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# BEACH FACE DYNAMICS AS AFFECTED BY GROUND WATER TABLE ELEVATIONS

by

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16. Abstract

This report presents the results of laboratory studies which were carried out in the Coastal and Oceanographical Engineering Laboratory to investigate the effects of ground water table elevations on the beach profile changes over the swash zone. The experiment was conducted at three different water table levels while the other experimental conditions were fixed to constant values with regular waves. The water table levels included (1) normal water table level which is the same as mean sea level, (2) a higher level and (3) a lower level than the mean sea level. Special attention was given to the higher water level to investigate whether this level enhances erosion of the beach face and also to methods of interpreting the experimental data. The experiment described herein was carried out with a fairly fine sand and has demonstrated the significance of beach water table on profile dynamics. The increased water table level caused distinct effects in three definite zones. First, erosion occurred at the base of the beach face and the sand eroded was carried up and deposited on the upper portion of the beach face. Secondly, the bar trough deepened considerably and rapidly and the eroded sand was deposited immediately landward. This depositional area changed from mildly erosional to strongly depositional. Third, the area seaward of the bar eroded with a substantial deepening. The lowered water table appeared to result in a much more stable beach and the resulting effects were much less. The only noticeable trend was a limited deposition in the scour area at the base of the beach face.

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# Beach Face Dynamics as Affected by Ground Water Table Elevations

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# 1 Introduction

The swash zone is defined as that region on the beach face delineated at the upper level by the maximun uprush of the waves and at its lower extremity by the maximun downrush. This region becomes alternately wet and dry, as the waves move up and down until they disappear into the beach or return to the sea. Knowledge of the swash zone is very important because not only does it provide the boundary condition for beach profile evolution models but sediment transport in this zone is directly related to the shoreline position. Additionally, a significant portion of the longshore sediment transport may occur in the swash zone. Hence, considerable research has been directed toward understanding and predicting swash mechanisms and related processes.

Studies by Bagnold (1940) and Bascom (1951) found that the dynamic sediment distribution in the swash zone is a function of the characteristics of the incoming waves and the sand size. The effects of incoming waves are obvious; they provide the mass and momentum of the water in the swash zone. On the other hand, the sand size of the beach face is related to its stability and will influence the water motion through the bed roughness and the porosity. If we change the point of view from individual factors to the forces induced by them, then we can say that the sediment transport in the swash zone is a function of several forces (e.g., friction, gravity, inertia and pressure gradient forces) acting on a water element within the swash zone.

With the combination of these forces, the waves rush up the foreshore until they lose all their forward momentum, at which time the velocity of the leading edge of the waves or the mass of uprush flow is zero. During that time, most of the sediment transported is deposited on the foreshore. As the foreshore slope is increased by sediment deposition, backrush velocities are increased thereby limiting further net acceretion. Finally, the equilibrium slope of the swash zone is reached. However, if there are any changes in these forces, the system will again be put into disequilibrium.

Grant (1948) noted by observations that the aggradation or degradation of a beach, and the value of the beach slope are functions of several variables, one of which is the position of the ground water table within the beach. A high water table accelerates beach erosion, and conversely, a low water table may result in pronounced aggradation of the foreshore. This concept has been supported by various researchers. Most of their studies have focused on tidal cycle response (Emery and Foster, 1948; Duncan, 1964) or on high frequency response to individual waves (Emery and Gale, 1951; Waddel, 1973 and 1976; Sallenger and Richmond, 1984). The results of these studies not only support Grant's idea very strongly but try to provide additional physical reasoning. If we have a low water table, water percolates rapidly into the sand and reduces the uprush mass as well as velocity and this facilitates deposition of sand over the swash zone. Conversely for a saturated beach, water escapes through the sand and increases mass and velocity of the backrush flow and this enhances erosion of the swash zone. Most of the available studies are based on field measurements and have not been carried out with controlled laboratory experiments.

Based on possibilities of beach stabilization, test installations of the beach drain system have been conducted; this approach consists of burying a pipeline along the beach to lower the water table level on the beach face by pumping (Machemehl, French and Huang, 1975; Chappell, Eliot, Bradshaw and Lonsdale, 1979; Danish Geotechnical Institute, 1986; Terchunian, 1989). Successful demonstrations have been carried out in the laboratory and apparently in the field, although the field data are more ambiguous. Most of these studies argued that beach dewatering stabilizes beaches by enhancing deposition on wave uprush and retarding erosion on wave backrush and hence, beach aggradation could be induced by maintaining the beach water table at a low level.

As noted by Dean and Dalrymple (1991), however, it is not obvious how this method works, which it clearly does in the laboratory. Kawata and Tsuchiya (1986) pointed out the ratio of the seepage velocities within the sand to the velocities within the jet of fluid rushing up the beach face are about 1/1000. Bruun (1989) claimed that the method ought to be more effective in mild conditions than storm conditions as the velocities are far higher in the surf zone during a storm. It was noted also by Chappel et. al. that, in the case of beach erosion, more is involved than the simple effect of high water tables increasing the backrush.

This brief report presents the results of a laboratory study of beach face dynamics as affected by the variations of ground water table elevations within the beach. To achieve this goal, an experiment was conducted at three different water table levels while the other factors (e.g., wave height, wave period, water depth, initial beach slope, etc.) were fixed to constant values with regular waves. The water table levels included : (a) normal water table level which is the same as mean sea level, (b) a higher level and (c) a lower level than the mean sea level. Special attention is given to the higher water level to investigate whether this level enhances erosion of the beach face or not and also to methods of interpreting the experimental data.

# 2 Laboratory Studies

## 2.1 Facilities

Laboratory studies were carried out in the Coastal and Oceanographical Engineering Laboratory to investigate the effects of ground water table elevations on the beach profile changes over the swash zone. The major facility was a wave tank which is 120 *ft* long, 6 *ft* wide and 6 *ft* deep. A long partition has been constructed along the tank centerline dividing it into two channels each of 3 *ft* width. A hydraulic driven piston-type wave maker is located at one end of tank and a sand beach was constructed at the downwave end of the parallel channel in which the tests were conducted. Regular waves with a period of 2.0 *sec* and height of 0.160 *m* were utilized for this experiment. The initial beach profile was linear at a slope of 1:18. The water depth at the toe of the beach slope was 1.5 *ft* at mean sea level. The beach was composed of well-sorted fine sand with a median diameter of 0.2 *mm* (2.32 in $\phi$ unit) and a sorting value of 0.53.

## 2.2 Procedures

The experiment was conducted over a duration of 4.5 *hrs* to examine the changes of an initially linear beach profile subject to a regular wave at three different water table levels. The duration of each test with the same water table level was determined based on an assessment that the beach profiles were near equilibrium and would not significantly change beyond this test duration. Throughout the test program, the beach profiles were monitored at one-half hour intervals.

The test procedures are as followings:

1. Measure the initial beach profile.
2. Run waves for 1.5 *hrs* with normal water table level.
3. Establish a new water table level which is 0.36 *ft* higher than normal.
4. Run waves for 2.0 *hrs* while maintaining the higher water table level.
5. Establish a new water table level which is 0.36 *ft* lower than normal.
6. Run waves for 1.5 *hrs* while maintaining the lower water table level.

The raised water table (at 1.5 *hrs*) was established by raising the entire water level in the wave tank and allowing the ground water table to equilibrate with no waves acting. The tank water level was then lowered and the water table was maintained by excavating a small depression in the berm below the desired water level, which was then maintained by filling periodically with a hose. For the lower water table, the procedure described above was followed except that water was siphoned out of the excavated hole in the beach berm to maintain the desired level.

## 2.3 Measurements

For two-dimensional laboratory experiments, sand should be conserved between a landward position of profile closure, where no changes in profile occurred, and a seaward depth of closure, where no sand transport occurred; this implies that the profile data measurements should cover the length between these two positions.

During the experiment, the landward closure could be defined easily by observation. However, defining the seaward depth of closure was more difficult since a small quantity of sand was transported beyond the toe of the beach slope and was spread in a thin layer over the horizontal section of the tank. Hence, the seaward closure was assumed to be located at 1 *ft* seaward from the toe of beach. These allowances of the small seaward transport could cause transport volume errors, which will be discussed later.

In this study, the origin is taken at the landward position of profile closure and at still water level, with the $x$-axis oriented seaward and the $z$-axis upward. For this origin, the seaward depth of closure was found to be approximately 30 *ft* and this length is designated as $\ell$. Fig.1 shows the schematic diagram of initial profile and experimental details.

Beach profiles over a 30.0 *ft* portion of the active profiles were documented by a combination of automatic bed profiler which only functions over submerged profiles and manual measurements at time intervals of 0.5 *hrs*. The profiler mounted on the carriage was used for measuring the beach profiles from 7.0 *ft* to 30.0 *ft*. The beach profile from 0.0 *ft* to 7.0 *ft* was measured manually since the water depth in this region was too small for accurate readings. Exceptions are the profiles at 0.0 and 1.5 *hrs*. For the initial profile, the whole profile over the measurement length was measured by using profiler after increasing the mean sea level. The profile at 1.5 *hrs* was documented by using the profiler except for the landward 1.0 *ft* portion. These two parts of bed profile data were combined later for subsequent processing. In addition, three profiles across the tank were measured over the whole measurement length to document three-dimensional effects; these three profiles were averaged to represent the mean profile. It is noted that the profiler did not operate properly during the profile measurements at 3.0 and 3.5 *hrs* and only one profile was taken at these times. It should be noted also that the offset of profiler changed approximately 0.04 *volt* after 3.0 *hrs*, which could cause the shift of bed profile as much as 0.03 *ft*. The effects of these errors in the measurements will be discussed in the next section.

# 3 Data Analysis

## 3.1 Compilation of Data

Sand conservation can be checked easily by calculating the time-averaged change in sediment volume per unit width of tank, which is obtained by integrating the profile differences from the initial profile over the portion of the active profiles as :

$$V(t) = -\int_0^{\ell} \left[ z(x,t) - z(x,0) \right] \, dx \tag{1}$$

here $z(x,t)$ is the profile elevation at a given point $x$ and time $t$ and $z(x,0)$ is the initial profile.

For complete conservation of sand, if the bulk density is unchanged, the integrated value $V(t)$ should be zero. However, as expected, the errors in transport volumes were found to be non-zero. To satisfy the condition of sand conservation the mean profile at each time step was adjusted. The details of this adjustment and a filtering procedure to remove the ripples are summarized in Appendix A.

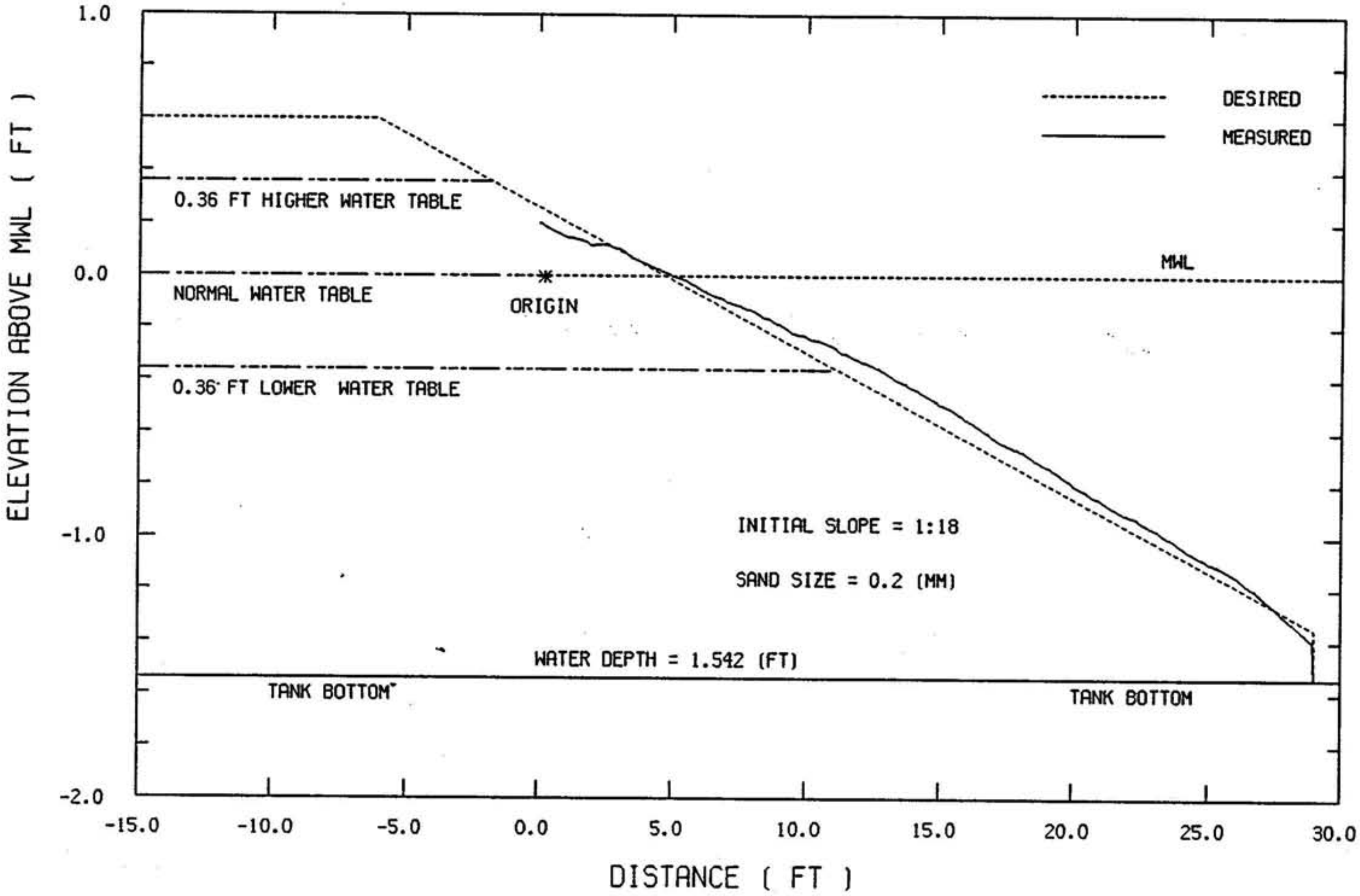


**Fig.1** Schematic Diagram of Initial Profile and Experimental Details

## 3.2 Equilibrium Criteria

For analyzing the data, it is helpful to define what is meant by 'equilibrium' profile and also to determine whether or not equilibrium has been reached. In the field, the equilibrium profile is considered to be 'dynamic' as the tide and incident wave field change continuously in nature and therefore the profile changes shape as well. In the laboratory it is relatively easy to establish an equilibrium profile, by running a steady wave train onto a beach for a long time. After the remolding of the initial profile, a 'final' profile results, which changes little with time. This is the equilibrium profile for that beach material and wave conditions. Hence, as a beach profile approaches an equilibrium, the incident wave energy is dissipated without any significant profile changes and the time-averaged sediment transport rate converges to zero at all points along the profile.

From this definition of equilibrium, we can develop criteria to indicate the approach of the profile to an equilibrium. In this study, three criteria are suggested as follows :

**(1)** Root mean square (RMS) profile change rate, $E_1$

$$E_1 = \sqrt{\frac{1}{\ell}\int_0^\ell e_1(x,t)\ dx} \tag{2}$$

where,

$$\begin{array}{lcl} e_1(x,t) & = & (\frac{\Delta z}{\Delta t})^2 \\ \Delta z & = & z(x,t) - z(x,t-\Delta t) \\ \Delta t & = & \text{the profiling interval ( 0.5 } hrs \text{ )} \end{array} \tag{3}$$

$E_1$ has dimensions of velocity and indicates the rate of profile change during consecutive times.

**(2)** RMS profile deviations from initial profile, $E_2$

$$E_2 = \sqrt{\frac{1}{\ell}\int_0^\ell e_2(x,t)\ dx} \tag{4}$$

where,

$$e_2(x,t) = [z(x,t) - z(x,0)]^2 \tag{5}$$

$E_2$ has dimensions of length and indicates the overall profile changes relative to the initial profile. As the profile approaches equilibrium, $E_2$ approaches a constant value, which implies that the decrease in slope of the $E_2$ curve is a measure of the rate at which the equilibrium is approached. This criterion may be misleading as a measure of equilibrium as it can be seen that a profile shifting along an initially planar slope would cause no change in $E_2$. Hence, it may not be a good measure.

**(3)** Average of the absolute transport rate, $E_3$

$$E_3 = \frac{1}{\ell} \int_0^{\ell} e_3(x,t)\, dx \tag{6}$$

where,

$$\begin{aligned} e_3(x,t) &= |q(x,t)| \\ q(x,t) &= \text{time-averaged sediment transport rate} \\ &= -\textstyle\int_0^x \frac{\Delta z}{\Delta t}\, dx \end{aligned} \tag{7}$$

$E_3$ has dimensions of transport rate per unit width of tank. This criteria is equal to the averaged sediment transport rate over the interval of change. Also, $E_3$ approaches zero with equilibrium conditions.

Smaller values of criteria $E_1$ and $E_3$ and steady values of criteria $E_2$ indicate that the profile is more stable and approaches an equilibrium. If there are any changes in experimental conditions such as variations in water table level, then we would expect the three criteria to reflect these changes.

# 4 Results and Discussions

The profile evolutions with three water levels are presented in Fig.2 through Fig.4. Fig.2 shows the profiles at 0.0, 0.5, 1.0 and 1.5 *hrs* measured during normal water table level. Fig.3 and Fig.4 show the profiles measured during higher and lower level, respectively, together with the initial profile and the last profile of the previous water table level. In general, the bar moved seaward with normal level, and the profiles were approaching an equilibrium. After changing to the higher level, the bar started to move landward rapidly at the initial stages and stayed stationary at the later times. Also at the higher water table, the trough deepened and the profile aggraded substantially in a zone immediately landward of the trough. The bar position remained almost fixed even after lowering the water table level. Profile changes in the swash zone were small during the normal and lower water table levels. However, the berm built up very rapidly during the higher level.

These general trends can be confirmed more clearly by examining Fig.5 through Fig.7, which represent the distributions of the squared profile change rate over the measurement length with the fixed water table level. Fig.5 shows the squared values at 0.0-0.5, 0.5-1.0 and 1.0-1.5 *hrs* with normal level while Fig.6 and Fig.7 show the distributions with the higher and lower level. During the first wave run, shown in Fig.5, significant changes occurred as the profile shape varied from a nearly planar slope to a barred profile. As the profile approached equilibrium, the values of the distributions approached zero at all points. As soon as the higher level was established, however, very large changes occurred at the bar crest with relatively smaller changes at the bar trough.

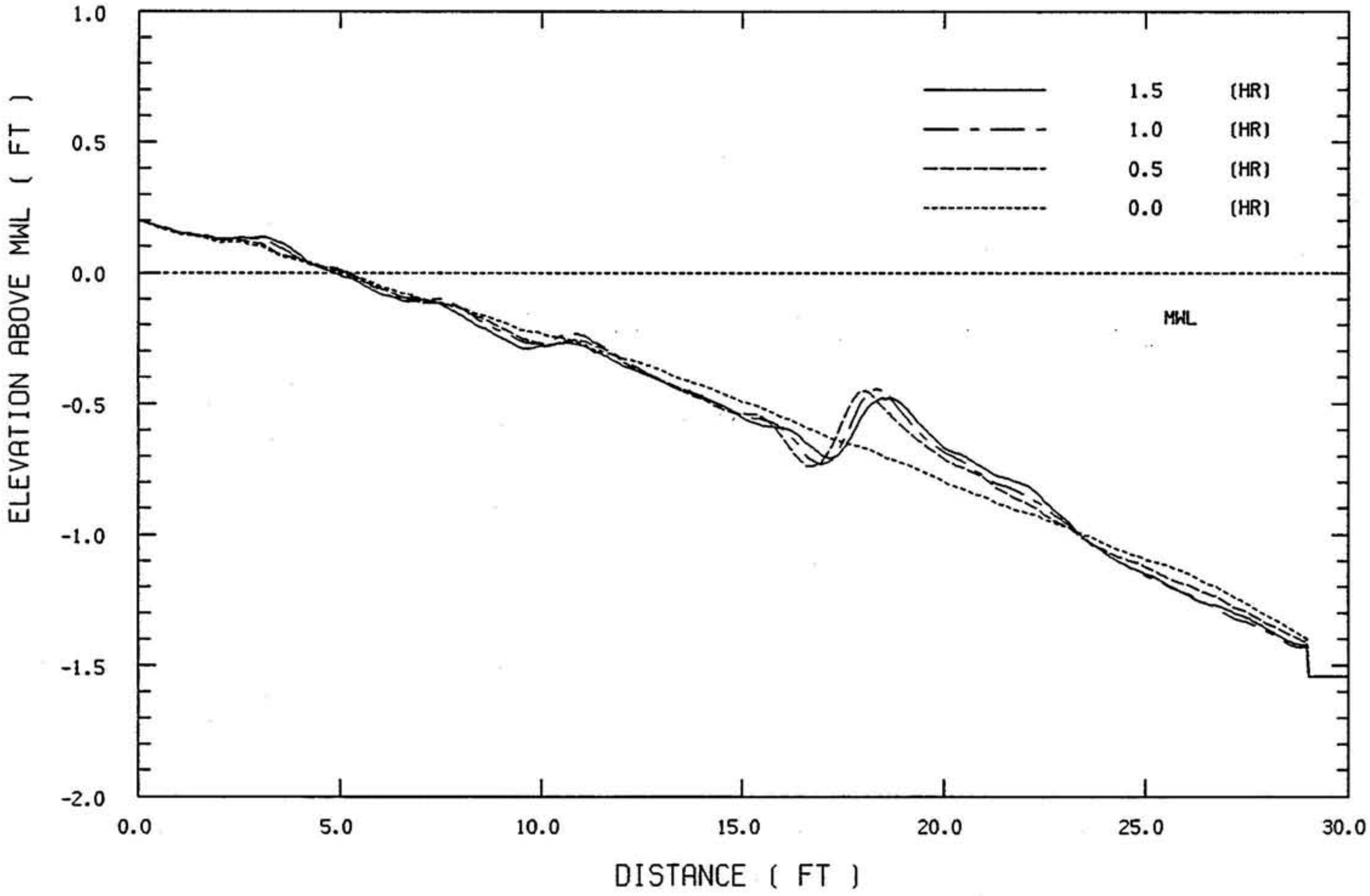


**Fig.2** Profiles at 0.0 *hrs* and 0.5, 1.0 and 1.5 *hrs* with Normal Water Table Level

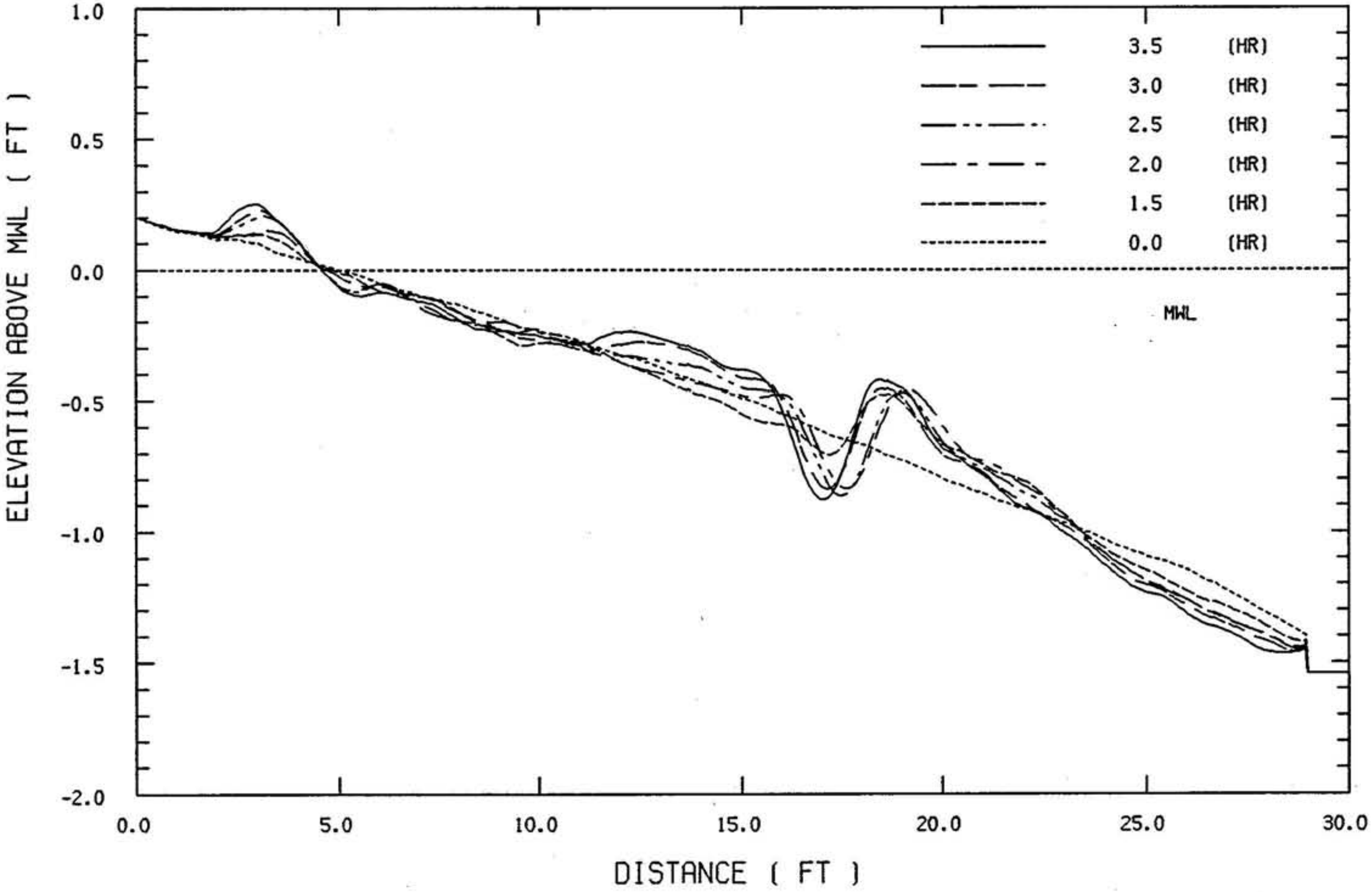


**Fig.3** Profiles at 0.0 *hrs* and 1.5 *hrs* at Normal Level and 2.0, 2.5, 3.0 and 3.5 *hrs* with Higher Water Table Level. Note the rapid build-up above the mean water level (MWL) and scour below MWL.

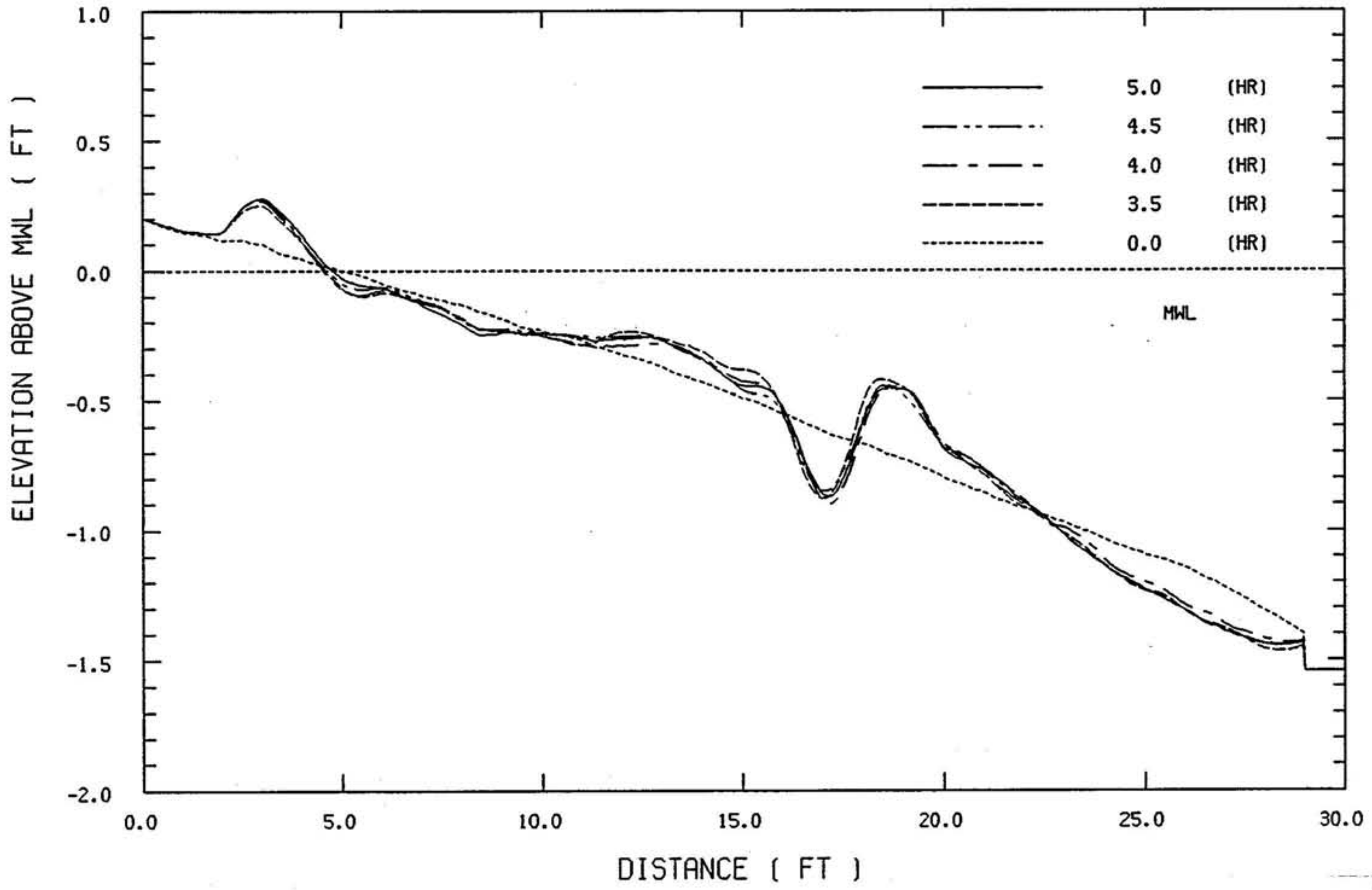


**Fig.4** Profiles at 0.0 *hrs* and 3.5 *hrs* at Higher Level and 4.0, 4.5, and 5.0 *hrs* with Lower Water Table Level. Note the relatively small changes.

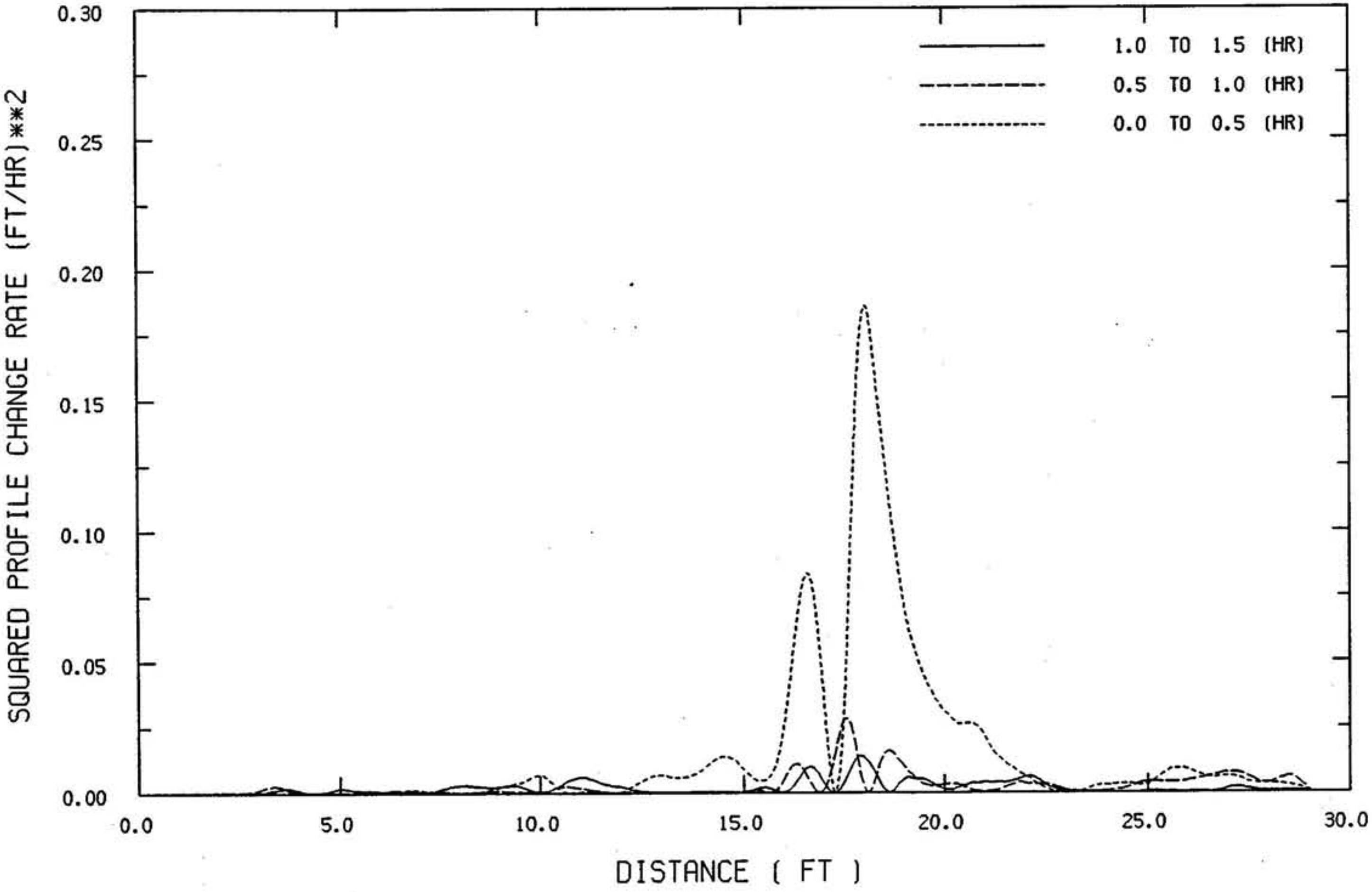


**Fig.5** Distributions of Squared Profile Change Rate ($e_1$) at 0.0-0.5, 0.5-1.0 and 1.0-1.5 *hrs* associated with Normal Water Table Level

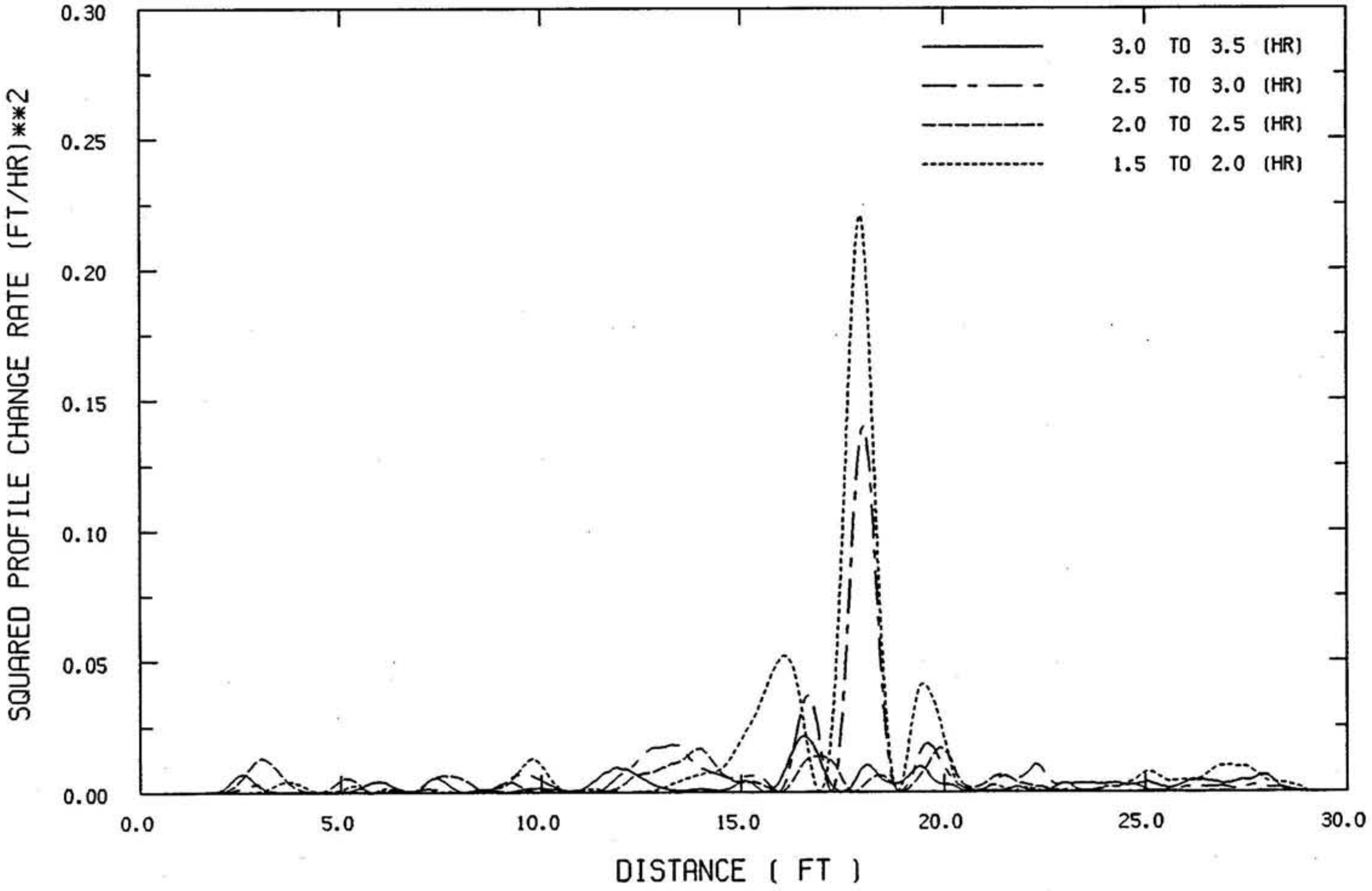


**Fig.6** Distributions of Squared Profile Change Rate ($e_1$) at 1.5-2.0, 2.0-2.5, 2.5-3.0 and 3.0-3.5 *hrs* associated with Higher Water Table Level

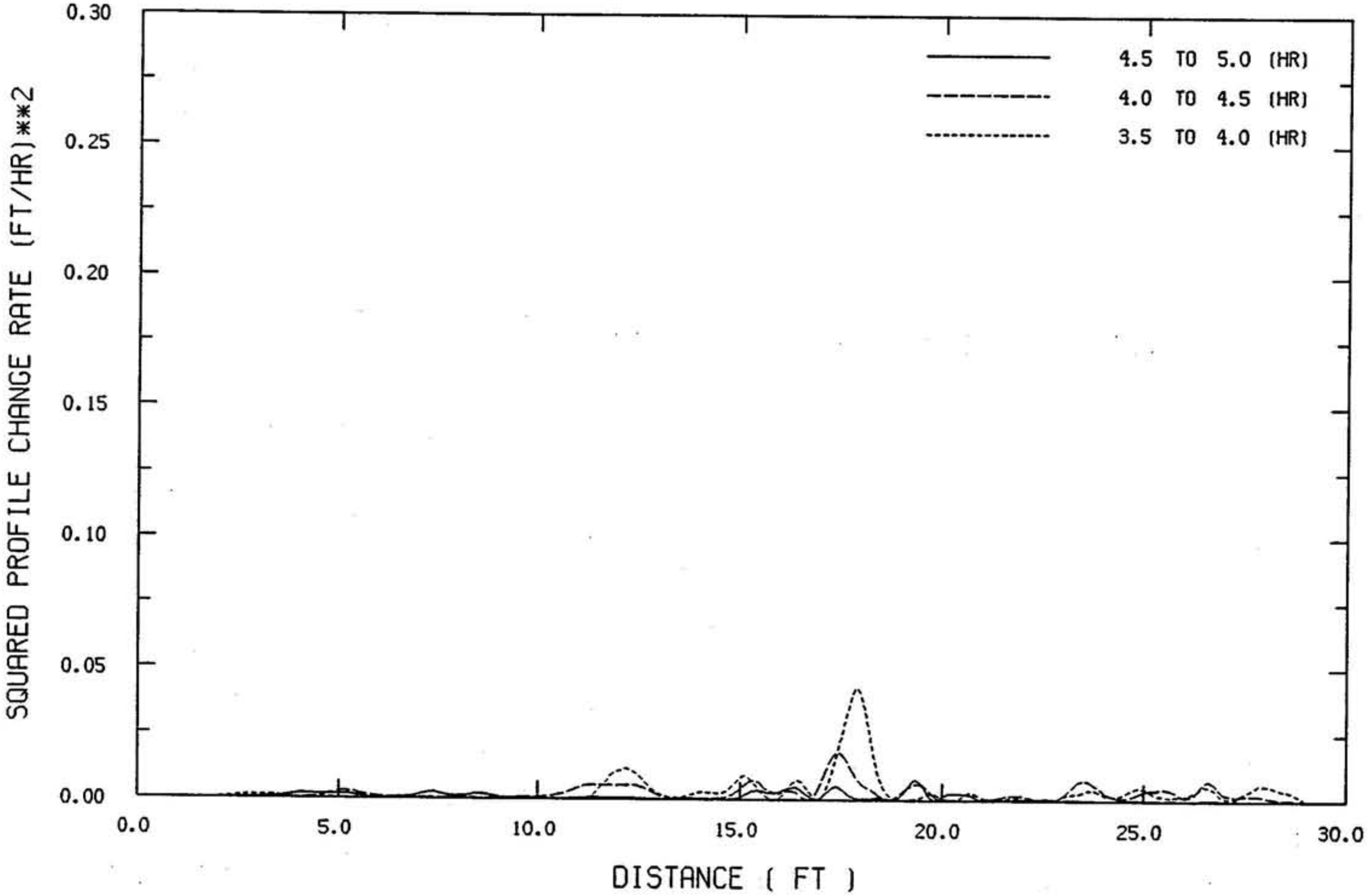


**Fig.7** Distributions of Squared Profile Change Rate ($e_1$) at 3.5-4.0, 4.0-4.5 and 4.5-5.0 *hrs* associated with Lower Water Table Level

Also, significant deposition commenced within the upper portion of the swash zone. During the experiment with the higher water level, the peak of the berm moved landward continuously, which meant deposition over the swash zone. This is contradictory to previous studies that higher water table level enhances erosion. However, there was erosion immediately seaward. It appears that this eroded material was deposited landward in the berm. As shown in Fig.7, little changes occurred with lower water table level.

Fig.8 shows the profiles, profile differences and transport rates during normal, higher and lower water table levels. We can see easily from the transport rate curves that during normal water level, sand was transported both onshore and offshore resulting in deposition at the berm and at the bar. During higher water table, sand was transported onshore and deposited at the berm and at the depositional area located immediately landward of the bar trough. Also it can be seen that relative small changes occurred with lower water table level.

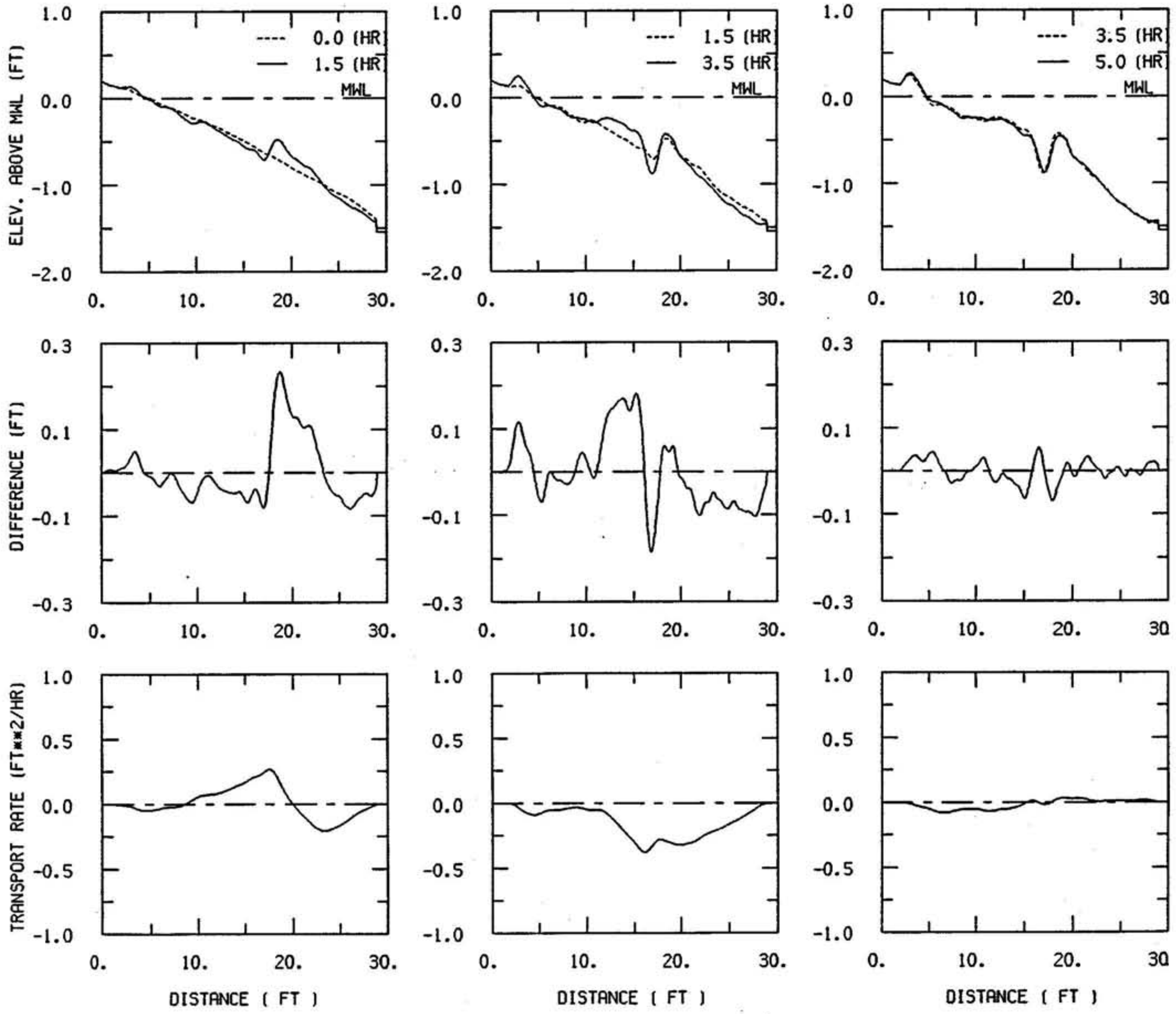
Fig.9 shows the definition of berm height, onshore scour depth, onshore deposition height, bar trough depth, bar crest height and offshore scour depth. All these variables are relative to the initial profile. A negative sign denotes erosion while a positive signifies deposition. The time variations of these variables are shown in Fig.10, which clearly demonstrates the features mentioned above.

The time variations of the three criteria, $E_1$, $E_2$ and $E_3$, are shown in Fig.11 through Fig.13, respectively. $E_1$ is the integrated value of the squared profile change rate, shown in Fig.5 to Fig.7. The value of $E_1$ increases by approximately a factor of three immediately after changing to a higher water table level. During higher water level, another peak value appears. This is because only one profile was measured at 3.0 and 3.5 $hrs$ and the measured one represents the highest part across the tank. During lower water table level, the variation shows that the profile remains in approximate equilibrium. The plots of $E_2$ and $E_3$ are in general agreement with the interpretation derived from $E_1$.

# 5 Conclusions

The experiment described herein was carried out with a fairly fine sand and has demonstrated the significance of beach water table on profile dynamics. Specific effects which have been clearly demonstrated by this experiment and recommendations for additional experiments are described below.

The increased water table caused distinct effects in three definite zones. First, erosion occurred at the base of the beach face and the sand eroded was carried up and deposited on the upper portion of the beach face. This resulted in a " hinge point " at about the mean water line. Secondly, the trough deepened considerably and rapidly and the eroded sand was deposited immediately landward. This depositional area changed from mildly erosional to strongly depositional. Third, the area seaward of the bar eroded with a substantial deepening. These effects are evident through inspection of Fig.2 and Fig.3 (before and after water table increased, respectively).



(a) NORMAL WATER TABLE (b) HIGHER WATER TABLE (c) LOWER WATER TABLE

**Fig.8** Profiles, Profile Differences and Transport Rate Curves during Normal, Higher ans Lower Water Table Levels

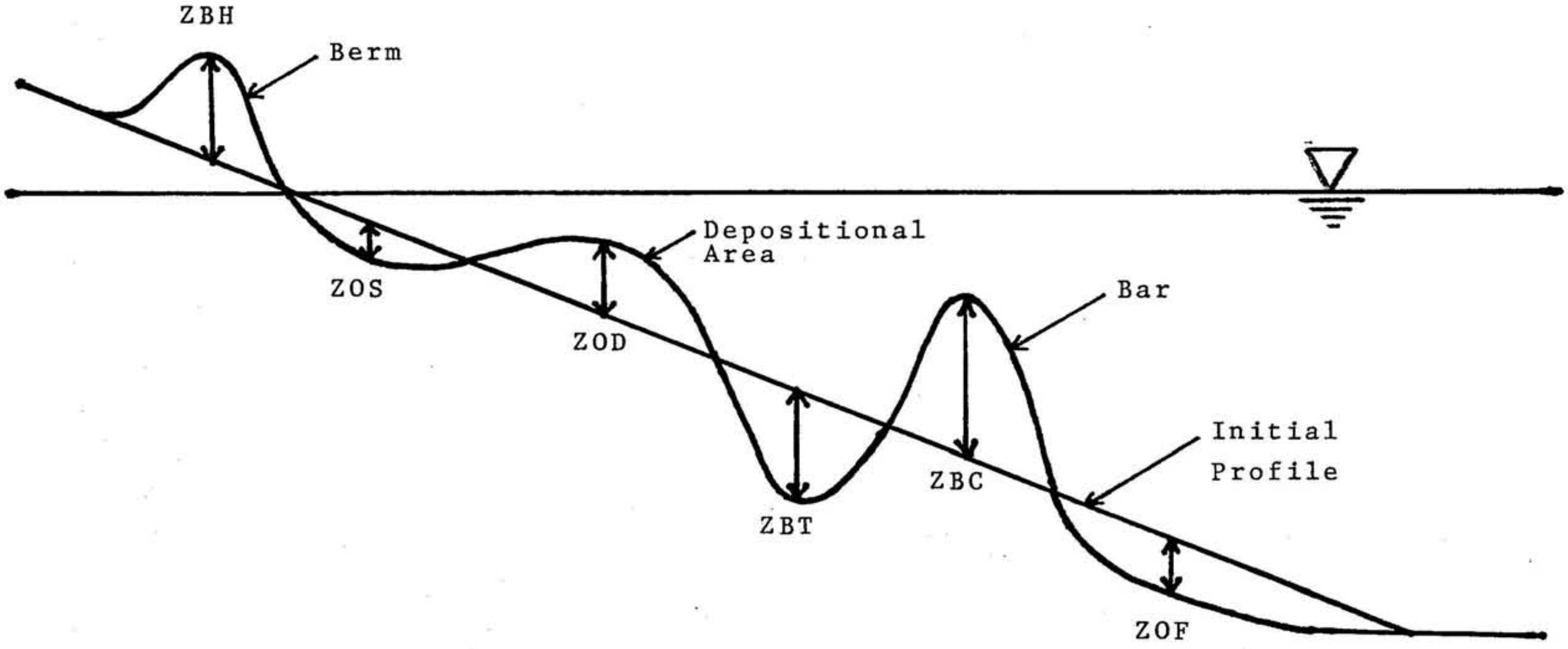


**Fig.9** Definitions of Berm Height, Onshore Scour Depth, Onshore Deposition Height, Bar Trough Depth, Bar Crest Height and Offshore Scour Depth

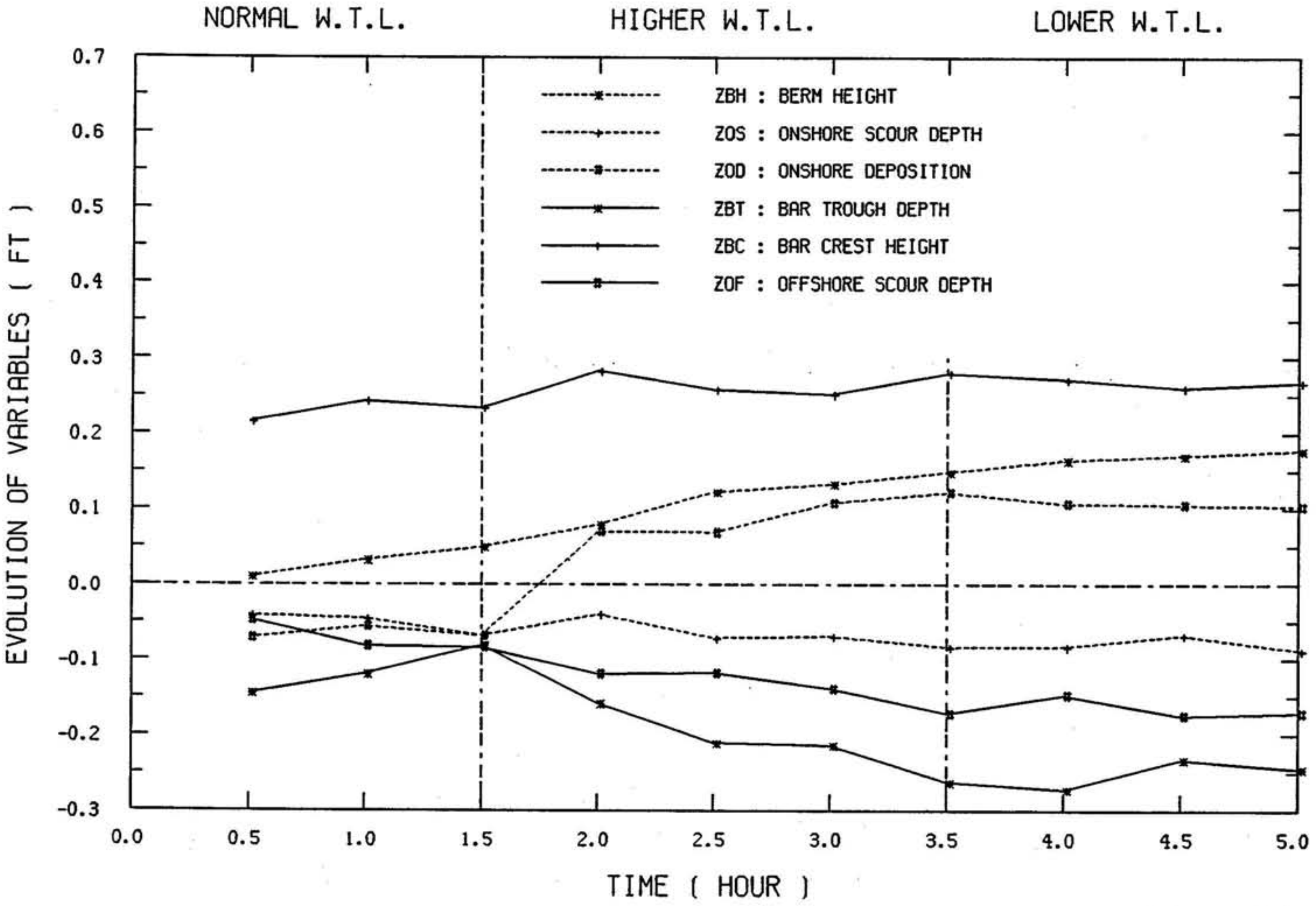


**Fig.10** Time Variations of Berm Height, Onshore Scour Depth, Onshore Deposition Height, Bar Trough Depth, Bar Crest Height and Offshore Scour Depth

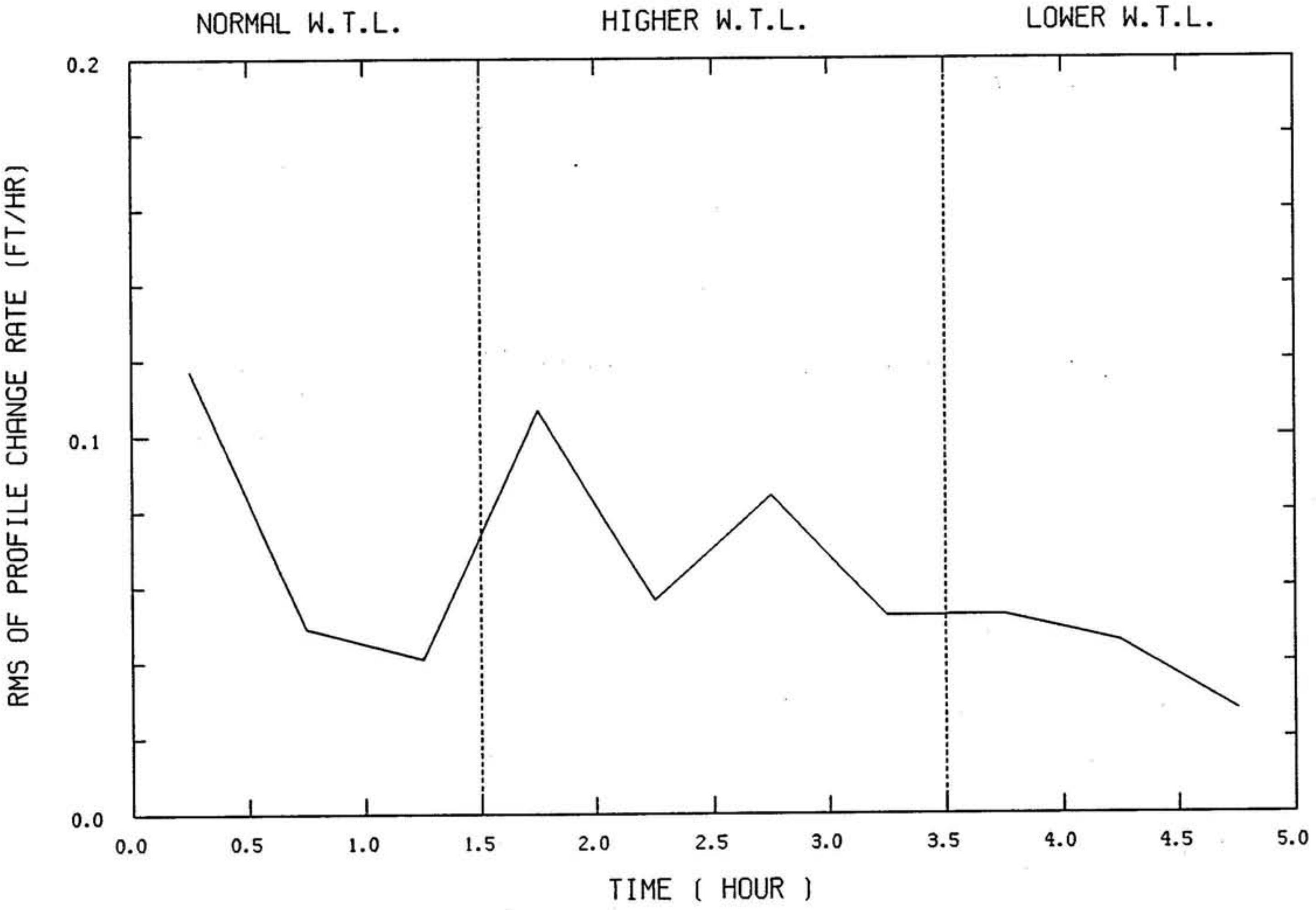


**Fig.11** Time Variations of Root Mean Square Profile Change Rate, $E_1$

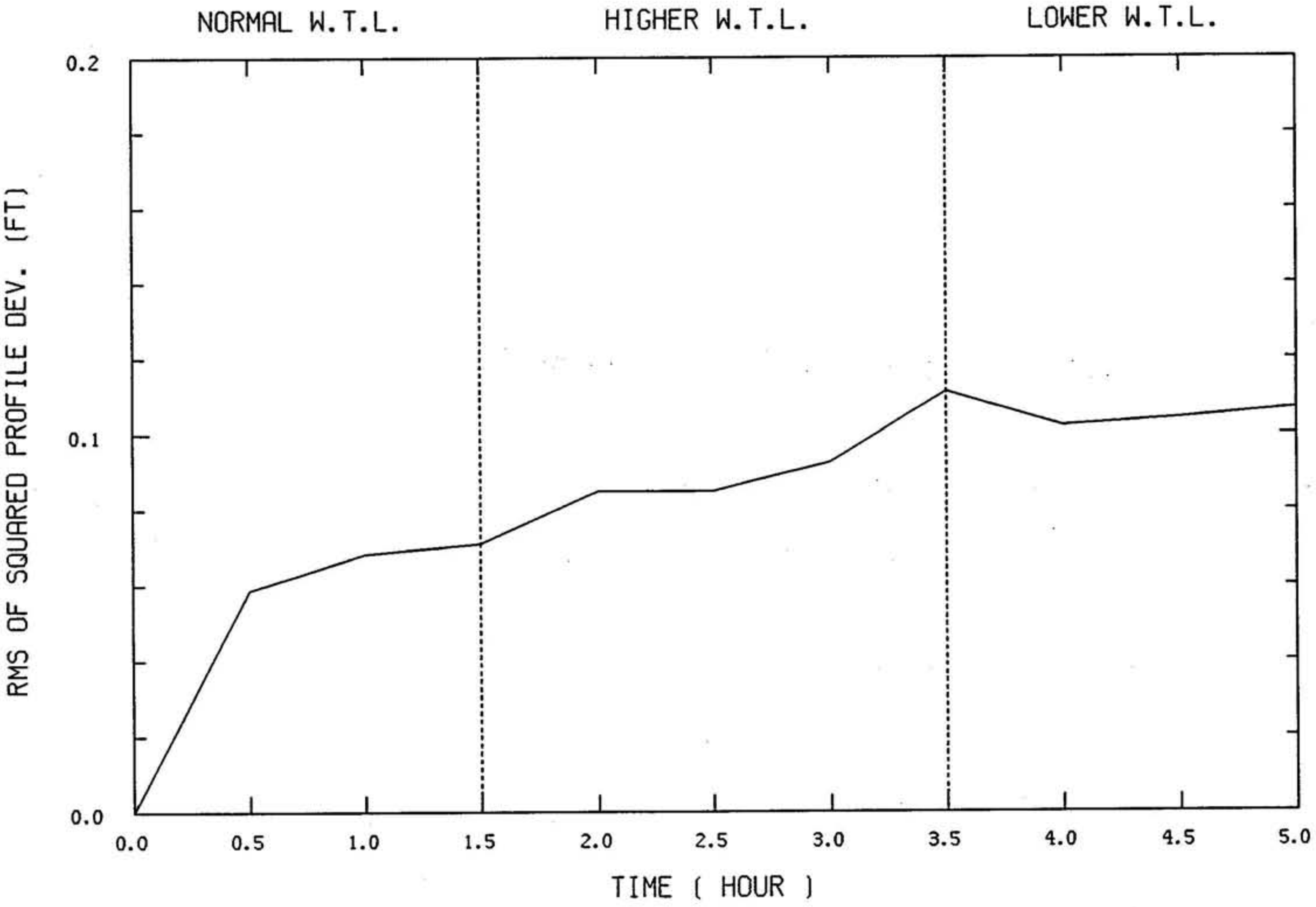


**Fig.12** Time Variations of Root Mean Square of Profile Deviations from Initial Profile, $E_2$

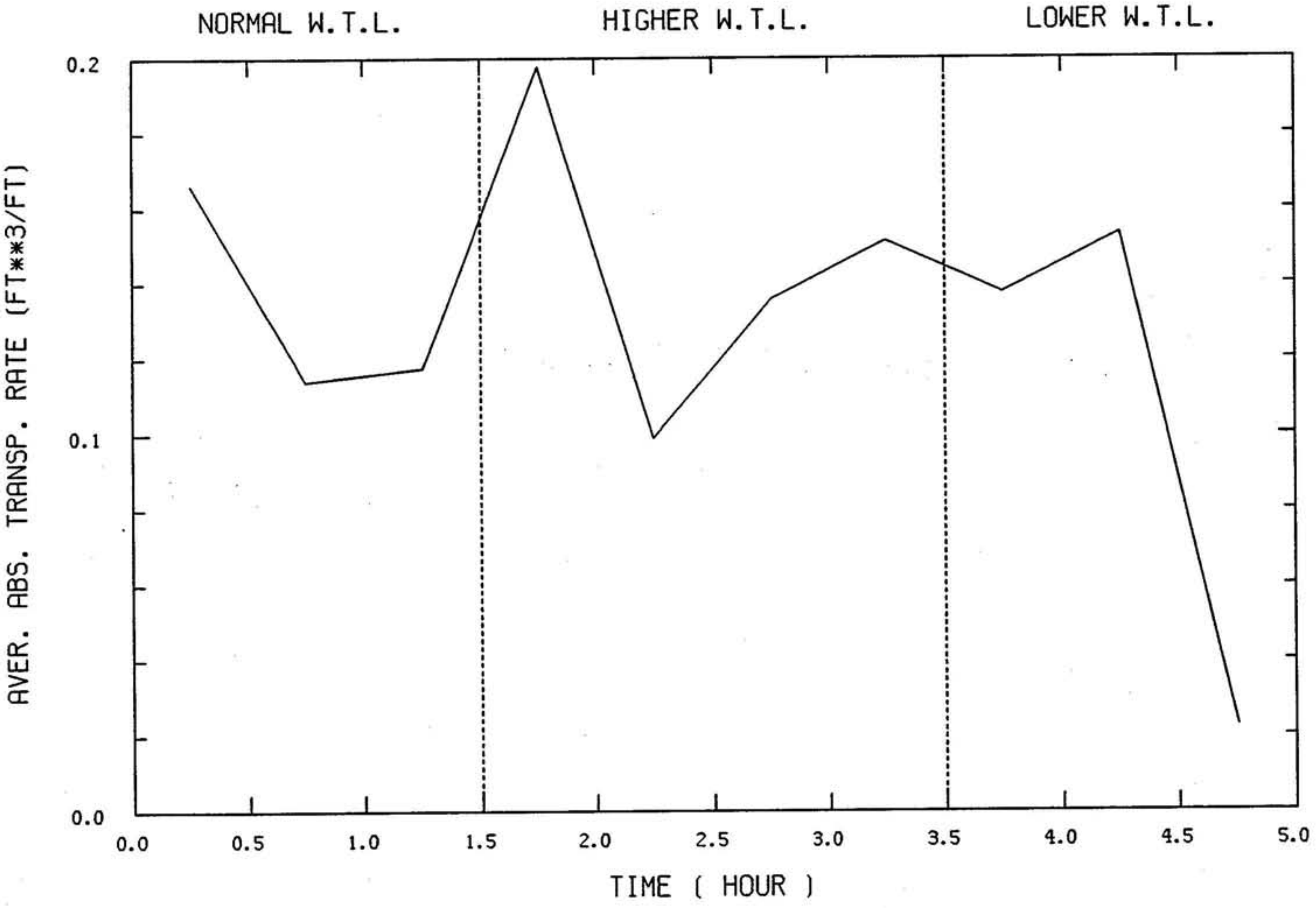


**Fig.13** Time Variations of Average Absolute Transport Rate, $E_3$

It is somewhat surprising that the increased water table was effective so far offshore. The common effect responsible for the changes in the three zones appears to be a destabilization of the bottom particles in areas of pre-existing marginal stability with the eroded particles transported to stable areas. The lowered water table appeared to result in a much more stable beach and the resulting effects were much less. The only noticeable trend was a limited deposition in the scour hole at the base of the beach face (Fig.4).

There is a substantial need for additional carefully controlled laboratory experiments. It is anticipated that results may differ substantially with sediment characteristics and thus experiments should encompass a range of sizes (and thus permeabilities) and sorting. Improved monitoring of the distribution of the ground water table elevations throughout the beach berm as well as the piezometric head within the beach across the surf zone should be considered. The temporal (wave period scale) small scale water table changes as the wave front rushes up and down the beach face should be documented for a range of sand size characteristics. Differences for irregular waves and regular waves as investigated here should be investigated. Finally, all comprehensive studies should include at least limited experiments to document repeatibility and experiments to provide controls illustrating beach profiles that would have occurred if the water tables had not been altered.

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# APPENDIX A

# DATA REDUCTION

In this appendix, the possible causes of errors in transport volumes are discussed at first in an attempt to provide a reference for future experiments. Next the method is presented to adjust the experimental data to remedy these errors within resonable limits.

The errors in transport volumes and mismatch at the point of manual and profiler measurement are believed to be caused by combinations of following :

(1) three-dimensional effects

(2) the small amount of sand that was transported seaward of the measurement limit

(3) consolidation of the sand under the beach

(4) change of profiler offset after 3.0 *hrs*

The errors from (1), (2) and (3) may be inherent in most of movable bed experiments, while the error (4) is confined to this experiment.

Three-dimensional effects can be removed by measuring several profiles along the lines parallel to the axis of the tank. In this experiment, three profiles were measured across the tank, which were averaged to represent the mean profile. However, at 3.0 and 3.5 *hrs* the profile along only one line was measured. Hence three-dimensional effects can be important for these two times. Due to the non-zero water particle velocity over the horizontal section of tank bottom, sand was transported beyond the seaward measurement limit and was spread over the horizontal-floor of the tank. During the experiment, no significant sand volumes were observed. Thus it appears that these errors are negligible. The effect of sand consolidation may be important as the sand within the beach becomes more compact under continued wave action. At the present time, however, there are no avilable means to consider the effects of sand consolidation.

As noted, it was found that in the overlap region in which the profile was obtained by both the profiler and manually, there was a mismatch of elevations. In this experiment, the manual measurements were used as one basis for calibrating the profiler. Later inspection of the data suggested that after 3.0 *hrs*, the profiler calibration changed considerably. The basis for post-calibrating the profiler for each run was to match the profiles in the overlap region to the manual readings and to require that the total volumetric changes were zero.

The calibration relationship between the elevation, $z_p$, and the output $v$ of the profiler is

$$z_p(x,t) = a + b\ v(x,t) - WL \tag{A.1}$$

where,

$$\begin{aligned}
z_p(x,t) &= \text{calibrated profile elevation } (ft) \\
v(x,t) &= \text{profiler data } (volt) \\
a &= \text{calibration offset } (ft) \\
b &= \text{calibration slope } (ft/volt) \\
WL &= \text{water depth to shift the origin from the tank} \\
&\quad\ \text{bottom to the water level } (ft)
\end{aligned}$$

For this experiment, the profiler was calibrated based on the initial profile and the results were

$$\begin{aligned}
a &= \quad 3.748362\ (ft) \\
b &= -\ 0.738907\ (ft/volt)
\end{aligned}$$

With these constants, transport volume errors and mismatch are found as summarized in Table A.1. For each run, the calibration was redetermined so that the profiler results provided;

(1) agreement over the range of manual profiles, and

(2) zero total volume changes.

If we express the bed profile data as

$$z(x,t) = \begin{cases} z_m \quad (x,t) & ,0 \le x \le x_1 \\ z_p \quad (x,t) & ,x_1 \le x \le \ell \end{cases} \tag{A.2}$$

where,

$$\begin{aligned}
z_m(x,t) &= \text{manual data at } x(ft) \\
z_p(x,t) &= \text{profiler data at } x(ft) \\
&= (a+\Delta a) + (b+\Delta b)v(x,t) - WL \\
\Delta a(t) &= \text{correction in calibration offset } (ft) \\
\Delta b(t) &= \text{correction in calibration slope } (ft/volt) \\
x_1 &= x \text{ position of a matching point} \\
\ell &= \text{total measurement length ( 30 } ft\text{ )}
\end{aligned} \tag{A.3}$$

Table A.1: Volume Errors and Mismatch

| Time | Transport Volume | Mismatch | |
|---|---|---|---|
| ($hr$) | ($ft^2$) | $x_1(ft)$ | $\Delta z^*(ft)$ |
| 0.5 | -0.0508 | 7.0 | 0.0090 |
| 1.0 | -0.0682 | 7.0 | 0.0224 |
| 1.5 | -0.1060 | 1.0 | 0.0088 |
| 2.0 | -0.0503 | 7.0 | 0.0283 |
| 2.5 | -0.0727 | 7.0 | 0.0126 |
| 3.0 | -0.4238 | 7.0 | -0.0142 |
| 3.5 | 1.3318** | 7.0 | 0.0895 |
| 4.0 | 1.4139 | 7.0 | 0.0772 |
| 4.5 | 1.6570 | 7.0 | 0.1016 |
| 5.0 | 1.4291 | 7.0 | 0.0828 |

* A positive $\Delta z$ denotes the elevation by the profiler is below that determined manually.

** After three hours, a significant change in profiler calibration apparently occurred.

then, we can set up two objective equations.

i) continuity at the matching point $x_1$

$$\Delta z(x_1) = z_m(x_1, t) - z_p(x_1, t) = 0 \tag{A.4}$$

ii) zero volume error

$$\Delta V(t) = \int_0^\ell [z(x,t) - z(x,0)]\, dx = 0 \tag{A.5}$$

$$\begin{array}{lcl} z(x,0) & = & \text{initial profile data} \\ & = & c + dv(x,0) - WL \\ c & = & 3.748362\ (ft) \\ d & = - & 0.738907\ (ft/volt) \end{array} \tag{A.6}$$

Based on the above, we can develop simultaneous equations for $\Delta a$ and $\Delta b$ as follows:

$$\begin{array}{lclcl} A_1\Delta a & + & B_1\Delta b & = & C_1 \\ A_2\Delta a & + & B_2\Delta b & = & C_2 \end{array} \tag{A.7}$$

Table A.2: Calibration Factors at Each Time Step

| Time ($hr$) | Slope ($ft/volt$) | Offset ($ft$) |
|---|---|---|
| 0.0 | -0.738907 | 3.74836 |
| 0.5 | -0.753827 | 3.80441 |
| 1.0 | -0.773760 | 3.88159 |
| 1.5 | -0.752734 | 3.79571 |
| 2.0 | -0.780490 | 3.90884 |
| 2.5 | -0.760062 | 3.82790 |
| 3.0 | -0.745610 | 3.75521 |
| 3.5 | -0.779667 | 3.97209 |
| 4.0 | -0.756362 | 3.88263 |
| 4.5 | -0.774138 | 3.96562 |
| 5.0 | -0.762894 | 3.90967 |

where,

$$\begin{aligned}
A_1 &= \ell - x_1 \\
B_1 &= \int_{x_1}^{\ell} v(x,t)\ dx \\
C_1 &= C_{11} + C_{12} + C_{13} + C_{14} + C_{15} \\
C_{11} &= (c - WL)x_1 \\
C_{12} &= (c - a)A_1 \\
C_{13} &= d\int_0^{\ell} v(x,0)\ dx \\
C_{14} &= -\int_0^{x_1} z_m(x,t)\ dx \\
C_{15} &= -bB_1 \\
A_2 &= 1.0 \\
B_2 &= v(x_1,t) \\
C_2 &= z_m(x_1,t) - [(a - WL) + bv(x_1,t)]
\end{aligned}$$

The final calibration factors are summarized in Table A.2.

These calibrated data are then filtered to remove high frequency bed change. The filter weighting function for this analysis is linear, symmetric triangular shape which can be expressed as

$$(WT)_k = \frac{K-|k|}{K}(WT)_0, k = \pm 1, \pm 2, \ldots, \pm K \tag{A.8}$$

$$\sum_{k=-K}^{K}(WT)_k = 1.0 \tag{A.9}$$

where,

$$\begin{aligned} 2K+1 &= \text{total number of filter weights} \\ (WT)_0 &= \frac{1.0}{K} \end{aligned}$$

Fig.A.1 shows the filter response function versus wave number, which has a low-pass character. The value of K represented in Fig.A.1 and used in this analysis is 10.

Finally, the output data, $z'_n(x_n, t)$, can be expressed by finite sum having the form

$$z'_n = \sum_{k=-K}^{K}(WT)_k \, z_{n+k} \tag{A.10}$$

Fig.A.2 shows the unfiltered and filtered data for the case of 3.5 *hrs*, which appears to contain the greatest ripple contents. The 'unfiltered' data represent the difference between the calibrated profile at 3.5 *hrs* and the initial profile, which has the effect of removing the linear trend from the calibrated data. The wave number spectrum of the unfiltered and filtered data and removed ripples for 3.5 *hrs* are shown in Fig.A.3. Fig.A.4 shows the time signal data of the removed ripples.

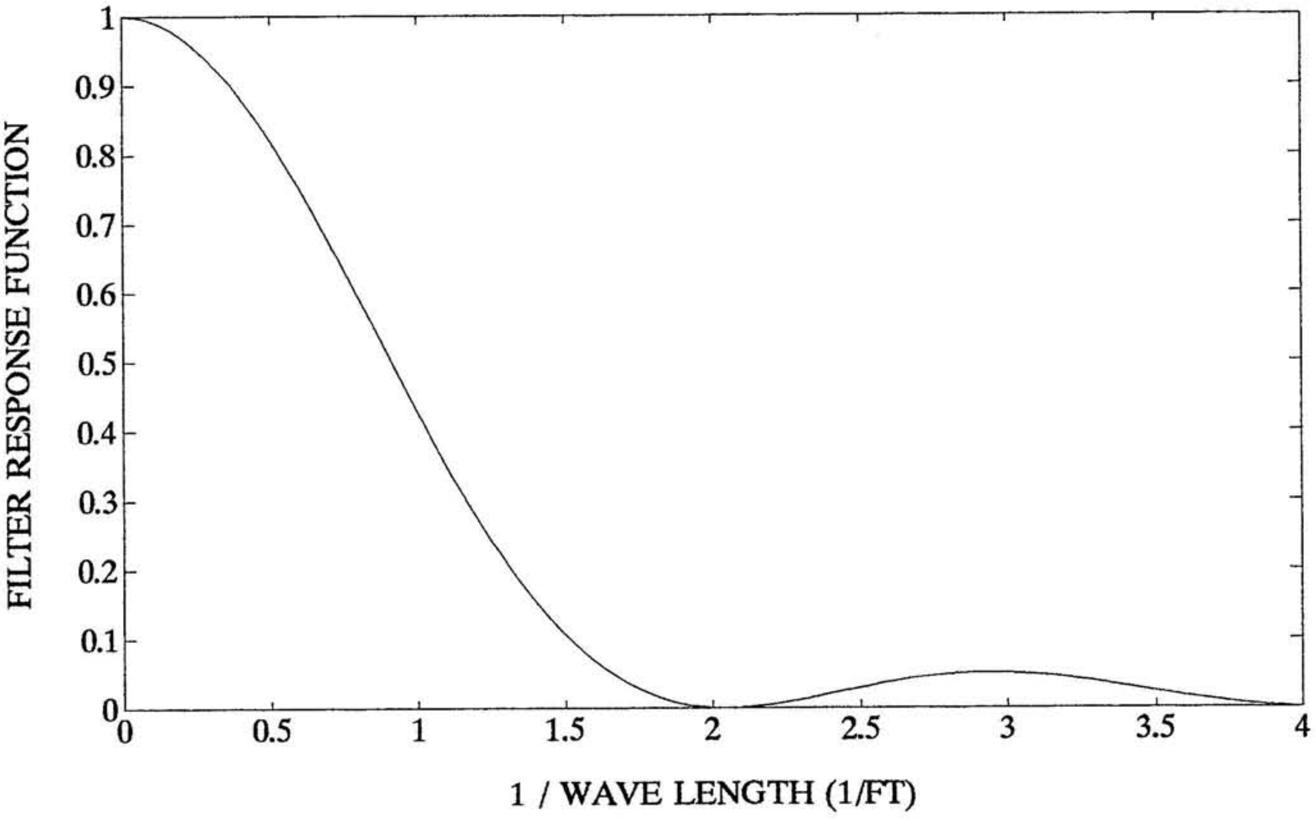

**Fig.A.1** Filter Response Function versus Wave Number

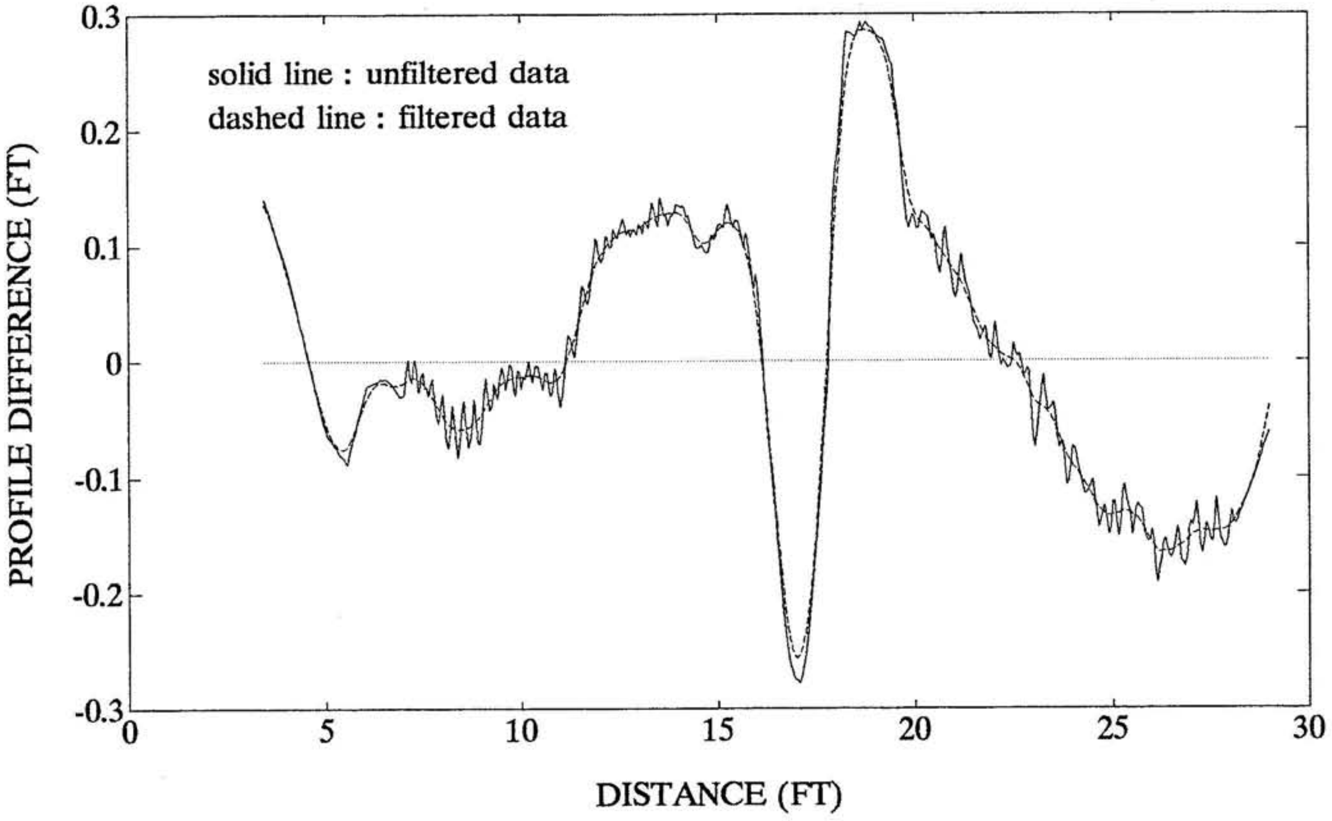

**Fig.A.2** Unfiltered and Filtered Data for 3.5 *hrs*

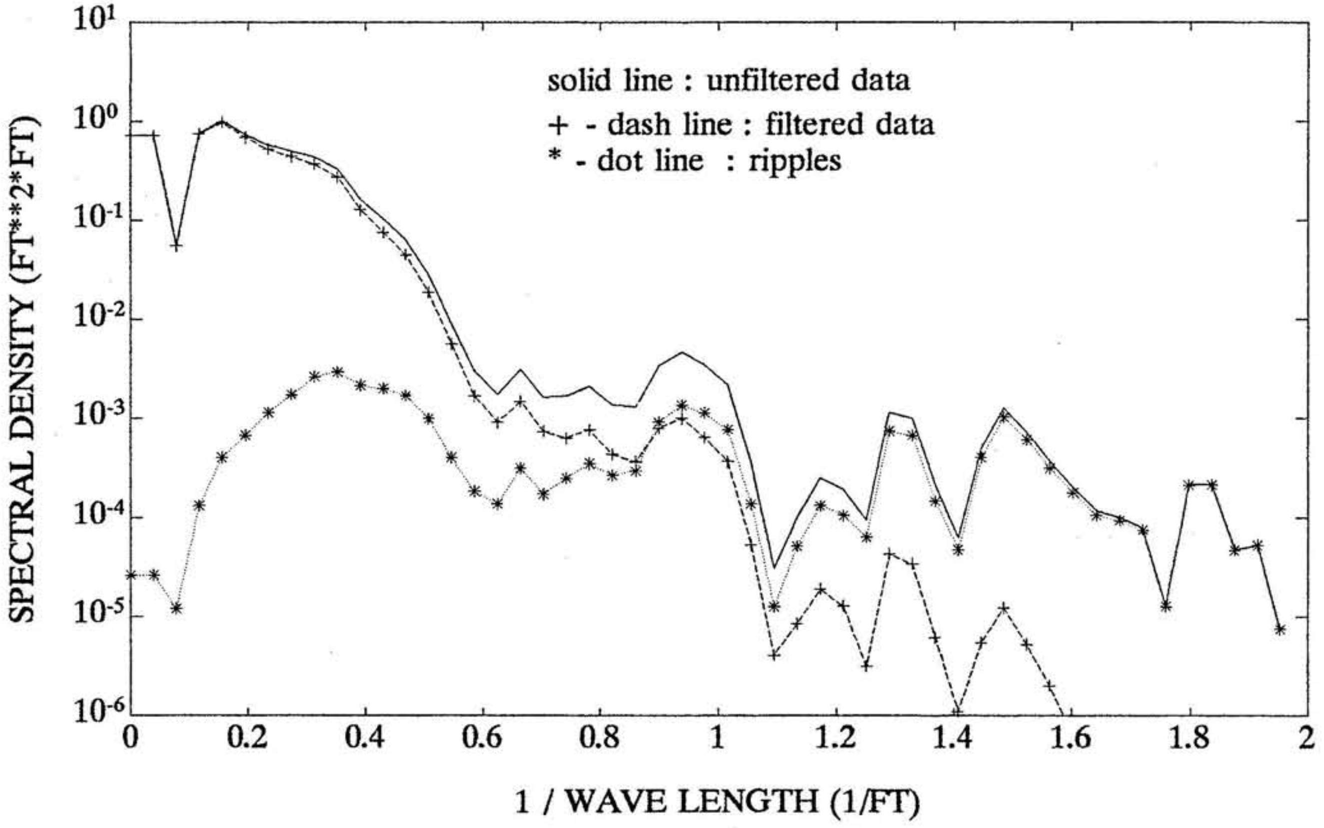

**Fig.A.3** Wave Number Spectrum of the Unfiltered and Filtered Data and Removed Ripples for 3.5 *hrs*

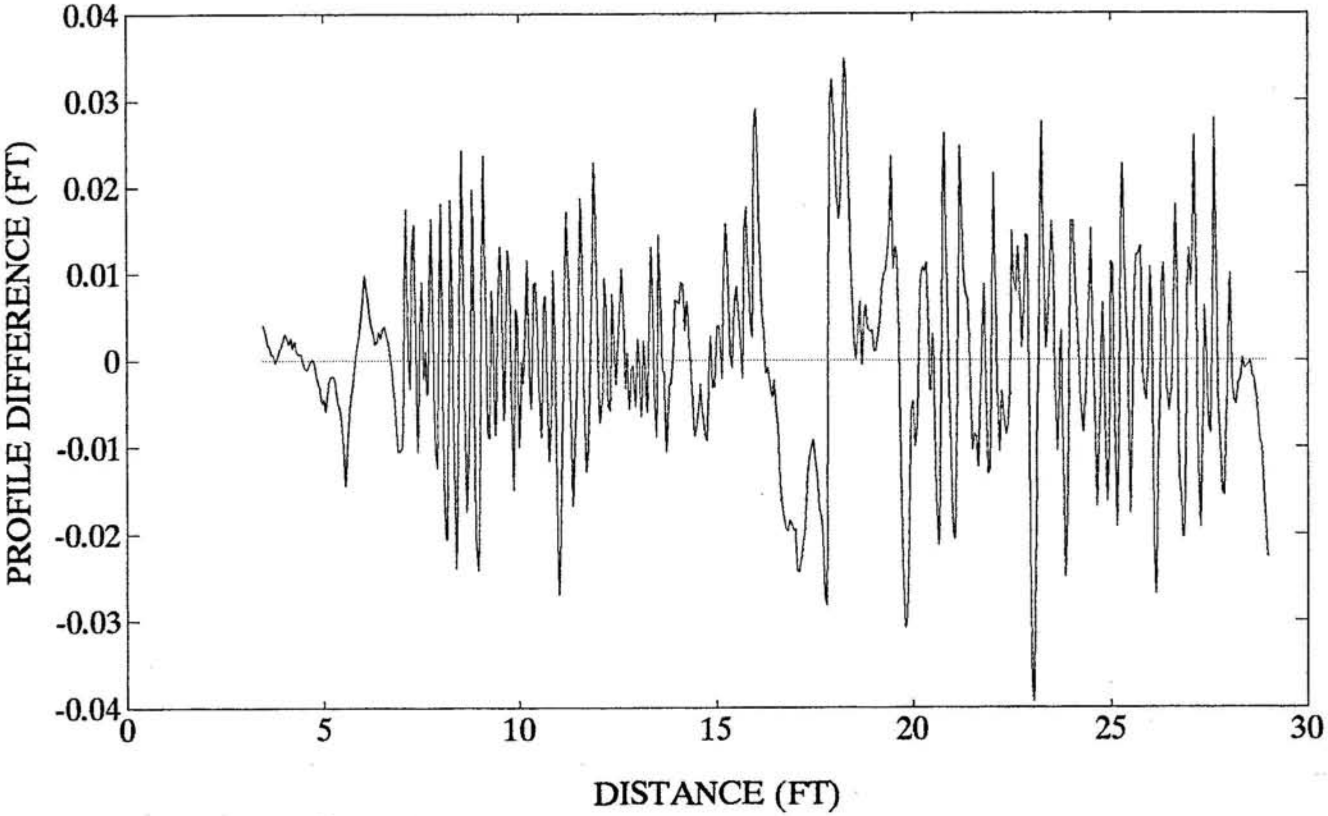

**Fig.A.4** Time Signal of Removed Ripples for 3.5 *hrs*