CHAPTER 201

UNDERGROUND WATER TABLE AND BEACH FACE EROSION

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Abstract

Numerical results show that the beach face of a tidal beach could be considered erosive due to the action of the surface flow formed by the escape of groundwater unless the action of moderate accretive waves, and that the effect will be intensified when the mean level of water table is higher than the mean sea level. Experimental results show that waves act to conceal the effect on the whole. These results suggest that the action of accretive waves are indispensable to maintain a tidal beach in a equiliblium condition. They also suggest that the cause of erosions of Surigahama beach and Iso beach was accumulative workings of the surface flow and insufficient wave action for the restoration during high tides.

Introduction

Field measurements of underground water table at Surigahama beach and Iso beach of Japan showed that the mean level of the watertable was higher than the mean sea level, and suggested that beach face erosion of the beaches was caused by the surface flow on the beach formed by the efflux of underground water. Another feature common to the beaches was that waves acting on these beaches are small all year around.

Previous researchers have considered about the effects of watertable and tidal cycle on changes in equilibrium beaches. Emery and Foster (1948), and

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Grant (1948) found that groundwater escaping to the surface of the foreshore during a low tide contribute to the sorting through elutriating silt from the beach, and the running water cut small streams known as rill marks. They also noted that the water enhances erosion of beach face through not only increasing velocity and depth of backwash flow by adding to the backwash but dilating the sand. And conversely, during a high tide, a low water table may result in pronounced aggradation of the foreshore (Grant,1948). Therefore, we may expect that eroded beach face during a low tide will restore during a high tide in usual states unless erosive storm waves act.

Minute changes in foreshore during tidal cycles were discussed by Duncan (1964), Otvos (1965), Strahler (1966), Schwartz (1969) and Hurrison (1969) based on their own field observation.

In this study, a little different situation in that mean level of water table is higher than mean sea level is considerd in association with erosions of beach face at Surigahama beach and Iso beach. Firstly, the erosions of foreshore at Surigahama and Iso beach are outlined. Then, thin flow on a beach face, formedby the efflux of underground water from the beach face, and beachmaterials which were washed away are discussed based on a numerical model. Lastly, the role of waves in the profile change of a beach where there is aninclined water table is considered based on some experimental results.

Field Measurements

Surigahama beach is famous for natural sandsteam baths and is one of the main features of a well-known hot spring town, Ibusuki. The beach is a small part of the Ibusuki coast, and is located on Kagoshima bay, Kagoshima Prefecture, Japan (Figure 1).

In 1951, a big typhoon struck the coast and caused heavy erosion. The shoreline is said to have retreated up to one hundred meters. Although most parts of the coast gradually recovered beaches from the erosion, the Surigahama beach did not restore at all.

As the beach is one of the important turist attractions, many different measures, suchas seawalls, jetties, detached breakwater and the like, have been tried to preserve the small beach area since 1950's (Figure 2). The beach isnow surrounded by concrete structures.

According to Sunamura (1980), C=18 defined by the following relationship demarcates erosion and accretion of natural beaches.

$$\frac{H_0}{L_0} = C(tan\beta)^{-0.27}\left(\frac{D}{L_0}\right)^{0.67} \tag{1}$$

where H_0 is deep water wave height, L_0 is deep water wave length, $tan\beta$ is average nearshore bottom slope to a depth of 20m.

Long term measured wave data was not available. But, waves had been hindcasted for the period from 1971 to 1975. And we conducted wave measurement for 16 days using three capacitance type wave gauges in 1978 (Figure 3). These results showed that 80 percents of the significant wave heights were smaller than 0.2m and 80 percent of the wave periods were between 2 and 4 seconds. They also showed that the probability of wave heights exceeding 1m is one percent. On the otherhand, the erosive wave height is estimated to be over 1.2m from the above relationship. Therefore, this beach may be taken to

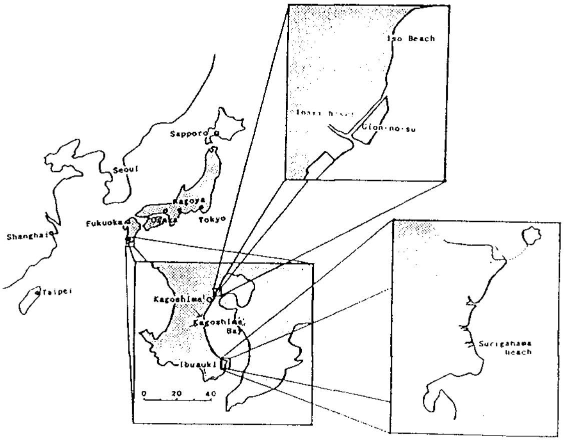


Figure 1. Location Map

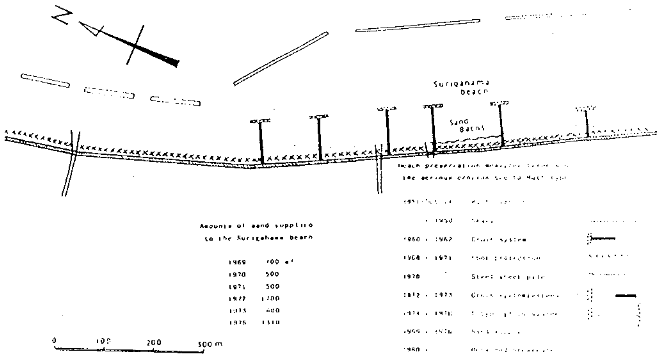


Figure 2.Measures taken since Ruth typhoon

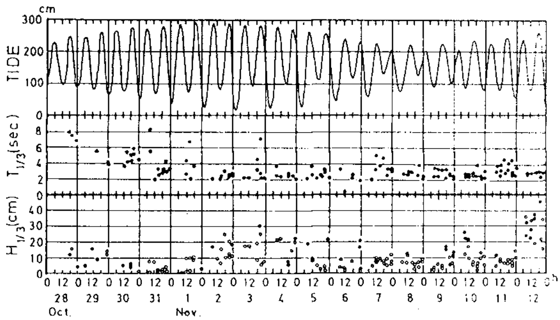


Figure 3. Results of wave measurements

be accretive. However, in spite of the great effort for many years to preserve the beach, it still needs artificial nourishment work.

A condition unique to the beach is the existence of hot springs underneath it. Besides, the range of spring tide is about 2.8m. Paying attention to these facts, we conducted a field measurement of the watertable under the beach.

In order to measure the level of water table, 18 pipes 3m long were driven into the sand. The inside diameter of each pipe was 40 mm. All of the measurements were repeated at half-hour intervals during the peirod between 9 and 13 of December, 1981.

Figure 4 is the contours of mean level of the water table and shows that the mean level of the water table is higher than the mean sea level. Figure 5 shows the water table at low tide. As the tide falls, underground water began to seep to the foreshore surface and cut meandering channels as shown in Figure 6. The temperature of underground water measured at the same time varied from 40 degree C to 80 degree C according to the tide. The high temperature reduces viscosity of the water and increases the permeability up to the double of the value under normal condition.

Iso beach is a similar example in that the mean water table is higher than the mean sea level. This is due to the topographical reason that there is a hilly area close to the beach (Figure 7). The beach is located about forty kilometers north from Surigahama beach and also on Kagoshima bay.

It had been nourished with the sediments supplied from the Inari river several kirometers south of the beach until the land between the river and the beach was reclaimed. The reclaimed land began to block the longshore sediment transport from the river to the beach, as did the highly developed waves from the south. Since the reclamation, Iso beach has been nourished artificialy by supplying sand. Waves acting on this beach are smaller than the ones acting on Surigahama beach on the average throughout the year.

Measurements of the profile changes of the water table transverse to the shore line in respond to the changing tide level were made at one hour interval in September, 1982. We can see that the mean level of the water table is higher than the mean sea level from the results shown in Figure 8.

From the above mentioned observations, it is necessary for us to take the effects of difference between mean water table and mean sea level on beach face erosion into account so that we could plan more effective measures for the situation under consideration.

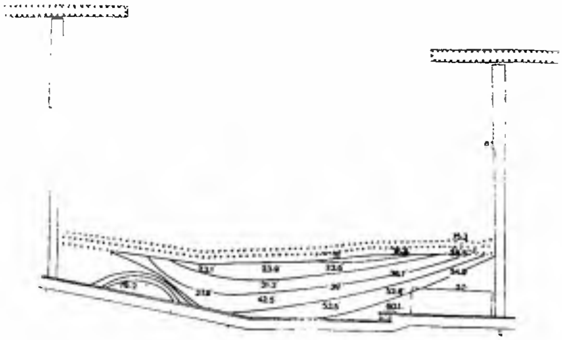
Numerical model

Though coastal aquifers often contain two fluids, freshwater and saltwater, for simplicity we consider only single fluid. Assuming two dimensional motion of underground water, the following equations were used for the analysis of the water table.

$$k\left(\frac{\partial^2 h}{\partial x^2}+\frac{\partial^2 h}{\partial y^2}\right)=S_s\frac{\partial h}{\partial t} \tag{2}$$

$$h=y+\frac{p}{\rho g} \tag{3}$$

Fifure 4. Contours of mean level of groundwater table



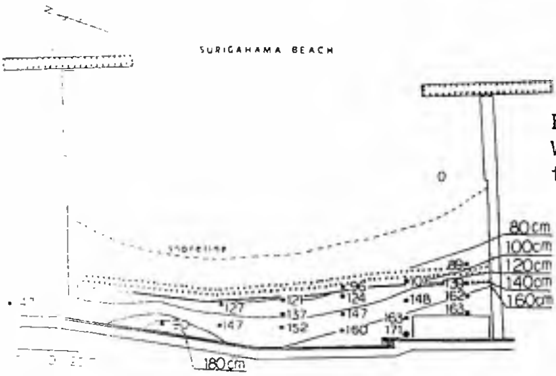


Figure 5. Contours of Water table at low tide

Figure 6. Beach face cut by surface flows

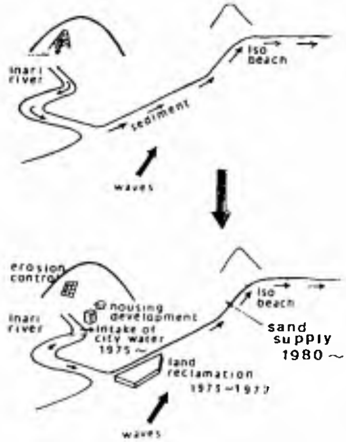


Figure 7. Changes of the area around Iso beach

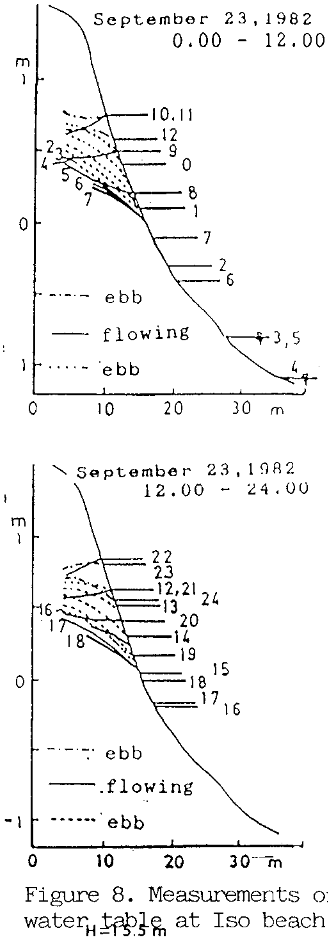


Figure 8. Measurements of water table at Iso beach

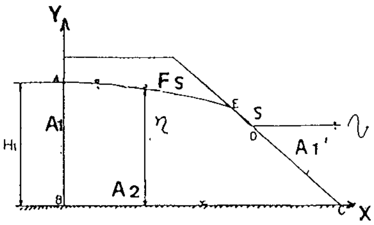


Figure 9. Difinition sketch

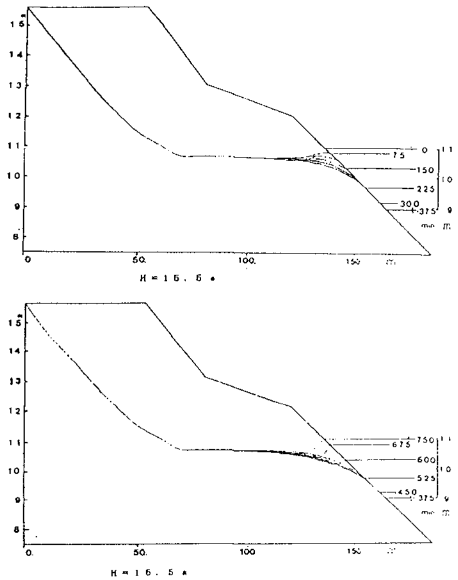


Figure 10. Numerical results of water table

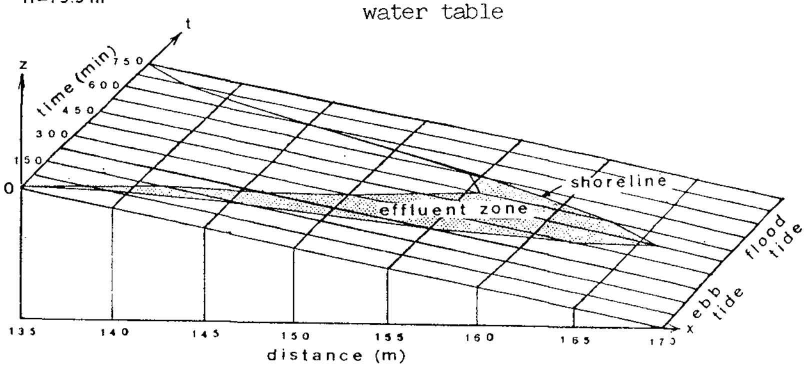


Figure 11. Tide cycle change of effluent zone

$$u = -\frac{\partial h}{\partial x}, \quad v = -\frac{\partial h}{\partial y} \tag{4}$$

where S_s is specific storage, h is the elevation of water table from the sea level, and k is the coefficient of permeability. The positive x-axis and y-axis point seaward and upward respectively.

Initial conditions are specified by prescribed functions for water table and head as

$$h(x, y, 0) = h_0(x, y) \tag{5}$$

$$\eta(x, t) = \eta_0(x) \tag{6}$$

The boundary condition on the left boundary A1 is

$$h(x, y, t) = H = constant \tag{7}$$

and on the boundary A1'

$$h(x, y, t) = H(t) \tag{8}$$

where $H(t)$ is the sea water level and assumed to vary sinusodaly with the period of 12.5 hours and the amplitude of 1 meter.

On the bottom of the aquifer, the boundary condition for a prescribed flux is given by

$$k\left(\frac{\partial h}{\partial x}l_x + \frac{\partial h}{\partial y}l_y\right) = -V \tag{9}$$

where V is the velocity of drain from the bottom and taken positive downward, (lx, ly) is a unit vector mormal to the boundary. In the following model, we put V equal to zero. On the free surface, two conditions must be satisfied

$$\eta(x, t) = h(x, y, t) \tag{10}$$

$$k\left(\frac{\partial h}{\partial x}l_x + \frac{\partial h}{\partial y}l_y\right) = S_y\frac{\partial h}{\partial t} \tag{11}$$

where S_y is the storage coefficient. The boundary condition for the seepage surface, along S, is

$$h = y \tag{12}$$

Introducing the variational principles, the functional χ of a minimizing function h is

$$\chi(h) = \int_R \left[\frac{k}{2}\left\{\left(\frac{\partial h}{\partial x}\right)^2 + \left(\frac{\partial h}{\partial y}\right)^2\right\} + S_s\frac{\partial h}{\partial t}\right] dR + \int_{A_2} V h\, dA_2 + \int_{F_s} S_y \frac{\partial h}{\partial t} l_y h\, dF_s \tag{13}$$

The finite element method based on the Rayleigh-Ritz method was used to obtain the head h from equation (13). The temporal change of the watertable h was obtained by using finite difference method.

The computation program was checked by comparing with an existing theoretical result and an experimental result obtained by the equipment described later.

As any detailed data on the aquifer were not available, we adjusted parameters so that the computation results satisfied the data of the elevation of ground water obtained from two wells, an old well about 140m from the beach and an observational well on the beach.

The results of the profile of the water table are shown in Figure 10. From this result we can see the temporal variation of the effluent zone as shown in Figure 11. The efflux from the beach face forms a thin surface flow. We attempted to investigate the natures of the flow two dimensionally neglecting the three dimensional characters for simplicity. The surface flow was analysed based on equation(14), and the depth averaged mean velocity was obtained. The derivation of the equation is given in Appendix.

$$\frac{dd}{dx} = \frac{i - \dfrac{q^2}{c^2 d^3} + \dfrac{H w_b}{q} - \dfrac{q w_b}{g d^2}}{1 - \dfrac{q^2}{g d^3}} \tag{14}$$

where i is the slope of the beach, d is the depth of the surface flow, w_b is the velocity of the efflux at the beach face, H is the elevation of the free surface of the flow measured from a datum, c is Chezy constant, g is the acceleration of gravity, and $q = \int_0^x w_b \, dx$. In this equation, the positive x-axis points downstream along the beach surface.

The results are shown in Figure 13. The calculated depth increases approximately linearly to the downstream of the flow and the maximum depth at the downstream end is small and less than 1cm. The calculated velocity of the flow is shown in Figure 14. The result shows that the velocity is about 14cm/sec and almost constant from the upper end to the downstream end except the flow after 150 minutes from the highest tide. The efflux from the beach face increases the depth. However, it does not accelerate the flow in this case.

When the velocity exceeds a threshold of sediment movement, the beach materials are washed away by the flow from the beach face. And this threshold was estimated to be 1.74cm/sec. Therefore, the whole flow has enough intensity to erode the beach face.

In order to contrast these results with the case in which there is no difference between the mean level of water table and mean sea level, similar computations were made. The results are shown in Figures 15, 16 and 17. In this case, the area of the effluent zone becomes a little smaller. However, these results show that the beach face will be eroded by the flow formed on it even if mean level of water is equal to mean sea level. And, in order for a tidal beach to be maintained in a equiliblium condition, the action of the changing tide must be canceled, or the beach must be restored during high tide, by the action of waves.

Figure 18 is the measured results of the effluent zone. This shows that the upper limit of the effluent zone does not become lower in comparison with the numerical result. And the length becomes double of the caluculated value. We are not certain about the reason of this discrepancy. In any case, this result

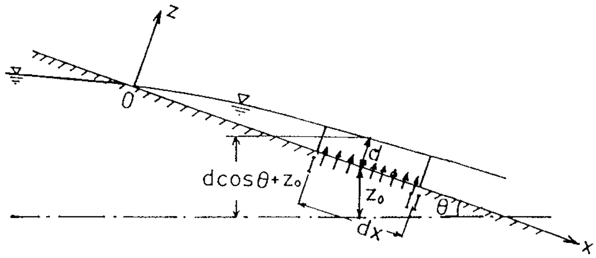


Figure 12. Difinition sketch of surface flow

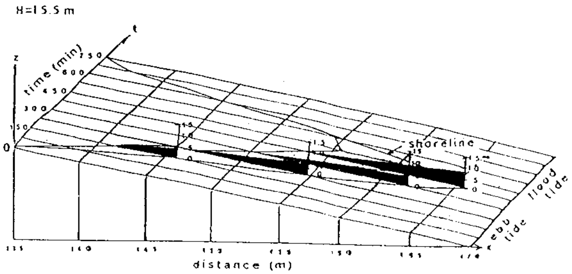


Figure 13. Change of thickness of surface flow

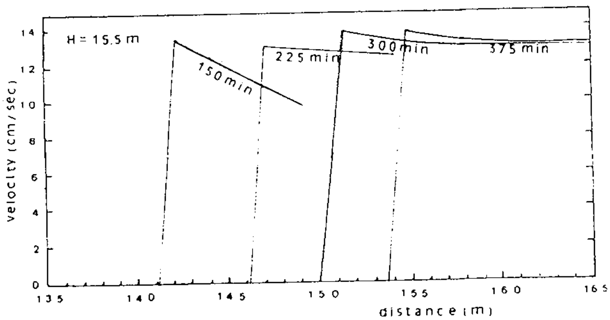


Figure 14. Change of velocity

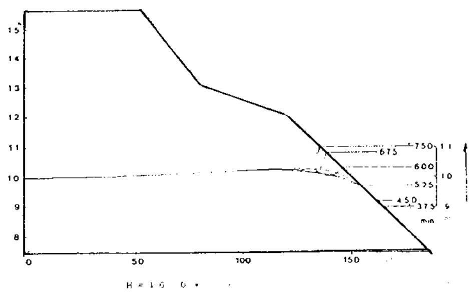


Figure 15. Numerical Result of water table

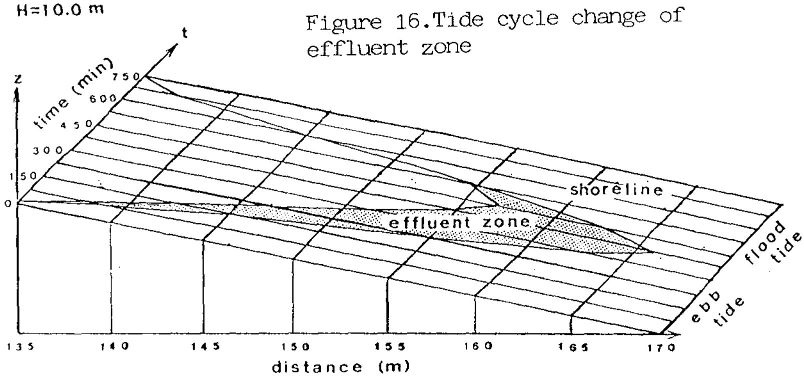
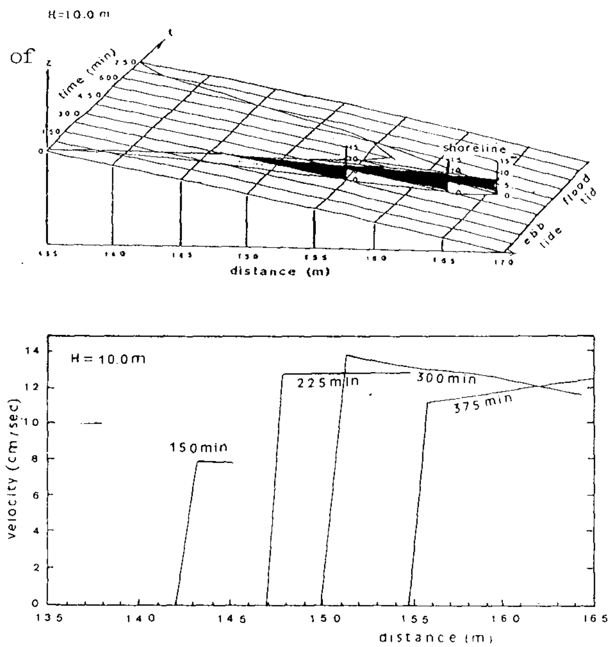


Figure 16.Tide cycle change of effluent zone

Figure 17.Change of thickness of surface flow and the velocity



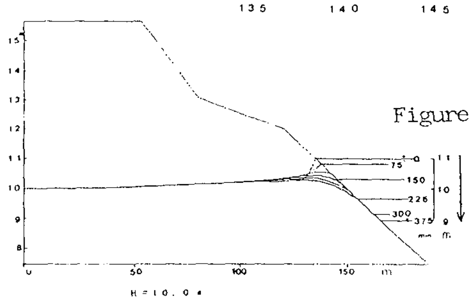


Figure 15. Numerical result of water table

shows that the erosion due to the surface flow will be enhanced as the mean level of landward water table becomes higher than sea level.

Experiments

In order to investigate two dimensional beach profile change due to waves under the situation where there is an inclined water table, some experimental studies were carried out. The main purpose of these experiments was to know the roles of waves acting on a tidal beach rather than to do model experiments of a special beach.

A wave channel of 13 m long, 0.4m wide and 0.4m deep was used (Figure 19). Three types of model beach with 1/10 slope were installed at the end of the channel. The grain sizes of the beaches were 0.2mm, 0.7mm and 0.7mm+0.2mm (2cm thick) respectively. The water level behind the beach model was adjusted to be +20cm, 10cm, 0cm, -10cm, -20cm higher than the sea level. Water lebels were measured by using 10 manometers which were connected with the bottom of the model beach through porous stones. Beach profiles were measured at 0.5, 1, 2, 4 and 8 hours after waves began to act. Final beach profiles for all runs are shown in Figure 20. Solid line and dashed line inside the beach denote water tables under the action of waves and without it respectively. We expected a little different beach profile changes for a different condition of water table even if the wave conditions were the same, considering the importance of the water table characteristics pointed out by Harrison (1969) as that no laboratory experiment on beach formation would adequetely model a natural beach unless provisions for simulation of them were included. Results did not show a remarkable difference of beach profile change due to the existance of the gradient of the watertable. Waves have a tendency to reduce the gradient of water table when the water level behind the beach is higher than the sea level, and this will weaken the efflux of the groundwater from the beach face. This is due to the effect of wave setup and infiltration of swash. When the water level behind the beach is lower than the sea level, the gradient becomes steeper and this will increase the subtraction of water from the backwash. However, these effects were too small to result in a remarkable difference of the beach profile change and waves acting on the beach concealed the effects as far as our experimental results were concerned.

Conclusion

Numerical model showed that tidal beachs could be considered to be erosive due to the flow formed on the beach surface whether or not the mean level of water table was higher than mean sea level without waves. When the mean level of water table is high, the effect will be intensified. However, when waves act on a beach, it is deduced from the experiments that waves act to conceale the effect on the whole. Therefore, moderate accretive waves are indispensable to preserve a beach in an equiliblium condition.

Judging from these results, the erosion of Surigahama and Iso beaches may be concluded to be caused by accumulative workings of surface flow. The surface flow is formed on the beach face by the efflux of underground water which washes the beach materials away, and small waves are insufficient for the recovery. Therefore, measures for beach erosion due to heavy wave attacks, some of which

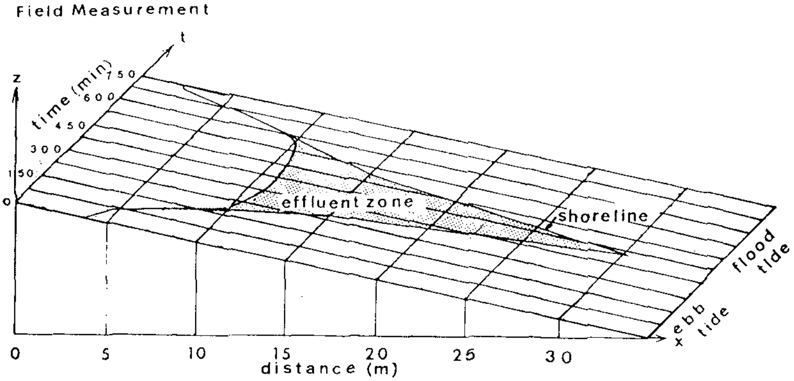
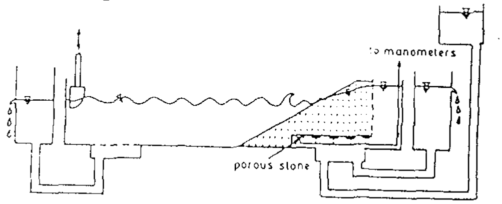


Figure 18. Measured tide cycle change of effluent zone

Figure 19. Experimental equipment



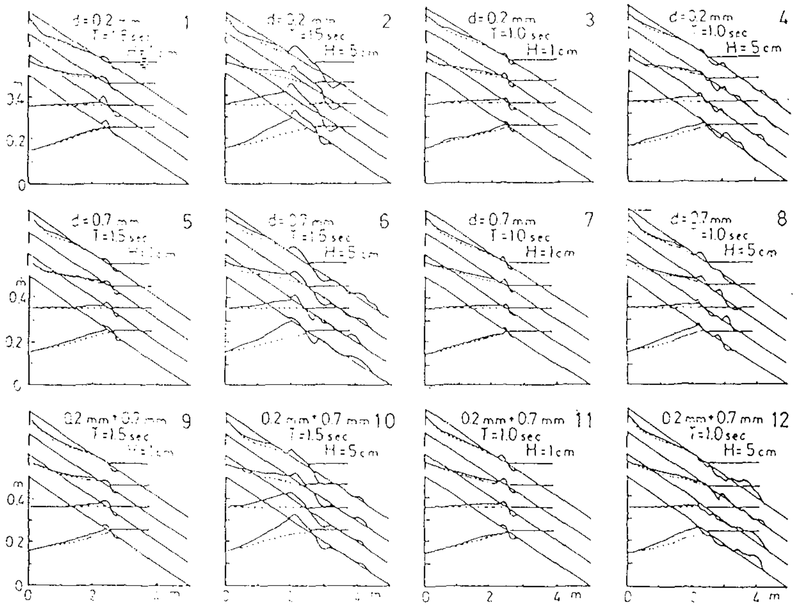


Figure 20. Experimental results of beach profile change

have been adopted at Surigahama beach, will not be effective for the cases considered.

Acknowledgements

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Appendix

Multiplying velocity component v_i ($i = 1, 2, 3$) and Reynolds equation for each component for incompressive steady flow and adding them, following expression is o btained.

$$v_i \frac{\partial E}{\partial x_j} = v_i \frac{\partial \tau_{ij}}{\partial x_j} \qquad (A1)$$

$$E = \frac{\rho}{2}\overline{q^2} + \rho\Omega + p, \quad \overline{q^2} = \sum_{i=1}^{3} v_i^2 \qquad (A2)$$

where τ_{ij} is Reynolds stress tensor, p is pressure and Ω is given by (see Figure 12)

$$\Omega = g(Z_0 + Z\cos\theta), \quad Z_0 = (x_0 - x)\sin\theta \qquad (A3)$$

Integrating equation (A1) from section I to section II, using Divergence Theorem and adopting conventional assumptions for slowly varied one dimensional flow, we obtain the following equation.

$$\int\int_S E v_n dS = -\int\int\int_V (-\rho\overline{u'v'})\frac{\partial u}{\partial z} dV \qquad (A4)$$

where S and V denote the surface area and the volume of the domain of the integration, respectively. Using w_b, left-hand side of this equation becomes

$$\int_0^{d_{II}} Eudz - \int_0^{d_I} Eudz - E_b w_b dx$$

On the other hand, using mean-value theorem for integral, right-hand side becomes

$$\left\{\int\int_A (-\rho\overline{u'v'})\frac{\partial u}{\partial z}dA\right\}_{x+\theta dx} dx, \quad (0 < \theta < 1)$$

where A denotes the area of the cross-section of the flow. Assuming that the depth is small compared with the width, we consider unit width of the flow. Substituting above expressions into equation (A4) and dividing it by dx, the following equation is obtained in the limit of $dx \to 0$.

$$\frac{d}{dx}\int_0^d Eudz = E_b w_b - \int_0^d (-\rho\overline{u'v'})\frac{\partial u}{\partial z}dz \tag{A5}$$

As $p = \rho g(d-z)\cos\theta, E_b w_b$ in the right-hand side becomes as follows

$$E_b w_b = \rho g(d\cos\theta + z_0)w_b$$

And left-hand side may be written as follows

$$\frac{d}{dx}\left\{\alpha\frac{\rho}{2}qv^2 + \rho g(d\cos\theta + z_0)\right\}$$

where

$$q = \int_0^d udz = vd, \quad \alpha = \frac{1}{qv^2}\int_0^d u^3 dz$$

Putting the head loss of the flow H_l as

$$\frac{dH_l}{dx} = \frac{1}{\rho g q}\int_0^d (-\rho\overline{u'v'})\frac{\partial u}{\partial z}dz = f'\frac{1}{d}\frac{v^2}{2g}$$

We obtain the following expression for equation (A5).

$$\frac{d}{dx}\left(\frac{\alpha v^2}{2g}\right) = \frac{Hw_b}{q} - f'\frac{1}{d}\frac{v^2}{2g} \tag{A6}$$

where $H = d\cos\theta + z_0$. From this equation, the following flow equation is obtained

$$\frac{dd}{dx} = \frac{\sin\theta - \dfrac{f'q^2}{2gd^3} + \dfrac{Hw_b}{q} - \dfrac{qw_b}{gd^2}}{\cos\theta - \dfrac{q^2}{gd^3}} \tag{A7}$$

When we put $\cos\theta \approx 1$ and $\sin\theta \approx \tan\theta \approx i$ and use $\frac{2g}{c^2}$ for friction factor f', we obtain equation (14).