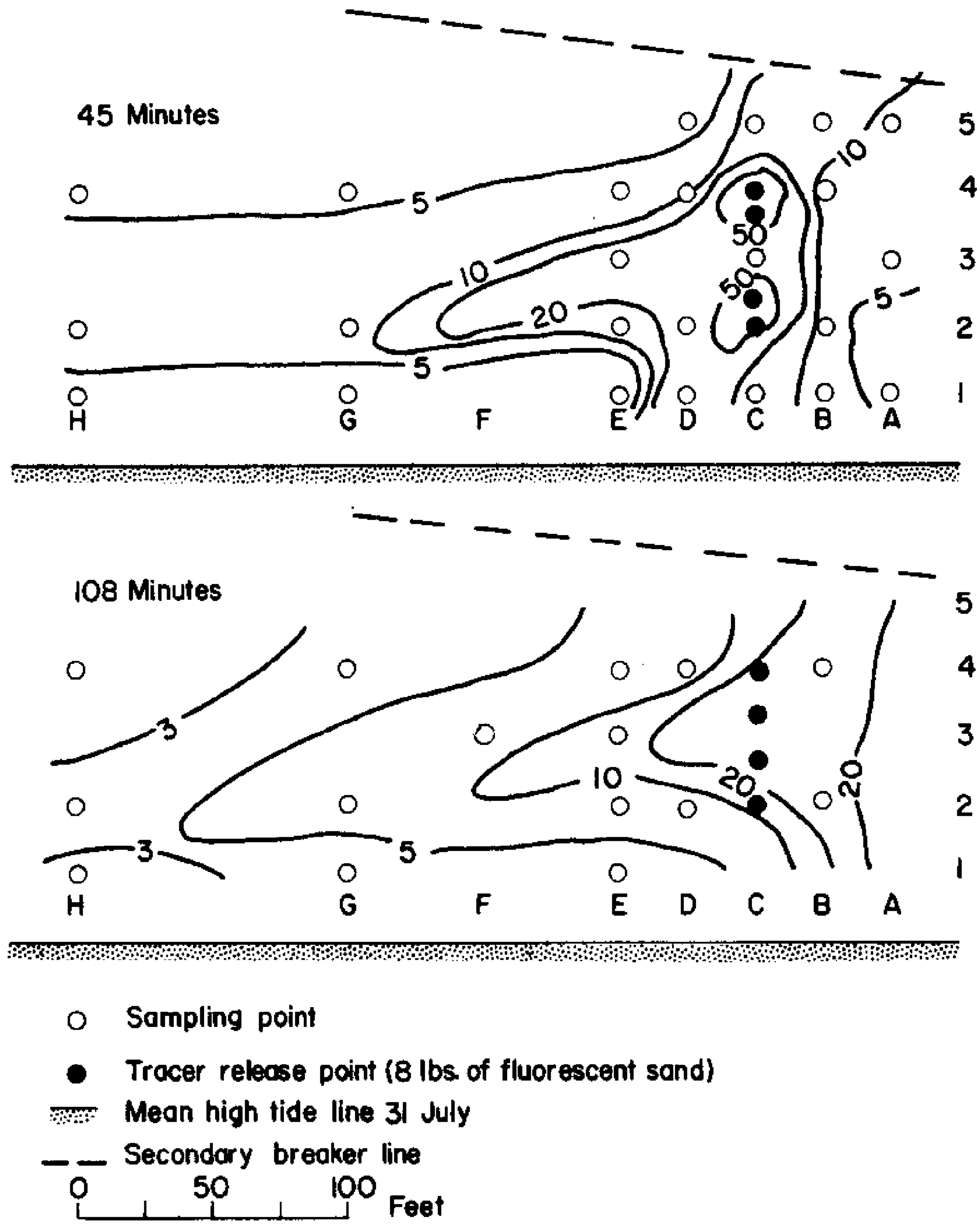
Mean high tide line 31 July

— — Secondary breaker line

0 50 100 Feet

Contours represent number of fluorescent grains per square inch

FIG. 18 – MOVEMENT OF TRACER SAND
At 2 Minutes and 15 Minutes After Tracer Release



Contours represent number of fluorescent grains per square inch

FIG. 19—MOVEMENT OF TRACER SAND
At 45 Minutes and 108 Minutes After Tracer Release

light. Although only fluroescent grains next to the tube walls could be seen, the depth of buried fluorescent tracer averaged one-half inch. This evidence from the cores indicates further possibilities for using fluorescent tracers to verify or disprove theories on depth of sand disturbance in relation to wave height.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

Conclusions.--Since the purpose of this study was to develop a reliable and suitable methodology for tracing the fine-grained sand of the Texas Gulf coast, the primary conclusion drawn from the study can be stated quite simply. A combination of the coating procedure originally developed by Yasso and the basic tracer collection and analysis method developed by Ingle can be used to trace sand movement on the Gulf coast. However, in order that future investigators may not be misled by the simplicity of the above statement, it is well to realize that these procedures may be specifically regarded as the best practical methods only for studying sand movement under the unique characteristics of the Texas Gulf Coast.

In its application to tracing sand movement on the Texas coastline, the dyeing technique of Yasso's is the least expensive for small quantities of sand (28¢ per pound of sand), is easy to apply, and can be accomplished both in the field and in the laboratory. Other fluroescent coating methods investigated present difficulties not inherent in Yasso's method. Wright's technique was unsuitable because of the lack of durability of the anthracene coating when applied to the fine-grained Texas beach sand. A secret commercial process was unsatisfactory because the only commercial firm available which could dye sand required too great a minimum order. The methods described by Teleki required crushing machinery which could not normally be used in the field.

The fact that sand coated with acrylic lacquer performs hydrodynamically the same as natural sand opens possibilities for sediment tracing studies in a variety of site conditions. The long life characteristics of the acrylic coating could be used to study sediment movement in streams over long reaches. And, since acrylic paint can be obtained in a variety of colors, the movement of different sized fractions could be investigated in a coastal environment as well as in harbors, inlets, and streams. The procedures found successful in this study would also have practical value for the proposed project by the Corps of Engineers at the mouth of the Colorado River. Tracer material could be injected into the river just upstream of the mouth while a different color tracer could be seeded on the inshore bottom just east of the spit. Both tracers could be followed over a period of a few days, which could give valuable information as to how the spit is formed and of what type of sediment material the spit and the bar are composed. In addition, tracer dispersion patterns obtained off the mouth of the Colorado should show how the littoral drift bypasses the channel.

As to the method of sand tracer collection and analysis, Ingle's technique is highly suited to the gentle surf and gentle beach slopes of the Texas coast. Plotting the tracer concentrations in contoured patterns provides an excellent visual representation of sand movement. From these plots, movement trends are easily shown. The small wave heights and calm surf on the Gulf Coast indicate that sampling from the surface of the inshore bottom does provide a good representation of littoral drift. However, since some fluorescent grains were found under the surface of the sand in the limited core tests, further investigation as to whether or not the buried tracer significantly affects the dispersion pattern could be profitably undertaken.

One unexpected finding from the experiments was that the grain size distribution of the beach sand at the test site did not appear to change significantly over a period of time. For the two months of the tests, the median grain diameter was almost constant. If, at other sites, the same results are found, it could be assumed that a collection of sand from the test site could be conveniently coated in the laboratory as a preparational procedure, rather than immediately prior to a field test. This not only saves time at the site but also allows use of laboratory equipment which cannot be transported to the field.

One drawback to the procedures used in the experiments is that a minimum of three persons are required. It is possible that only two persons could conduct a test if a very small grid were used, something on the order of 50 by 50 feet. With less than three persons, a collection round for a grid several hundred feet long would require so much time that only one or two rounds could be accomplished in under three hours.

Recommendations.--The procedures used provide a means by which sand movement along the Texas Gulf coast can be studied successfully. Although the primary concern has been the movement of beach sand, the procedures used could be adapted to the study of sediment movement in any body of water. Since so little definitive information is available concerning sediment movement along the Texas Coast and in adjacent inlets, the following recommendations are addressed to future studies as well as to improvements on the procedures used by the writer.

1. To speed up mixing procedures, a small hand turned mixer should be constructed. The capacity of this mixer should be at least ten pounds of sand.

2. A device is available for the detection of fluorescent grains which a future investigator could well use in a large-scale study. An instrument capable of detecting tracer concentrations ranging between $1 \cdot 10^{-3}$ and $1 \cdot 10^{-7}$ has been developed by the University of Florida. This instrument can also distinguish between several different fluorescent colors simultaneously. Use of this instrument would greatly enhance the speed and accuracy of the counting procedure.

3. If possible, several sand size analyses should be carried out at test sites a week or two before actual tracer tests. This should give the investigator an indication as to whether the dyeing process should be performed in the laboratory or in the field.

4. Since the acrylic lacquer has such long life, if a test is to be made at the same site where a test was made the previous day, and if the same color fluorescent tracer is to be used, the site should be sampled prior to seeding with new tracer to ensure that no particles of the old tracer have remained at the site.

5. Further investigation should be conducted concerning the significance that burial of tracer material has on the tracer dispersion patterns obtained from bottom surface sampling.

6. Littoral drift studies should be conducted as part of a feasibility investigation for any coastal project which will interfere with the natural movement of sediment. Using the procedures described in this study, further investigation of sand movement around the mouth of the Colorado can be conducted easily and inexpensively in conjunction with the proposed Corps of Engineers project, both before and after jetty construction. Such studies would provide information which could be invaluable in the design and maintenance of the jetties.

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APPENDIX 1

COATING TECHNIQUE

Dye Solution: Four parts acrylic lacquer (Preserv O Paint Mfg. Co., Houston, Texas): five parts Beetle Resin 227-8 (American Cyanamid Co., Dallas, Texas) cut to 08% solids by weight using ethyl keytone and toluene solvents (Fisher Scientific Co., Houston, Texas) in equal weight proportions.

Procedures: Five pounds of sand is placed in a two-gallon jar containing a measured amount of dye solution, agitated, and spread in the sun to dry. After drying the sand clumps are broken down into individual grains by crushing in a rotary mixer equipped with a crushing roller, and sieved back to original grain distribution.

Notes: (1) The test indicated that the Beetle Resin could be cut even more than 08% solids by weight. (2) Cost of dyeing was 28¢ per pound of sand.

APPENDIX 2

EQUIPMENT USED

For Coating:

1. Weight scale.
2. Two-gallon capacity wide mouth jars.
3. Tarpaulin (to place sand on for drying).
4. Rotary mixer equipped with crushing roller.
5. Sieves, mechanical sieve shaker.

For Field Test:

1. Transit, level, level rod, plumb bob, chaining pins, 100 foot survey chain.
2. Brunton compass.
3. Hand held anemometer.
4. Six foot stakes (or rods), two foot stakes.
5. Sample boards, collecting poles.
6. Pint cups, 1½ gallon capacity plastic freezer bags, baby food jars (for collection of size analysis samples), 3 x 3 inch sample cards, buckets, #10 tin can marked with graduated weight lines on the inside walls, vaseline, waterproof marking pen, 4 x 4 inch squares of wax paper (for covering sand coated sample cards), tablespoon, detergent, sledge hammer

(for driving in rods), watch with second hand.

For Analysis of Samples:

1. Hand tally counter.
2. Blacklight (Ultra-Violet Products, Inc., San Gabriel, Calif.).
3. Safety glasses.