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WATER TABLES IN MARINE BEACHES

By

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INTRODUCTION

Beach slopes, sand movements, and sand composition have been studied by a number of organizations and individuals, but the interstitial water and the possible interrelations between beach characteristics and changing water levels within the beach seem to have received little attention. The present study is an attempt to learn something of those relationships. Surveys were made on three occasions at El Segundo Beach near Los Angeles, and once each at Marine Street Beach and Scripps Institution Beach at La Jolla, California. The authors are aware of little previous related work. Isaacs and Bascom (in press) of the University of California measured some beach water levels in order to learn whether they might serve as indicators of mean sea-level elevation. Zinn (1942) of Rhode Island State College included an examination of beach water levels and water composition in a comprehensive unpublished study of the beach as an environment for micro-organisms. After this report had been written, an abstract by Grant (1946), which outlines much of the thesis of this report, was brought to the authors' attention. In this abstract Grant pointed out that when large waves, heavy rainfall, or small streams inundate a beach back-shore, the water seeps to the surface at the fore-shore, dilating the sediment and moving fine-grained particles. This dilation appears to account for seasonal destruction of beaches and for local degradation of parts of beaches immediately in front of gully mouths.

METHODS

Most of our effort was directed toward measuring the profile of the water table transverse to the shore line and observing the progressive changes of it in response to changing tide level. After an accurate profile of the sand surface was made, a series of pipes 3 to 7 feet long and spaced 5 to 30 feet apart were driven into the sand to a point below the water table. At the crest of the beach the depth to the water table was usually so great that the pipes had to be started from the bottom of
an excavation in the beach 5 to 6 feet deep. Each pipe was one inch in inside diameter, tapered and closed at one end, and perforated along the side. The perforations were covered by a fine mesh wire screen which permitted the passage of water but which excluded the sand so that the depth of the water table below the beach surface could be measured with a sounding stick inserted in the pipe. At points nearer the seaward side of the beach the depth to the water table was measured in small holes scooped in the sand. In addition, the position of the edge of the glassy-appearing saturated sand still farther seaward was recorded because it marked the intersection of the water table and the beach surface. Relative tide height and wave height were based on readings on an improvised tide staff driven into the sand. All of the measurements were repeated at half-hour or hour intervals throughout most of a 12-hour tidal cycle.

During some of the surveys, sand samples from various depths were collected and sealed in jars so that water and salt percentage analyses could be made the next day. In the laboratory the samples were weighed, dried at 100°C., weighed again, washed with distilled water, dried, and weighed a third time. The difference in successive weights indicated the amount of water and of salt. At each site a composite sand sample was also collected for mechanical analysis.

A rough measurement of permeability was made by determining the time required to pass a known volume of sea water having a constant head of 30 cm. through a column of sand 15 cm. high and 4.33 cm. in diameter. The sand was obtained by forcing a lucite tube vertically downward into the beach, removing it, and covering the sand-filled end of the tube with a thin cloth.

RESULTS

Profiles

The profiles measured at all of the sites showed that the water table 20 to 40 feet from the water line lags 1 to 3 hours behind the tide; thus, the water table continues to rise for 1 to 3 hours after the tide begins to ebb and continues to fall for 1 to 3 hours after the tide begins to flood. Apparently this is the result of a slowing of the velocity of the tide wave in passing through the beach sand, which, because of the small interstitial pores, offers much more resistance to passage of the wave than does the open sea. With increasing distance landward the wave lags a longer time and is of progressively smaller amplitude. One would expect, in a beach having high permeability, that the water table amplitude would approximate that of the tide, and that there would be a gradual decrease in amplitude in a landward direction.
Similarly, one would expect that in a beach of low permeability the amplitude of the water table movements would decrease abruptly landward. Examples of the actual changes in the profiles at El Segundo Beach and Marine Street Beach respectively are illustrated in Figs. 1 and 2. These and the other sets of profiles show that during ebb tide the seaward edge of the water table generally slopes seaward, while during flood tide it slopes landward. This is evidently in response to a loss of water from the beach during an ebbing tide and

Figure 1. Water table profiles in El Segundo Beach. Insert at top shows the beach with no vertical exaggeration.
A gain of water during a flooding tide. The high degree of irregularity in the profiles at El Segundo apparently is produced by local variations in permeability, a conclusion which is supported by the difference of grain size in samples collected at various times (Table I). The profiles at Marine Street Beach are much more regular, and a sand sample from that beach is much better sorted, indicating the probability of higher permeability throughout the beach than at El Segundo. The
seaward edge of some of the profiles, taken during an ebbing tide, slope landward (Fig. 2), but this is probably a temporary reversal produced by inflow of water from large waves which washed high on the beach. This wave effect is probably responsible also for the fact that the average seaward slope of the outer part of the profiles at each site taken during ebbing tides is less steep than the average landward slope at flooding tides (Table I). Profiles taken at Scripps Institution Beach were fairly regular, but they showed an amplitude of mostly less than 5 inches in contrast to the 45 to 55-inch amplitudes shown in Figs. 1 and 2. The low amplitude is the result of the small grain size and the low beach slope at Scripps Institution Beach.

**Permeability**

Permeability was computed from the field tests, using the usual equation derived from Darcy’s Law:

\[ P = \frac{Q l}{A h T} \]

where \( P \) is the permeability in darcys, \( Q \) is the quantity of water, \( l \) is the length of sand column, \( A \) is the cross-sectional area of the sand column, \( h \) is the hydrostatic head, and \( T \) is the time required for the water to pass through the sand. The method is the same as that used for Department of Agriculture soil samples (Fireman, 1944). Resulting permeabilities are given in Table I. Possibly these values are somewhat low because of introduction of air (Christiansen, 1944) during the collection of the sand columns, but air is also trapped in the sand in situ (Emery, 1945), decreasing the permeability in nature. In addition, the permeability measurements are based on vertical movement of water through the sand, whereas under actual conditions the water moves both vertically and horizontally. The vertical permeability must be lower than horizontal permeability, because the beaches contain thin alternating coarser and finer layers. Nevertheless, the most permeable sand appears to be that at Marine Street Beach, in accordance with its relative coarseness and excellent sorting; the least permeable sand is that at Scripps Institution Beach where it is fine-grained and less well sorted. It is noteworthy that at least for this set of data, the steeper the beach the greater the permeability, probably because both characteristics are the result of the same environmental factors at the time of deposition. Because Scripps Institution Beach has a very gentle slope, the underlying water table cannot attain the steep seaward slope which its low permeability would permit. The landward slope of the water table at flooding tide also is not steeper than at the other beaches because of the shallowness of the water table and because the tidal effect is partly obscured by water.
<table>
<thead>
<tr>
<th>Place</th>
<th>Date</th>
<th>Tide Range (mm.)</th>
<th>Wave Height (ft.)</th>
<th>Beach Slope</th>
<th>Slope of Seaward Edge Water Table</th>
<th>Median Diameter (mm.)</th>
<th>Sorting Coefficient (%)</th>
<th>Permeability (Darcy's)</th>
<th>Porosity (% volume)</th>
</tr>
</thead>
<tbody>
<tr>
<td>El Segundo</td>
<td>4/5</td>
<td>36&quot;</td>
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<td>4.6°</td>
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<td>30&quot;</td>
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<td>42&quot;</td>
<td>5.7°</td>
<td>2.8°</td>
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<td>30&quot;</td>
<td>0.4°—</td>
<td>0.3°—</td>
<td>1.2° (?)</td>
<td>0.18</td>
<td>1.18</td>
<td>20</td>
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</tbody>
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**TABLE I.** SOME CHARACTERISTICS OF THE BEACHES AND WATER TABLES
from waves which were able to wash a long distance up the flat beach. This effect of the waves makes it impossible to compute the velocity of flow from the slope of the water table.

**SALT CONTENT OF SAND**

Seven sets of sand samples were collected from El Segundo Beach and Scripps Institution Beach for water and salt content analyses. These show that the water content of sand drained by a falling water table varies from about zero at the beach surface to saturation below the water table. When saturated, the El Segundo Beach sand contains water equal to 26.1% by bulk volume (Table I). An average water content of about 10% by bulk volume is left behind in the sand as skin or pellicular water by the falling water table. The remaining 16.1% of the bulk volume then is pore space filled by air. Typical proportional volumes of water, air, and solid sand grains at various depths are shown in Fig. 3. Water collected from below the water table at El Segundo contained 3.8% by weight of salts, as determined by evaporation to dryness in the laboratory. Some evaporation occurs in nature, giving rise to higher than normal salt-to-water-ratios and even leading to visible deposits of salt at the surface of the sand. The amount of salt found in the dried sand is a measure of the water content at the time of sampling, plus the amount of water which had evaporated there before the sampling was done. The dashed lines in Fig. 3 indicate the amount of water at various depths, computed from the salt content of the moist sand. At both El Segundo Beach and Scripps Institution Beach the computed water content approximates the measured water content at depth, indicating lack of significant evaporation below about 12 inches in the beach. However, in both areas the salt content proves that considerable evaporation had occurred nearer the surface; in fact, more water evaporated than could have been held originally in the entire pore space of the surface sand. The extra water must have risen by capillarity from some depth in the sand. At El Segundo the top quarter-inch of the sand was cemented into a rigid crust by salt which filled most of the pore space. Such salty crusts are common on sandy beaches.

**GEOLOGICAL SIGNIFICANCE**

Reference to Fig. 1 shows that during the five hours between the times 1000 and 1500 the water table changed 42 inches at the 40-foot station of El Segundo Beach. It changed only 13 inches at the 0-foot station. We may reasonably assume that a negligible change oc-
Figure 3. Percentage volumes of interstitial water, interstitial air, and solid sand grains in El Segundo Beach and Scripps Institution Beach. The dashed line is the sum of water still present and water which has evaporated in situ as computed from the salt content of the sand.
curred at a point about 60 feet farther landward. Thus, the water table fell through a cross-sectional area of about 200 sq. ft.; for a strip of the beach one foot wide, the water table fell through 200 cu. ft. of sand. The sand at El Segundo has a porosity of 26%, which can be assumed to have been fully occupied by water at the high water table position. At the low water table position the sand had a water content of 5.0% by weight, which means that, of the 26% pore space, 10% remained filled with water while 16% then contained air. Thus, water corresponding to 26 minus 10 or 16% of 200 cu. ft. of bulk sand escaped. This amounts to 32 cu. ft., or 6.4 cu. ft. per hour. Only a relatively small percentage of this water escaped upward to the surface by capillarity and evaporated (Fig. 3). It is estimated from Fig. 3 that an average of 0.5 cu. ft. of water per hour rose by capillarity and evaporated at the surface of the transverse strip of sand one foot wide uncovered by the ebbing tide. The remainder, 5.9 cu. ft., had to run down the water table surface and escape through the beach sand. Fig. 1 shows that the escape area during five hours is 25 sq. ft. For any one-hour period the escape area is 5 sq. ft., only 26% of which is open pore space. Accordingly, every hour 5.9 cu. ft. of water passed through 1.3 sq. ft. of area. The escape velocity would have been 4.5 feet per hour, or 0.038 cm. per second. This is approximately the settling velocity of silt of 0.02 mm. diameter. It is obvious that the escape of water from the beach due to tidal change is sufficient to cause the elutriation and eventual loss of silt from the beach, thus contributing to the high degree of sorting of the beach. Mechanical analysis shows the presence of only 0.041% of grains finer than 0.062 mm. diameter (silt) and 0.374% of grains finer than 0.125 mm. diameter (very fine sand). To this tidal effect must be added the escape from the lower part of the beach of additional water which soaks into higher parts of the beach from each wave which runs up beyond the outcropping edge of the water table. The amount of water contributed by waves is unknown and is difficult to measure, but it must be very large during storms, when it certainly exceeds the amount of water from tidal changes. On some beaches, escaping fresh water would add to the velocity (Isaacs and Bascom, in press), although this was not a factor in the present measurements. Consequently, at times, the escape of water from the low part of the beach may be sufficient to exert an appreciable upward force on some of the sand grains composing the beach. Any such tendency toward lifting the sand grains must aid the turbulence of the overlying water to remove the sand and cause some beach erosion. It is noteworthy that Shepard and LaFond (1940) found that during times of spring tides or high storm waves the beach at about mean sea level is eroded and that
during neap tides and small waves it is filled again. One of the con-
tributory agents, therefore, may be the water from the falling water
table when it escapes through the sand surface.

It is a common observation that at extremely low tides a wide ex-
panse of glassy-surfaced sand may be exposed. Numerous rivulets
drain across this surface, beginning at points farther landward than
the limit reached by the waves at low tide. These rivulets drain away
the water from within the beach which it produced by the lowering
water table. Erosion by the running water cuts small meandering
channels belonging to the class of beach features known as rill marks.

The rigid crusts formed by evaporation of interstitial water at the
sand surface are widespread on marine beaches, but they have not
been noted on fresh-water lake beaches examined by the authors.
When one walks across a crusted beach the edges of the footprints
produced are characterized by a brecciated appearance. Conceivably,
such brecciated crusts have been preserved in some ancient beach
sands. Their presence might be useful supplementary evidence of
"tops and bottoms" in folded rocks, and of marine, or at least salt
water, environments of deposition. The temporary hardening of the
sand surface by formation of the salt crusts may also be instrumental
in the preservation of delicate trails and markings known in ancient
sandstones because of its resistance to erosion by waves and wind.
Beaches of calcareous debris in tropical regions are commonly ce-
mented into beach limestones. The cause of this cementation is not
well established, but it may be partly due to deposition of larger than
ordinary amounts of calcium carbonate with the other salts left by
evaporation of interstitial water. This cementation forms related but
more massive and permanent crusts than those observed on the Cali-
fornia beaches.

SUMMARY

Measurements of the changing profiles of the water tables in several
beaches throughout a tidal cycle show the presence of an interchange
of water between the ocean and the sand pores. Water escapes from
the beach during ebb tide with a velocity sufficient to elutriate silt
grains, and it may collect into rivulets which erode small rill channels
across the beach. Some water is drawn by capillarity to the sand
surface where it evaporates, cementing the sand into a rigid crust.
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