SAND MOVEMENTS ALONG THE SCRIPPS INSTITUTION PIER.*

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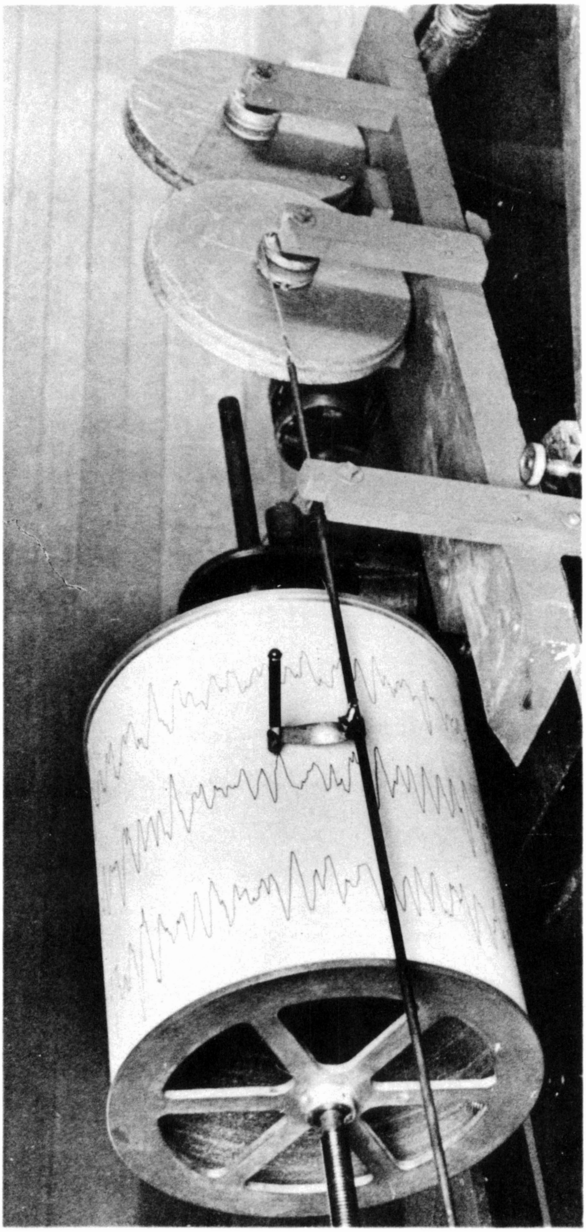
ABSTRACT. Discussion is presented of the results obtained from 600 repetitions of soundings along the Scripps Institution pier. The changes in sand level occurring at differing seasons of the year and accompanying various conditions of the sea are correlated with records of a current meter, a tide gauge, a wave-recording machine, and weather bureau instruments located on the end of the pier. The data show that sand cut away from the beach and foreshore during the stormy winter is deposited largely within 1,000 feet of the shore and is returned landward during the calm seas of the succeeding summer. The relation to cut and fill of various types of waves, of spring and neap tides, and of changes in current direction are all clearly demonstrated from the records.

INTRODUCTION.

IT has been known in a general way that waves, tides, and currents move sand along the shore and carry it in and out according to their character. However, up until the present investigation no comprehensive long range studies had been made to find out the exact nature of these movements and the degree to which the various factors were involved. The Scripps Institution of Oceanography at La Jolla, California, with its 1,000 foot pier extending out into the open ocean presented a unique opportunity to investigate these problems. Preliminary daily observations of the sand height on a rock face near the pier made in 1934, indicated the tidal and seasonal cycle of fill and cut of the beach. Beginning in 1936, measurements were taken from the deck of the pier to the sand at 45 equally spaced stations about once a week for two years; twice a week for one year; and daily for one year, October, 1937, to October, 1938. In addition, for one 28-hour period, measurements were made every 40 minutes along the entire length of the pier.

This work has been coördinated with many other observations. Almost continuous data have been available from the Coast and Geodetic Survey tide gauge and from the Dahl-Sverdrup current meter both located at the end of the pier. Wave heights were estimated from a tide staff at first, but beginning in 1938 a wave-recording device was installed for daily readings.

* Contribution from the Scripps Institution of Oceanography. New Series No. 83. Assistance in the preparation of these materials was furnished by the personnel of the Works Progress Administration Official Project No. 665-07-3-141.



The recording drum and reduction gears of the machine developed to record the character of the waves at the Scripps Institution pier.

Scripps Pier is located off the sea wall of the Scripps Institution and extends out from a beach of fine sand. Along the straight coast north of the pier a series of marine cliffs of Eocene sandstone and conglomerate rise to a height of 300 feet and extend as far as Torry Pines State Park which is four miles up the coast. To the south there are low cliffs cut into soft silts and alluvial sands of recent age. These extend for half a mile where they merge into a low plain, which formerly consisted of a sand bar built across a lagoon, but the lagoon has now been filled. This lowland also extends for half a mile and is terminated by more cliffs which rise near the bend in the coast at the head of La Jolla Bay.

Outside the pier at a distance of 3,000 feet is a submarine canyon which runs diagonally to the coast. Another canyon extends in almost to the beach a mile south of the pier. The sand along the pier, however, is not directly influenced by the canyon since the sloping bottom which extends along the pier is not terminated by the canyon but is bordered by a narrow 20 fathom terrace which separates this slope from the canyon. No doubt the presence of La Jolla Bay to the south and of the row of cliffs to the north exert a greater influence on sand movements.

ACKNOWLEDGMENTS.

The writers are indebted to C. I. Johnson for his help to LaFond in designing and for constructing much of the equipment used in this study. Appreciation is also expressed for the careful measurements and plotting work performed by K. D. Langley, K. O. Emery and R. S. Dietz.

PIER EQUIPMENT.

Sounding Machine.

The sounding machine consists of a ten-foot boom which rests on the pier railing and can be rolled along the dock and rail of the pier sounding for a distance of 900 feet. Paying over the end of the boom is a graduated piano wire which supports a 15 pound weight. The machine allows the taking of soundings at the 45 stations in a period of approximately half an hour. The machine is light enough so that it can be changed from one side of the pier to the other. By taking soundings half way between pier pilings and out ten feet, a distance of 14 feet is maintained from obstructions which would set up special conditions.

Wave Recording Machine.

In order to record the heights of waves which pass under the end of the pier, a drum is allowed to float on the water guided in a vertical plane by two wires. Its up and down movement is recorded by means of an attached wire, connected through reduction gears to a moving arm which in turn records the character of the waves on a rotating cylinder (Plate I). Ordinarily this machine is run every day for a period of five to 15 minutes.

Dahl-Sverdrup Current Meter.

Near the end of the pier a current meter with an electrical recording device is kept in almost continuous operation. The current was determined for a level of approximately eight feet below mean sea level. Both speed and direction of the current are recorded on a continuous tape which is located in the laboratory on the end of the pier. This current meter was devised by O. Dahl and H. U. Sverdrup.[1]

Other Equipment.

In connection with other studies a rain gauge and anemometer are maintained on the pier. The records from these sources were consulted when looking for causes of beach and long shore changes. The direction of the wind was observed in connection with the daily anemometer reading. The pier is also used by the U. S. Coast and Geodetic Survey as a permanent tidal station. A tide gauge is maintained in constant operation and hourly records from this were obtained for tidal curves and for determining mean sea level.

NATURE OF SAND CHANGES.

Profiles have been made from most of the sand measurements along the pier. In order to show daily changes each new profile was plotted along with the profile of the preceding day. In this way it soon developed that there were large and rapid shifts in sand going on along the pier. When continuous soundings were made for a 28-hour period it was even found that there were appreciable shifts taking place during intervals as short as 40 minutes.

[1] Sverdrup, H. U., and Dahl, O.: Two oceanographic current recorders designed and used on the "Maud" Expedition. Jour. Optical Soc. Amer., Vol. 12, pp. 537-45, May, 1926.

The shifting of the sand was found to be particularly great in the breaker zone where, during 24 hours, a change of as much as 3.2 feet was observed. While the majority of these large changes were of the nature of cutting, the largest change on record was due to a fill.

Seasonal Changes.

In order to obtain a clearer idea of changes that were taking place along the pier, the sand heights at several stations were averaged together and plotted by groups. By this means the seasonal trend of the sand was determined for different zones. Interesting features became apparent from the plotting of these trends. Thus it can be seen from Text Fig. 1, that at stations 1—4, which are most of the time all above mean sea level, the sand undergoes a single major cyclic change during the course of a year which, however, has numerous smaller cycles superimposed upon it. Looking at the mean for stations 36—45, about 700 to 900 feet from the coast line, it can be seen that a less regular cycle has taken place during the year. During the spring months when the sand was lowest at the near shore stations it was highest near the outer end of the pier, and in the fall, when the sand had reached its highest level along the shore, it was reaching its lowest level around the pier end. Also, further examination will show that times of active cut near shore were generally times of active fill outside. This is particularly true in the fall months. Observing the mean for stations 21—30, which represent half way stations, it can be seen that a somewhat intermediate action has taken place, with, however, the greatest oscillation occurring during the time when the shore stations had reached low marks and the outer stations had reached their high marks. It will be observed that during the winter and spring the changes in all three of these zones were of a rapid and fluctuating character. On the other hand, in the summer and early fall the changes both inside and outside were gradual and consistent in their direction. During this same time the mid pier stations showed very little variation, being situated near the node of the sand shift.

Relation to Waves.

Comparing these seasonal changes along the pier with the daily record of maximum swells (Text Fig. 1), we find numerous points of correspondence. In the first place, it is perfectly clear that the period of greatest cut inside and greatest fill outside is closely related to the season of largest waves. Conversely, the period of shore fill and pier end cut is associated with months of very small waves. Exceptions to these rules will be noted, such as the most striking cut along the entire length of the pier on the second of May, due to the exceptional size of the waves, which were larger than any recorded along the pier before or since.

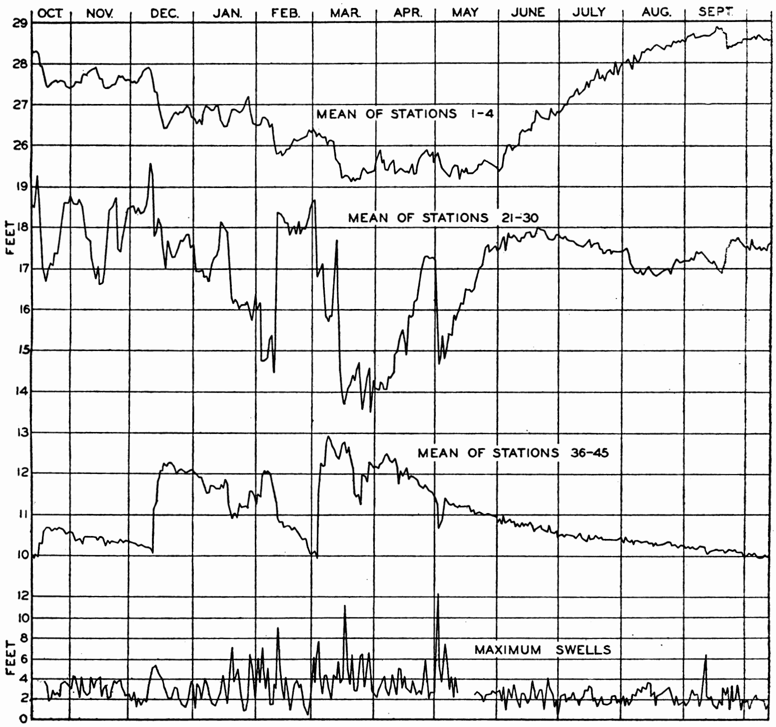


Fig. 1. The daily changes in the sand level for a year along the inner, middle, and outer sections of the Scripps Institution pier. Also the height of the maximum recorded waves for the same period.

It was found that the waves in this region averaged around three feet in height and have an average period of about nine seconds (Text Fig. 2, sec. A). In order to show the effect of various types of waves, profiles have been constructed which show the average daily change in sand height produced along the pier by waves of different size and period. The curves were selected for days with maximum waves between seven and 12 feet high (Text Fig. 2, sec. B), waves of 3.0 foot height with

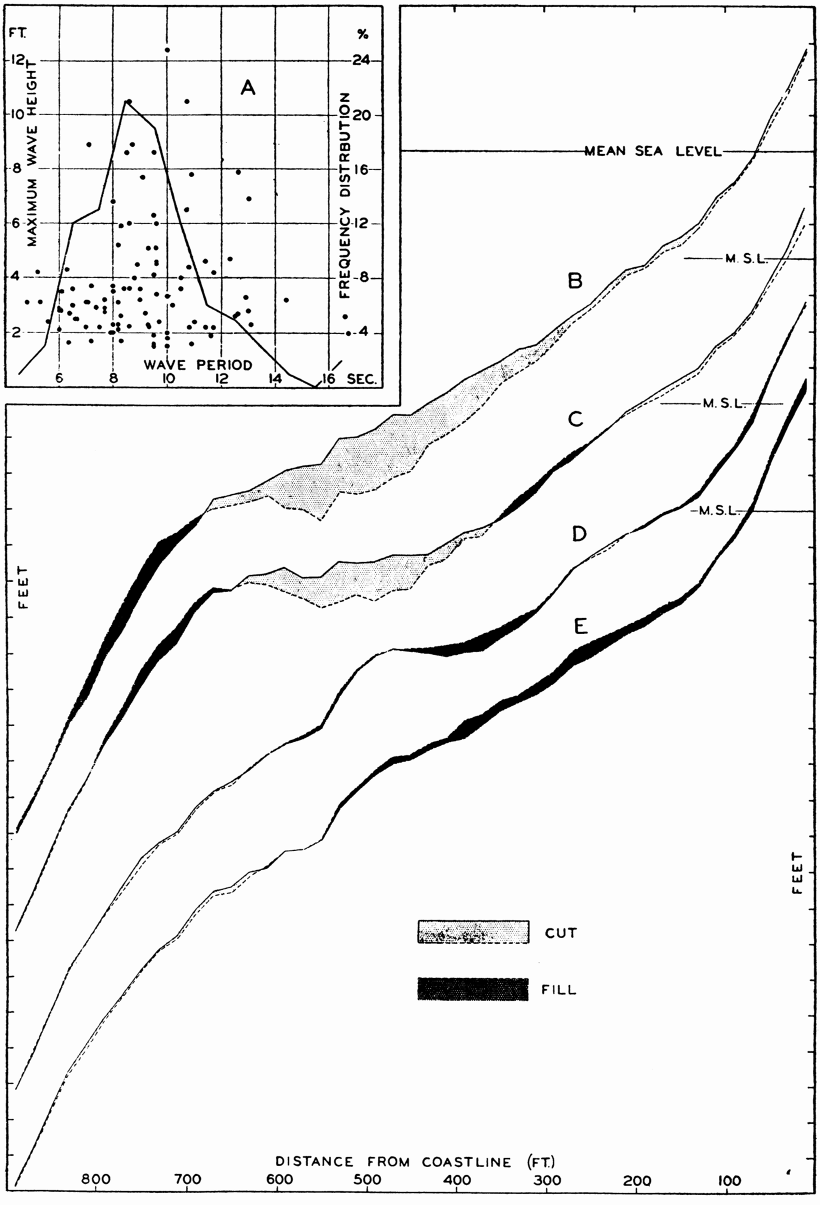


Fig. 2. (A) Maximum wave height plotted against wave period, represented by dots, and the frequency distribution represented by the solid line; (B) the average change in bottom profile during the first day of very high waves; (C) during three days of long period waves; (D) during three days of short period waves and, (E) during one week of low amplitude waves.

periods of over 11 seconds, (Text Fig. 2, sec. C), waves of 3.0 foot height with periods of about six seconds, (Text Fig. 2, sec. D), and waves of less than 2.5 foot height (Text Fig. 2, sec. E).[2] From these curves it will be seen that the large waves produce a considerable cut in the central part of the pier and a less pronounced fill outside. The average size waves with long period resulted in a similar but smaller change in profile. The average size waves with short periods, on the other hand, were followed by very small changes although rather appreciable fill in the middle and inner sections. The small waves were accompanied by still larger fill inside and a small amount of cut along the

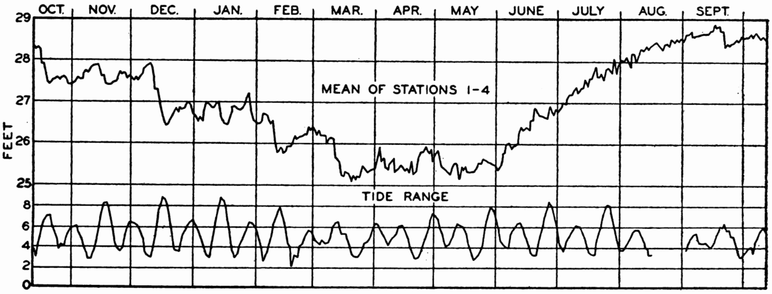


Fig. 3. The relationship between the changes in sand height along the inner pier zone and the range of the tide. High points on the lower curve represent spring tides and low points neap tides.

outer pier. These results show that both the size and period of the waves have important effects on the sand movements. Also, the waves of short period appear to act in the same way as waves of longer period and smaller size. Probably the failure of some fairly large waves to cut, and the large cutting of some waves of moderate size, can be explained to a considerable extent in this way.

Effect of Tidal Variation.

The sand level is shifted not only by the daily change of tide, which shifts the zone of breakers towards and away from shore, but is affected more markedly by the change from spring to neap tides. Ordinarily there are two highs and two lows each day. The tide range is obtained by taking the difference be-

[2] LaFond, Eugene C.: "Sand Movements Near the Beach in Relation to Tides and Waves." Submitted for publication in Proceedings of the Pacific Science Congress, 1939.

tween the higher high and lower low of the day. When the tide range is plotted with respect to time the neap tides appear as troughs and spring tides as crests. Comparison of the tide range for the year with the changes in stations 1—4 shows that there is some correspondence between the two, particularly from October till the large fill along the shore in June (Text Fig. 3). During this period the spring tides are almost invariably accompanied by a cut and the neap tides by a fill on this inner part of the beach. The relationship is, of course, obscured by the effect of the waves, but the tide appears to have fully as important an effect as the waves at these stations.

The influence of the tide is shown much better by plotting the changes at single stations where the greatest influence was felt. Thus in Text Fig. 4 we have chosen stations 1 and 6, which were located respectively at about 1.5 feet above mean sea level, and about 2.5 feet below mean sea level at this time of year. In order to neutralize the effect of other short period influences such as large waves, etc., each point on these curves showing sand level was made by averaging the day's observations combined with the two preceding and the two succeeding days. Examining the resulting curves we find that during April and May the sand at station 1 receives a maximum fill about two or three days after each neap tide, and a maximum cut about two or three days after each spring tide. Conversely, the sand at station 6 shows its maximum fill shortly after spring tides and its maximum cut shortly after neap tides. This, of course, suggests that sand had been moving back and forth between these stations according to the range of the tide.

Considering the changes in June we find that after the early part of the month the cut-fill relationship at station 1 ceases to conform with the tides and even some fill occurs during the spring tide. However, if we bring the record from station 2, which is 20 feet farther out, into the picture at this time (Text Fig. 4) we find the former correspondence of fill with neap tide and cut with spring tide. The explanation for this situation seems to be that by the tenth of June station 1 had been so filled that it ceased to have the proper relation to the sea level, and that station 2 had assumed this position. Stations which are several feet above mean sea level are likely to show fill instead of cut during the spring tides, partly because the waves carry sand far up the beach and the water sinks into the sand leaving the load behind. It may be seen, therefore, that measurement at one station along the beach or even the

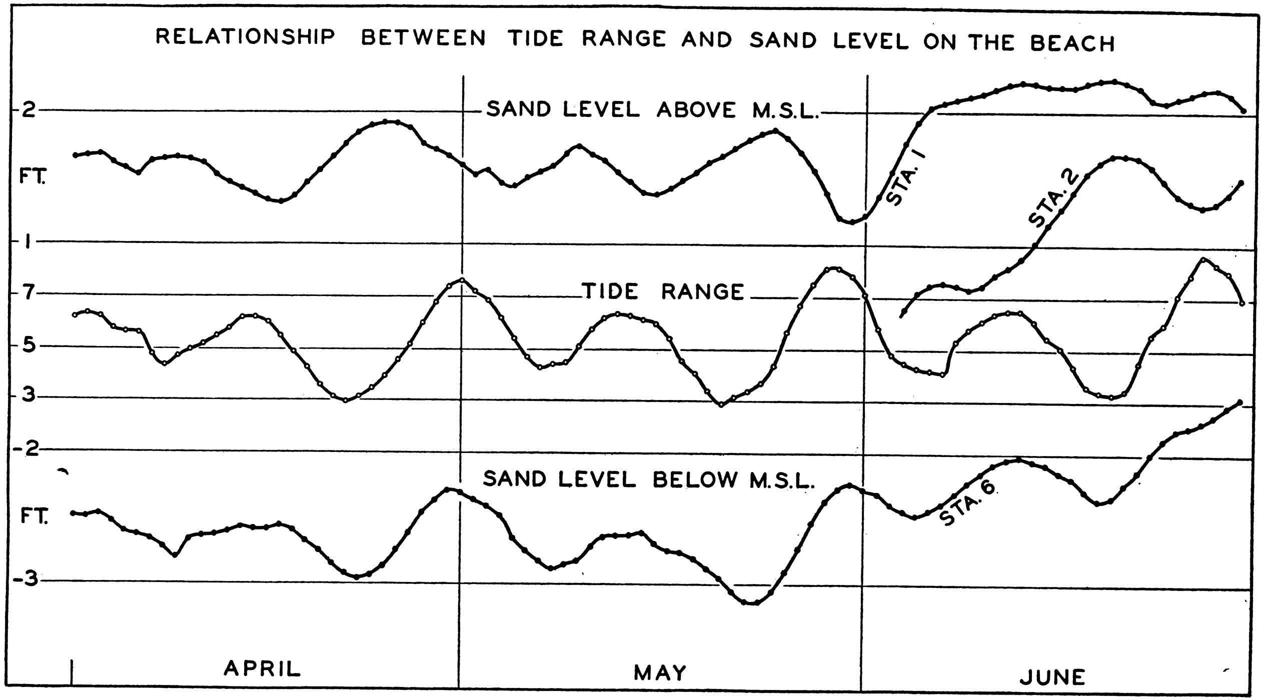


Fig. 4. Illustrating the effect of spring and neap tides on stations located approximately 1.5 feet above mean sea level and 2.5 feet below sea level.

grouping of several stations may fail to show the same relationship to spring and neap tides continuously throughout the year. However, by shifting the stations so as to keep them in the proper relationship to mean sea level, a correspondence can be shown throughout the year which is as good as in Text Fig. 4, except perhaps in July and August. Since the latter are, in general, the two months of greatest fill along the beach, it seems possible that the operation of this bi-weekly sand cycle may be partially obscured during this period of most rapid fill.

Relation to Grunion Runs.

The grunion spawning which takes place on this beach shows a remarkable correspondence to the curve of stations 1—4, (Text Figs. 3 and 5). The grunion deposit their eggs two and a half to three inches under the sand on the beach near the high tide level just before a period of fill so that the eggs become more deeply covered thus allowing them time to mature.[3] If the sand is removed in about two weeks the eggs are mature enough to hatch and the young go out to sea. The grunion choose April, May, and June as their chief spawning months when the tidal cycle is still in effect and when the sand has been cut to its lowest level, at least in April and May of 1938, so that neither seasonal cut nor fill will interfere with the process. It can be seen from the curves that no other months would serve these purposes as well.

Effect of Currents.

The relation between the currents and sand level can be shown best by a diagram showing both speed and direction. Since the currents are almost always to the north or south, parallel to the shore, the graph (Text Fig. 5), shows the resultant north or south current. It will be observed that currents to the south are more common. The record is not quite continuous because of occasional difficulties arising due to the meter being located relatively near the breaker zone.

Comparing the current record with the changes in the mean sand level of all the pier stations (Text Fig. 5), a rough correspondence may be observed. Generally, currents to the north are either accompanied or followed by fill, while currents to the south are generally accompanied or followed by cut. Also, it

[3] Thompson, Will F.: assisted by Julia Bell Thompson. "The Spawning of the Grunion." Fish Bull. No. 3, State of California Fish and Game Commission, 29 pages, 1919.

appears that the time of fill in the late spring and summer is a time of rather small currents. One of the cases where currents appear to be especially important is in February where a general cut along the pier is interrupted during a series of days of north flowing current, by a fill which lasted for about a month. The strongest north flowing current, which occurred in the middle of April, was followed by a fill that was distinctly ahead of the average seasonal trend. Still more significant, the three strongest south flowing currents correspond with the three largest cuts along the pier.

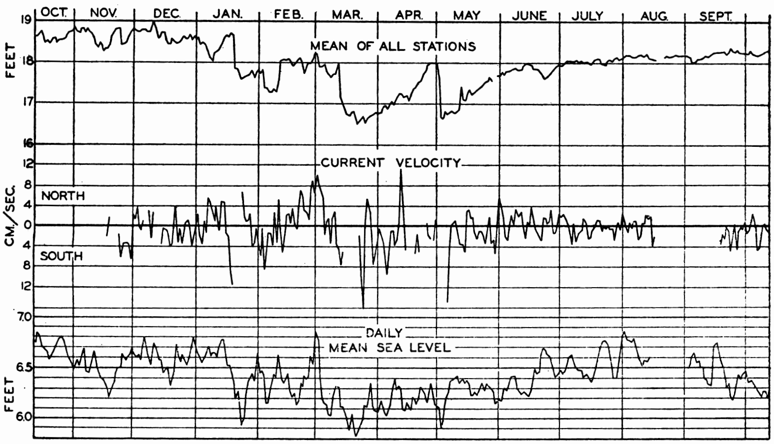


Fig. 5. Comparison of the fluctuations in the mean sand level for all the stations along the pier, with current movements and also with the variations in daily mean sea level.

The Influence of Mean Sea Level.

Mean sea level is obtained by taking the mean of the hourly heights of tide for any desired period. This has been done for each day (Text Fig. 5). The sea level is closely related to the speed and direction of the currents.[4] It will be noted that the three strongest currents to the south approximately correspond in time in the same order with the three lowest sea levels. Also, the second highest velocity to the north occurred the day after the highest sea level of the year.

The daily and weekly sea level curves probably show as close

[4] LaFond, Eugene C.: "Variations of Sea Level on the Pacific Coast of the United States." Sears Foundation: Jour. of Mar. Res., Vol. 2, No. 1, pp. 17-29, 1939.

a correspondence with the changes of mean sand elevation along the pier as with any of the various other factors considered. The sea level even goes through the same annual cycle as the sand, with a depression during the winter and spring and a rise in summer. The changes, however, will be observed to occur in general somewhat ahead of the changes in the sand level. This close correspondence has been observed for several years.[5] The changes in sand level occurring during a change in sea level are mostly due to the currents which primarily control the sea level. However, some variations in sand height must be caused by the differences in water level itself.

Effect of the Wind.

The wind plays an indirect part in fill and cut along the pier since longshore winds influence currents and strong onshore winds in addition produce large waves. The wind records show that the time of lowest stand of sand both on the beach and along the pier corresponds roughly with the period of occasional high wind velocities, in this case from the middle of January till the beginning of May. Wind velocities at La Jolla do not run very high. The maximum recorded wind during this period averaged 26 miles an hour for the 24-hour period. This was accompanied by a large cut along almost the entire pier.

Combination of factors producing large cuts.

Three unusually rapid and striking cuts were general in their effect (Text Fig. 5). In each case within a couple of days the sand level showed an average lowering of over a foot. It has already been shown that the currents reached a maximum to the south on these occasions, and that the sea level showed a correspondingly large lowering. However, other factors combined to produce these results. Thus the large changes about the middle of March and in early May were accompanied respectively by the second largest and the largest waves of the year. The large change in January corresponded only with the fifth largest waves of the year, but the wind velocity at this time reached its maximum for the year. Also the tides in the case of each of these large cuts had just passed the maximum spring range so that they were having their greatest action on the beach. Thus it can be seen that a combination of various

[5] LaFond, Eugene C.: "Relationship Between Mean Sea Level and Sand Movements." Science, Vol. 88, No. 2274, pp. 112-113, 1938.

influences serves to produce the greatest removal of sand in a near shore area of this type.

Underlying Causes of Cut and Fill.

Having shown what factors produce cut and fill it remains to discuss briefly the reasons why these agents act as they do. This is not an easy undertaking, particularly as regards the influences of currents and sea level changes. Accordingly, the suggestions should be considered as tentative and probably subject to change as the work continues.

Waves approaching the coast stir up the sediment on the bottom thus developing a suspended load. The stirring effect is, of course, particularly important in the breaker zone. The motion of the water is more violent towards the shore, however, as it moves seaward more slowly and for a longer period of time.[6] As a result coarser particles tend to move towards shore whereas finer particles move seaward. Probably this same influence is developed where the water thrown towards the shore by waves is returned as a rip current.[7] The latter carries fine sediment outward but has less effect on the coarse sediment. During large wave periods the greater turbulence causes the landward movement to be confined to particularly coarse material such as gravel, if any is available, while the outward moving rip currents find plenty of sand available for transport seaward. With small enough waves, on the other hand, only the forward surge is powerful enough to move the sand typical of this region. Therefore, the sand is carried toward the beach.

Currents and sea level have been shown to follow very similar trends and that, so far as effect is concerned, the currents are the important factor. When the currents are moving to the north they are probably damped by the pier, so that deposition tends to form on the south side which is the side on which soundings are taken. However, taking soundings on the north side of the pier has shown that this explanation is only a partial solution. Possibly the change of the current to the north from its usual southerly direction causes the normal southerly shift of sand along the coast to be interrupted, causing deposition.

The effect of tidal range is partially explicable on the ground

[6] Interim report, Beach erosion board, U. S. Army Engineers, April 15, 3/33-3/35, 1933.

[7] Shepard, F. P.: "Undertow, Rip tides and Rip currents," Science, Vol. 64, pp. 181-182, 1936. Shepard, F. P., and LaFond, E. C.: "Undertow," Science, Vol. 89. No. 2300, pp. 78-79, 1939.

that the high tides of the spring tide periods allow waves to break nearer shore, and thus stir up sand into suspension in an area where sand is normally not disturbed. Sand having been brought into suspension is likely to be carried away from the area where the waves are acting. Also, the large range of sea level allows stirring of sediment by breakers over a wider belt, with corresponding lifting of more sediment into the water for the currents to carry away.

SUMMARY.

It has been shown that the sand is constantly shifting in level along the Scripps Institution pier. During the stormy season of winter and early spring the sand is shifted from the beach towards the outside of the pier, while it is shifted landward during the calmer weather of summer and early fall. Cutting of sand is produced on the foreshore and in the breaker zone especially by large waves and by waves of long period. Small waves and short period waves produce fill in the same zones. The neap tides produce fill a few feet above mean sea level and spring tides produce cut at the same level. Along the beach the correspondence of large waves with a period of spring tides causes a particularly large cut. North flowing currents, which accompany high sea level, produce fill at least on the south side of the pier, whereas south flowing currents which accompany low sea level produce cut along the pier.

As work continues it is hoped that a more perfect understanding of other factors will be obtained. While measurements to date appear to indicate a recurrent cycle without permanent change, the maintaining of the records for a number of years may show a significant trend. Also, the effect along the pier of changing supplies of sand introduced by winter floods can perhaps be evaluated after more data are available.

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