ON-OFFSHORE SEDIMENT TRANSPORT RATE

IN THE SURF ZONE

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ABSTRACT

In this paper, models of the distribution of net on-offshore sedi-
ment transport based on two-dimensional equilibrium beach profiles and
an equation of continuity of sediment transport are proposed. Various
parameters of net on-offshore sediment transport in those models are
discussed. Furhter, the relative importance of bed load and suspended
load in the two-dimensional beach deformation are examined by measuring
both of them on model beach experiments.

1. Introduction
    A problem of fundamental importance to the mechanics of sediment
transport on beaches under wave and wave-induced current system is the
relative magnitude of the littoral sand drift and on-offshore sediment
transport. In the previous report (Sawaragi et al.,1978), the authors
have formulated the littoral sediemnt transport rate considering long-
shore current as a sediment transporting flow. However, as to on-off-
shore sediment transport rate, the authors could not evaluate quantita-
tively because of the complexity of mechanics of sediment transport.

    The purpose of this study is to examine the relation between on-
offshore sediment transport and the deformation process of two-dimen-
sional beach profile. The first half of this paper will be constructed
around a model of the distribution of net on-offshore sediment trans-
port rate based on experimental results about two-dimensional beach de-
formation which were conducted by many investigators. The final part
of this paper will examine a relative importance of suspended and bed
load in the two-dimensional beach deformation by measuring directly
suspended and bed loads in two-dimensional model beach experiments.

2. Model of the distribution of net on-offshore sediment transport rate
    along a beach profile
    As suggested by Tanaka et al.(1973) and Horikawa et al.(1974),
beach profiles which seem to reach a quasi-equilibrium condition can be
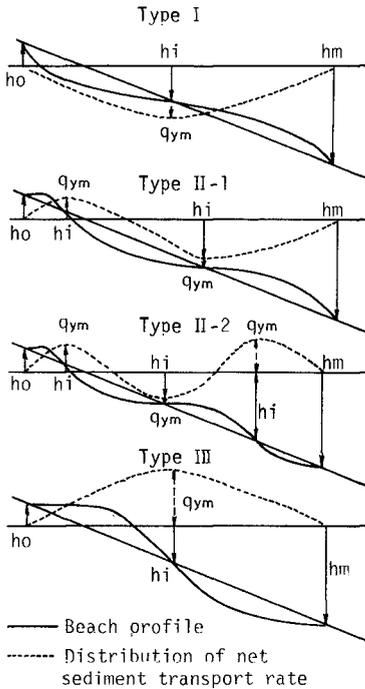classified into three types as shown in Fig.1. The distribution of net

Type I

Type II-1

Type II-2

Type III

——— Beach profile

┄┄┄ Distribution of net
      sediment transport rate

Fig.1 Model of the distribution
       of net on-offshore sedi-
       ment transport rate

on-offshore sediment transport,
which would have taken place in the
processes of those beach deforma-
tion, can be modelled as dotted lines
in Fig.1 from the equation of con-
tinuity of sediment transport.
In Type I (erosion type), the direc-
tion of net on-offshore sediment
transport is always toward offshore.
In Type III (accretion type), onshore
net sediment transport takes place
in the entire range of beach pro-
file. In Types II-1 and II-2, both on-
shore and offshore net sediment
transport spring up.

     The distribution of net on-
offshore sediment transport rate
can roughly determined by h_o, h_m, h_i
and q_{ym} shown in Fig.1 where,
h_o and h_m : the critical height and
depth of beach deformation, respec-
tively,
h_i : the depth of the point of in-
tersection of two beach profiles
measured in succession, ie, the depth
where the maximum net on-offshore
sediment transport takes place,
q_{ym} : the maximum net on-offshore
sediment transport rate, and h_o is
taken upward, while h_m and h_i are
taken downward from the still water
level.

     The authors rearrenged about
80 experimental results on the two-
dimensional beach deformation con-
ducted by many investigators and
evaluated h_o, h_m, h_i from the beach
profiles, and calculated q_{ym} from the change of beach configurations by
using the equation of continuity of sediment transport. In the follow-
ing sections, these four characteristic quantities are analyzed by
taking account of previous results obtained from the two-dimensional
model beach experiments.

3. Analysis of h_o, h_m, h_i and q_{ym} which determine the distribution of net
   on-offshore sediment transport rate.
     The four characteristic quantities will be expressed by the fluid
density ρ, fluid kinematic viscosity ν, density of sediment ρ_s, median
grain size d_{50}, wave height H, wave period T, beach slope i, gravity
accerelation g, friction velocity u_*, wave running time t_s, and so on.
Some important parameters such as the Shield's parameter

$u_*^2/(\rho s/\rho-1)gd_{50}$ and the surf similarity parameter $\xi=i/\sqrt{H_0/L_0}$ are already derived by combining above-cited variables to explane various phenomena in the surf zone. So far, however, there is no objective way to judge whether the beach profile reaches equilibrium or not. The authors, first, examine the time variations of h_0, h_m, h_i and q_{ym} to determine the wave running time for quasi-equilibrium beach profile.

3-1 Time-variations of the characteristic variables

Time-variations of h_0, h_m, h_i and q_{ym} of typical 2 cases in TypeI and TypeIII are shown in Figs.2 and 3, respectively. In the figures, q_{ym} are calculated from differences of the water depth Δh, measured in succession with time interval Δt, by using the equation of continuity of the sediment transport. Therefore, they are given as average values taken over the time interval Δt. From Figs.2 and 3, the following results can be pointed out.
1) Net offshore sediment transport does not readily decrease even after a fairly long running time as seen in Fig.2. While, onshore net sediment transport decays soon, as seen in Fig.3.
2) In accordance with 1), h_0 and h_m in TypeI and h_m in TypeII-1 increase after a large number of waves propagated. On the other hand, h_0 and h_m
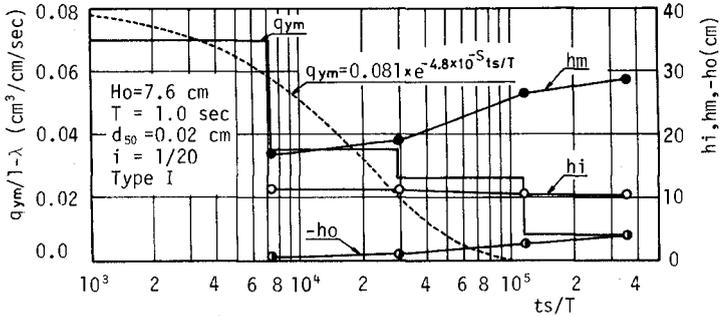

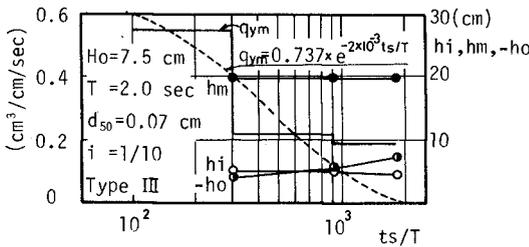Fig.2 Time-variations of characteristic quantities of TypeI

Fig.3 Time-variations of characteristic quantities of TypeIII

in TypeIII and TypeII-2 almost remain constant or increase a little with increasing the running time.
3) h_i does not indicate significant changes with time.

Taking these results into account, beach profiles after 7.2×10^4 waves propagated were picked up to analyze h_o, h_m and h_i. In the case where the beach profile at this running time was not measured, we estimated those quantities by interpolating from the time-variations of them. The data, whose running time were less than $7.2 \times 10^4 T$, were omitted. However, experimental results of Saville(1957) who employed waves almost corresponding the full scale waves and Rector(1954) which have been quoted by many investigators were analyzed for reference, although they did not satisfy this limitation of running time.

On the other hand, we can assume the time-variations of q_{ym} expressed as Eq.(1) to clearly grasp the rate of decay of q_{ym} with running time.
$$q_{ym} = q_{ymo} \exp(-At_s/T) \tag{1}$$
where q_{ymo} is the initial value of q_{ym} and A is a constant. Here, q_{ymo} and A are calculated by the following procedure:
1) Select the data whose running times are more than $7.2 \times 10^4 T$ in which beach profiles were measured at least 3 times.
2) Let $t_s = 0, t_{s1}, t_{s2}, \cdots$ be the times when the beach profile was measured and $q_{ym1}, q_{ym2}, \cdots$ be the maximum onshore net sediment transport rate in the time interval $\Delta t_1 = t_{s1}, \Delta t_2 = t_{s2} - t_{s1} \cdots$.
3) Calculate q_{ymo} and A by substituting $q_{ym} = q_{ym1}$ at $t_s = t_{s1}/2$ and $q_{ym} = q_{ym2}$ at $t_s = (t_{s1} + t_{s2})/2$.
In Figs.2 and 3, Eq.(1) determined by the above-mentioned procedure are also shown by dotted curves. As can be seen from these figures, it is found that the time-variation of q_{ym} can be expressed fairly well by Eq.(1) and at $t_s/T = 7.2 \times 10^4$, the maximum onshore net sediment transport rate q_{ym} in TypesIII and II-2 almost dimnish and the maximum offshore net sediment transport rate of Types$\text{I}$ and II-1 become less than 25% of their initial value q_{ymo}.

3-2 Analysis of h_o
    h_o will be determined by factors which controll a wave run-up height and a change of shore line. The wave run-up height is said to be closely related to the surf similarity parameter ξ (Battjes,1974). While, the change of shore line should be considered as one part of the whole beach deformation rather than related to local parameters near the shore line. Hence, the authors use the non-dimensional force, $N_s = H_o/T \sqrt{(\rho_s/\rho - 1)g d_{50}}$ as the parameter to indicate the magnitude of the ability of the beach to deform. The derivation of N_s will be mentioned latter. Fig.4 shows the relation between h_i/H_o and ξ with N_s as a parameter. From this figure, it is found that h_i/H_o increases with increasung ξ and that for the same value of ξ, h_i/H_o also increases with increasing N_s.

3-3 Analysis of h_m
    In the initial stage of the beach deformation, h_m can not be deeper than the critical depth for an initial sediment movement. Generally,
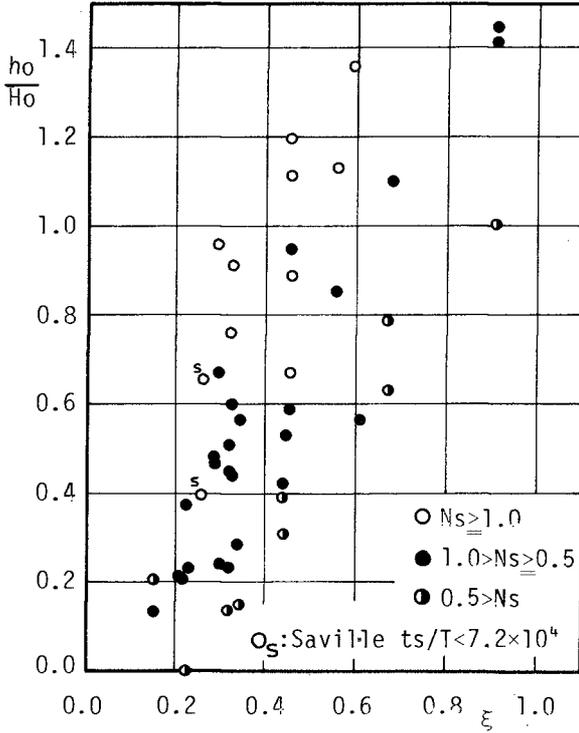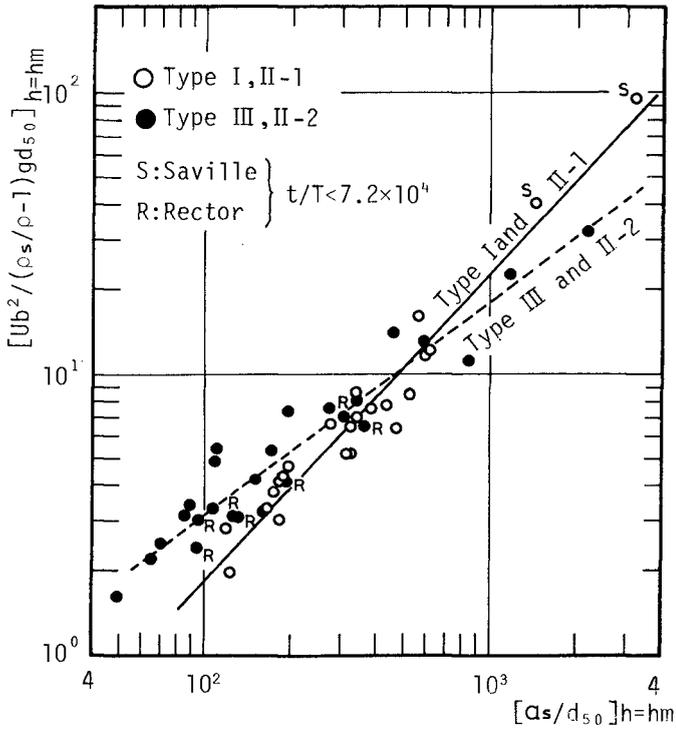
Fig.4   Relation between ho/Ho and ξ

Fig.5   Relation between $Ub^2/(\rho_s/\rho -1)gd_{50}$
and a_6/d_{50} at $h=hm$

the critical depth for the sediment movement is determined from the
balance between the forces acting on a grain and the resistance force
of the grain which can be given as follow:

$$(\pi/6)gd_{50}(\rho_s-\rho)\tan\phi = K(\pi/4)d_{50}^2\rho fu_b^2 \tag{2}$$

where $\tan\phi$ is the friction angle of the sediment, f the friction factor,
u_b the maximum water particle velocity at the bottom, and K the coeffi-
cient. f is usually expressed by $u_b\delta/\nu$ or $u_b^2 T/\nu$ in a laminor region and
a_δ/z_o in a turbulent region where $\delta=(\nu T/2\pi)^{1/2}$, $a_\delta=Tu_b/\pi$ and z_o the equiv-
alent roughness height. However, the effect of Reynold's number on the
initial movement of sediment seems to be small compared with a_δ/z_o (
Dingler,1975). Hence, Eq.(2) can be given as follow:

$$u_b^2/(\rho_s/\rho-1)gd_{50}\propto 1/f\propto F(a_\delta/z_o) \tag{3}$$

Assuming that the same relation as Eq.(3) holds with h_m , the authors
calculated $u_b^2/(\rho_s/\rho-1)gd_{50}$ and a_δ/z_o at $h=h_m$ by using the linear wave
theory. The results are shown in Fig.5. In this calculation, z_o is taken
equal to d_{50} in order to take account of only the skin friction regard-
less of the bottom configuration according to Madsen(1976). As seen from
Fig.5, the relation between $u_b^2/(\rho_s/\rho-1)gd_{50}$ and a_δ/d_{50} at $h=h_m$ can be
approximated fairly well by the following equations:

$$u_b^2/(\rho_s/\rho-1)gd_{50} = B(a_\delta/d_{50})^n \tag{4}$$

in which,

$$\begin{array}{llll} B = 0.18 & n = 1.1 & \text{for TypeI and TypeII-1} \\ B = 0.10 & n = 0.75 & \text{for TypeIII nad TypeII-2} \end{array} \tag{5}$$

By using the linear wave theory and $N_s=H_o/T/\sqrt{(\rho_s/\rho-1)gd_{50}}$, Eq.(4) can be
modified as Eqs.(6) and (7).

$$\{(H/H_o)(1/\sinh kh_m)\}^{-1} = CN_s(d_{50}/L_o)^m \tag{6}$$

$$\begin{array}{llll} C = 400 & m = 0.6 & \text{for TypeI and TypeII-1} \\ C = 20 & m = 0.3 & \text{for TypeIII and TypeII-2} \end{array} \tag{7}$$

The left hand side of Eq.(6) is the function of h_m/L only. And if N_s
and d_{50}/L_o are given, h_m/L can be calculated from Eqs.(6) and (7).
Fig.6 shows the comparison of h_m calculated from Eq.(6) with h_m meas-
ured from the beach profile. From this figure, it is found that Eq.(6)
together with Eq.(7) give a sufficiently accurate estimate of h_m.

3-4 Analysis of h_i

   h_i is defined as the depth where the maximum on-offshore sediment
transport takes place. The limit depth of "D-profile" proposed by
Swart(1970), "cut-depth" defined by Hallermeier(1977) seem to corres-
pond to h_i of TypesI and II-1. "Stable point" proposed by Raman et al.
(1972) may also be equivalent to h_i . Although the concept of "D-profile"
or "cut-depth" can be applied only to the beach of TypesI and II-1, h_i
as defined above, can be applied extencively to all types of beach
profiles.

   In the consideration of h_i , it is necessary to take into account
the difference of the mode of sediment transport between TypeI and
TypeIII. The causes of net on-offshore sediment transport have been
studied for long time and may be summarized as follows:
1) stational flow such as mass transport current due to waves.
2) asymmetry of water surface profile,ie,asymmetry of the time-vari-

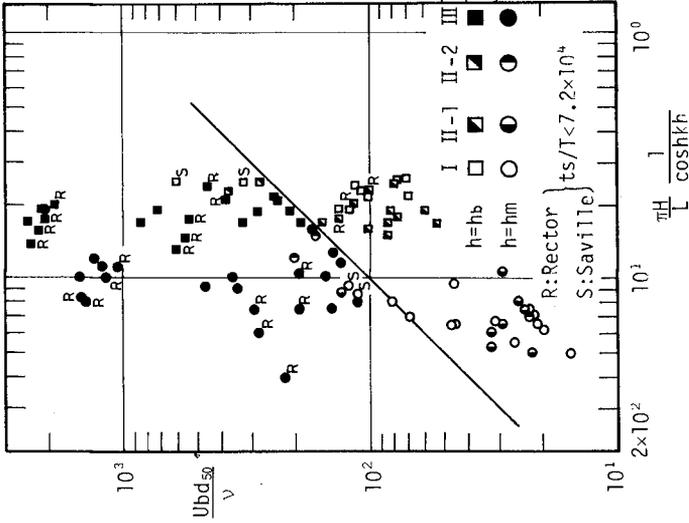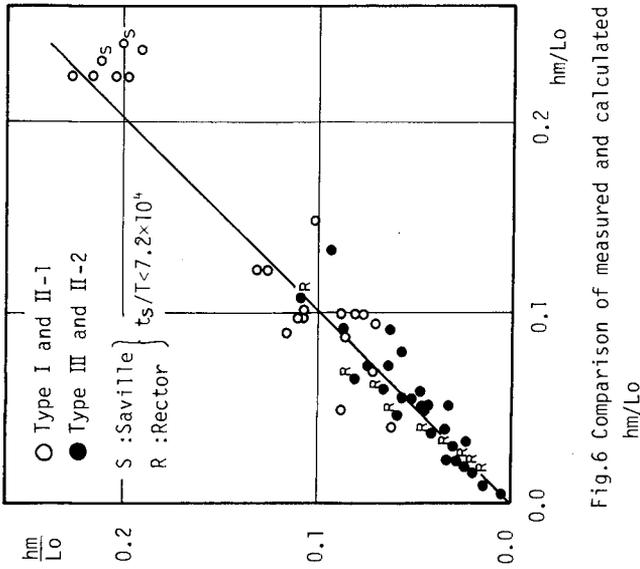Fig.7 Relation between $U b d_{50}/\nu$ and $(\pi H/L)(1/\cosh kh)$ at $h=h_b$ and $h=h_m$

Fig.6 Comparison of measured and calculated

ation of water-particle velocity.
3) effect of gravity,ie,the existance of beach slope.
4) distorted profile of time-variation of the concentration of suspended
sediment due to asymmetrical sand ripple or breaking waves.
Referring from theoretical and experimental results by Sato et al. (1962),
Inman et al.(1963), Horikawa et al.(1974) and Bowen(1979), the necessary
condition for the occurrence of net offshore sediment transport seems to
be the existance of sufficient amount of suspended sediment, and net on-
shore sediment transport is mainly caused by bed load.

However, in the surf zone, although the asymmetrical property of
time-variations of water-particle velocity increases, ripples usually
disappear and the existance of the steady flow becomes dubious because
of large turbulence brought by breaking waves. Hence, so far, the authors
can not explain the reason why net onshore sediment transport can take
place in the entire beach profile of Type III and net offshore sediment
transport happens in the whole beach of Type I. Then, to begin with, the
authors examine the direction of net on-offshore sediment transport in
the offshore regions of three types of beach profiles by using two pa-
rameters proposed by Sato et al.(1962). They give the criteria for the
occurrence of net on-offshore sediment transport on a horizontal bed by
a function of sediment Reynold's number $u_b d_{50}/\nu$ and the amplitude of non-
dimensional pressure gradient at the bottom by waves $(-1/\rho g)(\partial p/\partial x) =$
$(H/L)(\pi/\cosh kh)$. They also found that asymmetrical ripples caused net
offshore sediment transport by using radio active tracers. Although
$u_b d_{50}/\nu$ is a non-dimensional parameter, it expresses a magnitude of drag
force acting on a grain in a fluid and $(-1/\rho g)(\partial p/\partial x)$ indicates the re-
lative magnitude of the accerelation of water-particle to that of the
gravity. Fig.7 shows the relation between $u_b d_{50}/\nu$ and $(H/L)(\pi/\cosh kh)$
at $h=h_b$, calculated from the new-breaker-index presented by Goda(1970),
and $h=h_m$. Again, u_b and L were calculated by the small amplitude theory.
Taking into account the direction of net on-offshore sediment transport
of Type I and Type III, the direction of net on-offshore sediment trans-
port can be distinguished by Eq.(8)

$$u_b d_{50}/\nu \begin{array}{c} < \\ > \end{array} (H/L)(\pi/\cosh kh) \times 10^3 \quad \begin{array}{l} \cdots \quad \text{offshore} \\ \cdots \quad \text{onshore} \end{array} \qquad (8)$$

Taking the ratio of $u_b d_{50}/\nu$ to $(H/L)(\pi/\cosh kh)$ and let the ratio be N_{sr},
the criteria of Eq.(8) can be written in a simple form,

$$N_{sr} = (u_b d_{50}/\nu)/\{(H/L)(\pi/\cosh kh)\} = gTd_{50}/2\pi\nu$$

$$N_{sr} \begin{array}{c} < \\ > \end{array} 10^3 \quad \begin{array}{l} \cdots \quad \text{offshore} \\ \cdots \quad \text{onshore} \end{array} \qquad (9)$$

However, as can be seen from Fig.7, two data of Saville(1957) can not
be classified by Eq.(8). He employed large waves as in the field and
H_0/L_0 of his experiments were larger than other cases. Therefore, to
apply Eq.(8) or Eq.(9) to the large scale model beach as the field,
some modifications including the effect of wave height itself or H_0/L_0
explicitly seems to be required.

The direction of net sediment transport in Types II-1 and II-2 are
also shown in Fig.7, and they are classified by Eq.(9). This means that
the change of the direction of net on-offshore sediment transport in

in these two types will occure in the surf zone.

    As discussed above, the direction of net sediment transport in the
offshore region can be determined by N_{sr}. On the other hand, h_i seems to
be closely related to wave breaking as the first order action of fluid
motion. So, the authors examine the relative depth of h_i to h_b ,h_i/h_b
of three types of beach profiles. Fig.8 shows the relation between h_i/h_b
and N_{sr}. It can be seen from this figure that for the offshore net sedi-
ment transport of Types I and II-1, h_i/h_b ranges between $1.0 < h_i/h_b < 1.5$,
for the onshore net sediment transport of Type III, $0.3 < h_i/h_b < 0.9$ and for
the onshore net sediment transport of Type II-1, $-0.4 < h_i/h_b < 0.0$. This in-
dicates that a longshore bar in a storm beach (Type I or Type II-1) has to
be generated in the offshore region. For the beach of Type II-2, no sig-
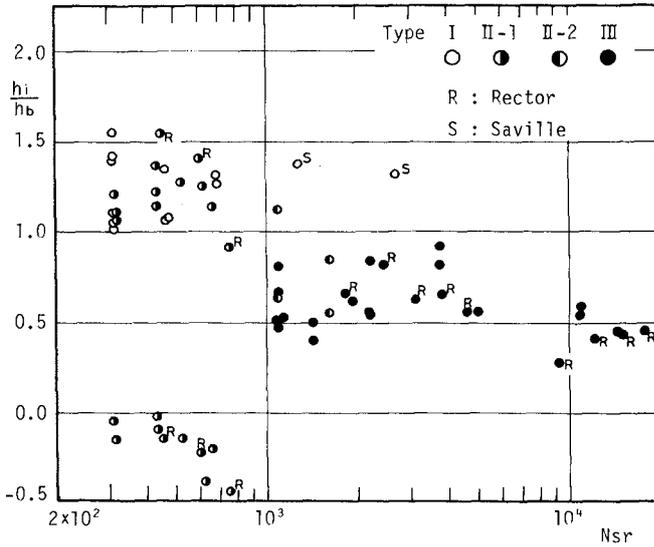nificant tendency can be found out for the deficiency of the data.

Fig.8 Relation between h_i/h_b and N_{sr}

    Because h_i of Types I and II-1 appears outside the surf zone, the
procedure proposed by Hallermeier(1977) seems to be effective. Hence,
the authors compared h_s calculated according to Hallermeier with h_i
measured from the beach profile of Types I and II-1. As a result, the
correlation between h_i and h_s is relatively high for small scale experi-
ments, however, h_s seems to give smaller values of h_i for large-scale
experiments. On the other hand, within the breaker zone, wave character-
istics and wave-induced flow pattern are controlled by H_o/L_o and i

(Nakamura et al.,1966). Hence, h_i for onshore net sediment transport
of Type III may also be controlled by H_0/L_0 and   . The authors also dis-
cussed the relation between h_i of Type III and those two parameters. It is
found that h_i/h_b have a tendency to decrease with decreasing H_0/L_0,
however, i seems to have little influence on h_i/h_b.

3-5 Analysis of q_{ym}

Referring Madsen's presentation(1976), the time averaged rate of
on-offshore sediment transport by bed load $\bar{q}_y$,ie, the amount of sedi-
ment which have a capacity to be transported as net on-offshore sedi-
ment transport, can be expressed as follow: •

$$\bar{q}_y/w_0 d_{50} = D(u_*^2/(\rho_s/\rho-1)gd_{50})^n \qquad (10)$$

where D is a coefficient, w_0 the settling velocity of sediment and
$n=3$. Assuming that the same kind of relation as Eq.(10) can be applied
to suspended load and that the direction and the rate of net sediment
movement can be expressed by N_{sr},H_0/L_0 and i, net on-offshore sediment
transport rate q_y will be given as a first order approximation by

$$q_y/w_0 d_{50} \propto q \; F_1(N_{sr},H_0/L_0,i)\cdot F_2(t_s/T)$$
$$=D(u_*^2/(\rho_s/\rho-1)gd_{50})^n\cdot F_1(N_{sr},H_0/L_0,i)\cdot F_2(t_s/T) \qquad (11)$$

Further, it seems resonable to assume the turbulent flow condition
near $h=h_i$ and consequently a constant friction factor. Then, for Types-
I and II-1,u_* at $h=h_i$($>h_b$) can be replaced by $(H_0/T)(H/H_0\sinh kh)_{h=h_i} =$
$(H_0/T)F_3(h_i/L_0)$, and h_i/L_0 is also expressed by H_0/L_0 according to
Hallermeier(1977). Hence, the maximum net sediment transport q becomes

$$q_{ym}/w_0 d_{50} = q_{ymo}\exp(-At_s/T)$$
$$= E(H_0/T/\sqrt{(\rho_s/\rho-1)gd_{50}})^{2n} F(N_{sr},H_0/L_0,i)\exp(-At_s/T) \quad (12)$$

where $N_s=H_0/T/\sqrt{(\rho_s/\rho-1)gd_{50}}$ and E is the coefficient of proportionality.
N_s was already used to analyze h_0 and h_m. The authors ferther consider
that Eq.(12) can be applied to Types III and II-2.

Fig.9 shows the relation between A in Eq.(12) and N_s. It can be
seen that A is closely related to N_s and the direction of net on-off-
shore sediment transport. Namely, the larger, the N_s, the faster net
sediment transport decays. And onshore net sediment transport decreases
faster than offshore sediment transport.

Finally, Fig.10 shows the relation between non-dimensional net on-
offshore sediment transport rate q_{ymo}^* and N_s. Here,q_{ymo}^* is derived by
taking four parameters in Eq.(12) into account as follow:

$$q_{ymo}^* = (q_{ymo}/w_0 d_{50})^{2n}(1/\lambda)(1/N_{sr})(H_0/L_0) \qquad (13)$$

where λ is the porosity of sand. From Fig.10, it is concluded that q_{ymo}^*
is proportional to N_{sr} regardless of the direction of net on-offshore
sediment transport. And the exponent n in Eq.(10) is 3. The result
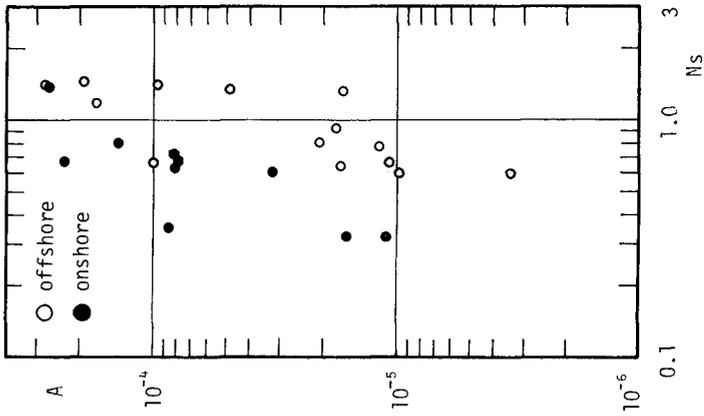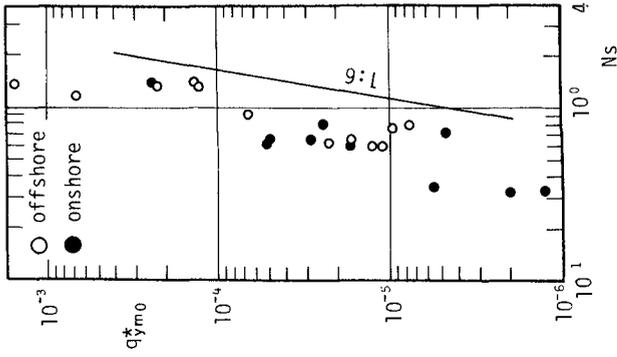corresponds to that obtained by Madsen et al.(1976).

Fig.10 Relation between q_{ymo}^* and Ns

Fig.9 Relation between A and Ns

4. Experiments to measure on-offshore sediment transport rate in the
   two-dimensional model beach
      Since net on-offshore sediment transport discussed above includes
both bed and suspended loads, the relative magnitude of bed load and
suspended load can not be examined. In this section, based on the exper-
imental results, relative importance of bed load and suspended load in
the deformation of two-dimensional model beach is discussed.

4-1 Equation of continuity of the sediment transport including suspended
sediment
      Consider the co-ordinate system taken X-axis horizontal to the
shore line, positive y-axis shoreward, positive z-axis vertically upward
from the stillwater level. The diffusion equation for any arbitrary
volume is

$$\partial C / \partial t = -\nabla (C \vec{v_s})$$ (14)

where C is the sediment concentration, $\vec{v_s}$ the sediment-particle velocity
vector. After taking time average and integrating Eq.(14) from $z=-h$(
bottom) to $z=\eta$ (free surface), the equation of continuity can be ob-
tained as follow:

$$\frac{\partial}{\partial t} (\int_{-h}^{\eta} C \, dz + (1-\lambda)h) + \frac{\partial}{\partial x} \int_{-h}^{\eta} q_x dz + \frac{\partial}{\partial y} \int_{-h}^{\eta} q_y dz = 0 \, ,$$ (15)

where $(q_x, q_y) = (u_s C, v_s C)$, $\vec{v_s} = (u_s, v_s, w_s)$, $(1-\lambda)\partial h/\partial t = [w_s C]_{z=-h}$

In the previous section, the authors consider Eq.(11) as a first order
approximation of $q_y = v_s C$. In Eq.(15), $z=-h$ corresponds to bed load and
$z>-h$ to suspended load, respectively.

      Based on these consideration, the authors examine the relative
importance of bed load and suspended load by measuring directly bed load
and suspended load in model beach experiments.

4-2 Experimental procedure
      Two wave tanks of different dimension were used. One is 26m long,
1.5m wide and 1.8m high, and other one is 51m long, 0.64m wide and 0.97m
high. Two kinds of beach materials, ie, $d_{50} = 0.54mm$ $\rho_s = 2.65gr/cm^3$ and $d_{50} =$
0.34mm, $\rho_s = 2.68gr/cm^3$ were used to form a model beach of 1/20 initial
beach slope. The bed load was measured by a sand trap consisted of an
outer casing and inner box made of a tin plate. The inner box has two
compartments to separately measure the amount of onshore and offshore
sediment transport rate. The dimension of this inner box is 10cm in
width, 10cm in length and 5cm in depth. While the beach profile was de-
veloped, the inner box was not instolled and the outer casing was burried
into the bottom sand bed. Just before the measurement was conducted, the
outer casing was pulled up to the bottom surface and sands in it were
taken out to replace them with the inner box. Bed load was measured at
10 different locations covering from swash zone to the offshore zone, and
the measured time was from 2 to 6min.. The average sediment transport
rate q_{bt} and net sediment transport rate q_{bnet} were calculated from the sum
and the difference of the amounts of sediment trapped in both shoreward
and seaward compartments respectively in the unit of (dry weight/cm/sec).
The suspended load was measured by collecting the water samlpes through
siphons with intake nozzles as shown in Fig.11. the reasons why' such a

primitive apparatus was used are as follows:
1) by the optical method, the direction of suspended load can not be dis-
tinguished,
2) small babbles brought into water by breaking waves decrease the ac-
curacy of the measurement by optical method,
3) direct measurement of the amounts of sediments is possible by col-
lecting the sediment larden water samples by siphons.

Fig.11 Sketch of the intake
nozzles of siphon

    The measurements of suspended sediment were done orienting the in-
take nozzle both toward onshore and offshore directions at each mea-
suring point setting the lower part of the nozzle above 1mm from the
bottom. Samples of 4points distributed vertically at each measuring
point were collected. Sampling time was from 40 to 80sec., and 200~400
cc was gathered. The concentration of suspended sediment C and net on-
offshore sediment transport rate q_{snet} are calculated from the following
procedure. Let S_{ion} and S_{ion} be weights of samples and dry net weights of
sediments included in S_{ion} which was collected by orienting the intake
nozzle offshore at $z=z_i$; height of the ith intake nozzle and S_{ioff} and
S_{ioff} be the amounts of those collected by orienting the intake nozzle
onshore. The authors calculated C at $z=z_i$ from

$$C(z_i) = (S_{ion} + S_{ioff})/(S_{ion} + S_{ioff}) \text{ (dry weight/weight)}.$$

While net on-offshore sediment transport by suspension, q_{snet} was calcu-
lated from

$$q_{snet} = (1/T_s)[((S_{1on} - S_{1off})/a_1)((z_2 + z_1)/2) + ((S_{2on} - S_{2off})/a_2)((z_3 - z_1)$$

$$/2) + ((S_{3on} - S_{3off})/a_3)((z_4 - z_2)/2) + ((S_{4on} - S_{4off})/a_4)(h - (z_4 + z_3)$$

$$/2)] \text{ (dry weight/cm/sec)}$$

in which T_s is the sampling time and a_i is the area of ith intake nozzle.
These method to separately measure the amount of onshore and offshore
sediment transport by suspension is fundamentally based on the time-

variation of the velocity of fluid sucked through the intake nozzle
which is calculated from the generalized Bernoulli's theorem; pressure
equation. A head difference between the intake nozzle and the outlet
was adjusted to coincide the intake velocity with the maximum water-
particle velocity in both direction of offshore and onshore. However,
when the orientation of intake nozzles directed onshore or offshore, a
few sediments which were moving in the direction of offshore or onshore,
seemed to be sucked. Consequently, the measured concentration might be
little larger than the true concentration. Besides, due to an accuracy
of weighing dry sands in the sample, the accuracy of concentration mea-
sured by this method decreases when C is less than 10^4ppm.

     The authors confirmed the reliabirity of the siphon by comparing
the concentrations measured by the siphon with those of ductivity meter
using an optical method.

4-3 Experimental results
     6 experiments were conducted.
Their detailed conditions are shown in
Table-1. In three cases of N_{sr} =636,
suspended load will be expected to
dominate and in the other three cases
of N_{sr} >1200, bed load will be predom-
inate.

Table-1 Experimental conditions

H cm	T sec	d_{50} mm	$\rho s/\rho$	N_{sr}
17.8	1.2	0.34	2.68	636
7.3	1.2	0.34	2.68	636
3.8	1.2	0.34	2.68	636
33.1	1.7	0.54	2.65	1431
12.4	1.7	0.54	2.65	1431
5.4	1.5	0.54	2.65	1263

i) Time-averaged on-offshore sediment transport by bed load q_{bt} and sus-
pended load q_{st}
     First, let's investigate the diffrence of the relative magnitude
of q_{bt} and q_{st} between two beaches of different N_{sr}. Fig.12(a) and (b)
show two examples of the distributions of q_{bt} and q_{st}. When N_{sr} =636,as
shown in Fig.12(a), time-averaged suspended load q_{st} clearly surpasses
bed load q_{bt} in amount. The ratio of the maximum time-averaged sediment
transport rate q_{st}/q_{bt} is about 2.0. While in the case of N_{sr} =1263,
as shown in Fig.12(b), suspended load is less than bed load and the
ratio of the maximum transport rate q_{st}/q_{bt} is 0.5.

     The authors also measured a bottom shear stress on a fixed flat
bed by a shear meter. Details of the shear meter are discribed in the
previous paper(Sawaragi et al.,1978). From Fig.12 and the results of the
measured shear stress, it was found that q_{st} was larger than q_{bt} in the
region of u_*/w_0 >0.8, and q_{bt} became larger than q_{st} when u_*/w_0 <0.8.
However, u_* measured on a fixed bed, does not include the effect of the
bottom roughness. So, in order to determine the strict criterion for the
initiation of sediment suspension, it is necessary to clarify the sedi-
ment movements on the bottom which are closely related to the water-
particle motion near the bottom.
ii) Relative importance of suspended load versus bed load to the beach
deformation
     Finally, the authors examine the realtive importance of suspended
load versus bed load to the beach deformation by investigating the re-
lations among net sediment transport rate q_{ynet} calculated from the
time-variations of beach profiles , measured net on-offshore sediment
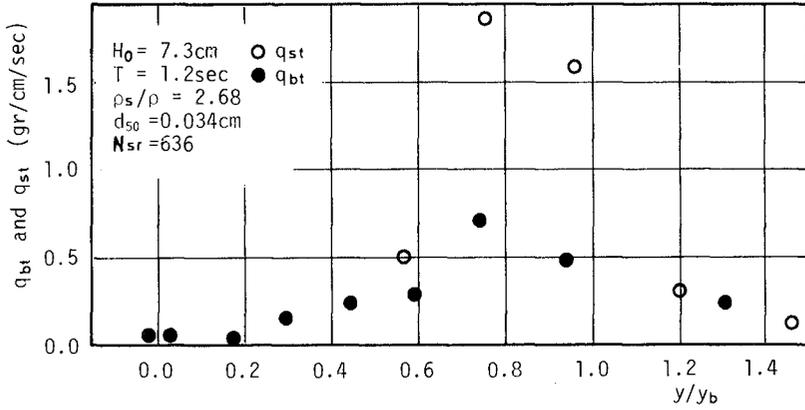transport rate by suspension q_{snet} and bed load q_{bnet}.

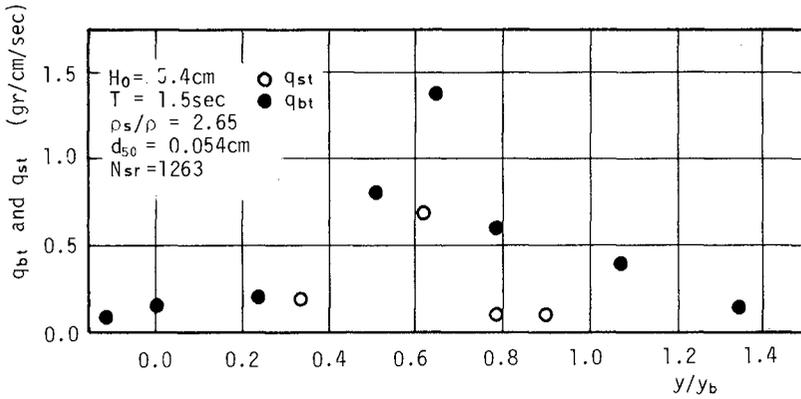Fig.12(a) Distributions of q_{st} and q_{bt}
(N_{sr} = 636)

Fig.12(b) Distributions of q_{st} and q_{bt}
(N_{sr} = 1263)

Fig.13 shows one example of the distribution of q_{ynet}, q_{bnet} and q_{snet} together with the beach profile of $Nsr = 636$. q_{bnet} and q_{snet} were measured in a relatively short time compared with running time $t_s/T = 1.5 \times 10^3$, in which the beach profile in Fig.13 was developed. So, they might change with running time. q_{ynet} is given as an average over $t_s/T = 0 \sim 1.5 \times 10^3$. In Fig.13, the distribution of q_{bnet} is similar to that of q_{ynet}, and q_{snet} has a sharp peak at $y/y_b = 0.75$ which corresponds to the location of the bar. To examine the relative importance of q_{bnet} and q_{snet} in the beach deformation, the authors calculated the change of water depth caused by q_{bnet} and q_{snet} by using the equation of continuity of sediment transport without considering the effect of time-change of concentration of suspended sediment indicated by the first term in Eq.(15). The result is shown in Fig.14. In this figure, Δh shown by solid line is calculated from the difference of beach profiles between $t_s/T = 0$ and $t_s/T = 1.5 \times 10^3$, Δh_b, shown by heavy line, is calculated from q_{bnet} and represents the changes of mean water depth between two neighbering measuring points and Δh_s, shown by broken line is calculated from q_{snet} as well as Δh_b. As can be seen from this figure, the bar near $y/y_b = 0.75$, the typical beach profile of this case, seems to be created not only by bed load but also by suspended load. However, Δh_s gives fairly large beach deformation compared with Δh in this region. According to Eq.(15), this difference between measured and calculated water depths have to be compenciated by the increase of concentration of suspended sediment. On the other hand, the measured concentration increased about $6 ppt$ at $y/y_b = 0.75$ during $t_s/T = 1.5 \times 10^3$. This increment of concentration only accounts for few milimeter of erosion near $y/y_b = 0.75$. This indicates that, even in the case where suspended load dominates bed load, the first term of Eq.(15) becomes less than 1/10 of other terms.

Fig.15 shows the relation between q_{ynet}, q_{bnet} and q_{snet} in the case of $Nsr = 1263$. In this case, q_{bnet} is in the direction of onshore through the entire range of the beach profile and the distribution of q_{bnet} almost coincides with q_{ynet}. While the direction of q_{snet} is mainly offshore and its magnitude is less than 1/2 of q_{bnet}. Fig.16 shows the relation between Δh, Δh_b and Δh_s. Same notations and symbols as in Fig.14 are used. From this figure, it can be found that the fundamental mode of the beach deformation of Type III with deposition in the shallower region and erosion in the deeper region as shown in Fig.1 is mainly created by q_{bnet}. However, q_{snet} also seems to contribute to the beach deformation of secondary mode in addition to the fundamental mode.
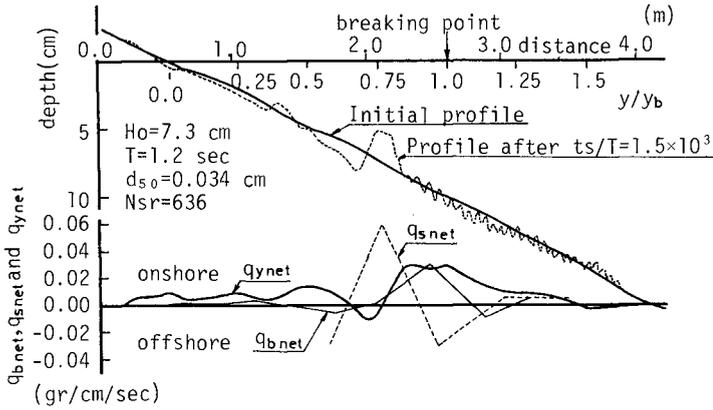
Fig.13 Beach profile and distributions of calculated and measured net on-offshore sediment transport rates (Nsr =636)
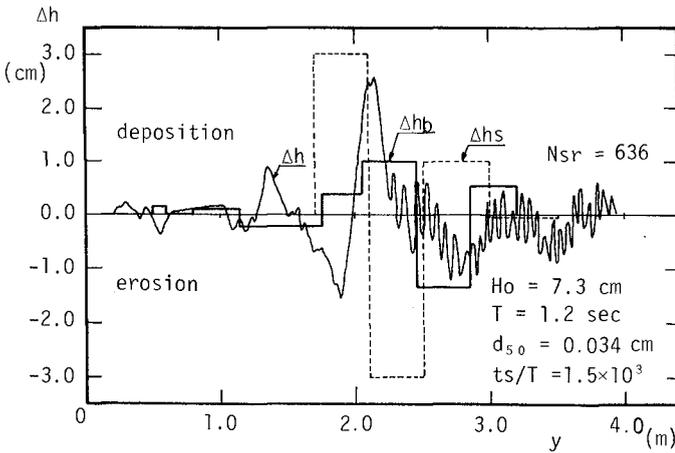
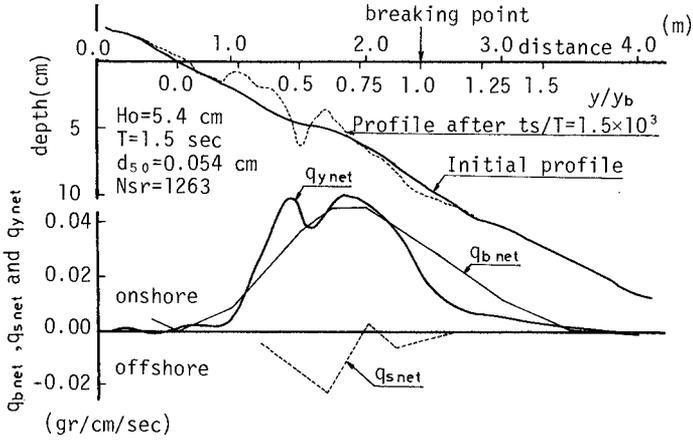Fig.14 Comparison among Δh, Δhb and Δhi (Nsr =636)

Fig.15 Beach profile and distributions of calculated and measured net on-offshore sediment transport rates (Nsr =1263)

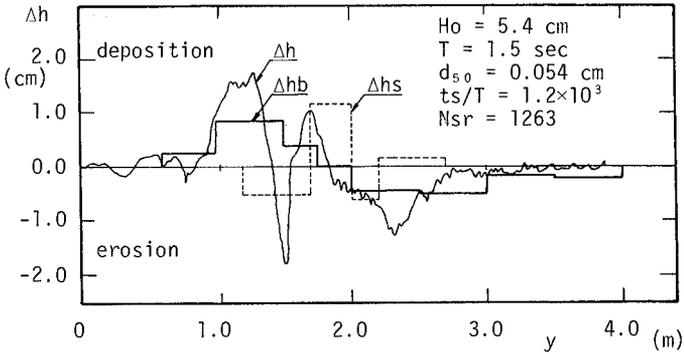Fig.16 Comparison among Δh, Δhb and Δhi (Nsr =1263)

5. Conclusions

The authors analyzed experimental results about the two-dimensional beach deformation conducted by many investigators to propose the models of net on-offshore sediment transport rate and carried out two-dimensional model beach experiments to examine the relative importance of bed load and suspended load in the beach deformation. Following results are obtained.

1) When $N_{sr} = gTd_{50}/2\pi\nu > 10^3$, the direction of net sediment transport is onshore(TypeⅢ) and when $N_{sr} < 10^3$, net offshore sediment transport is apt to take place(TypeI). However, even when $N_{sr} < 10^3$, net onshore sediment transport may spring up near the shore line.

2) Net onshore sediment transport decays faster than that of offshore sediment transport. And when $N_s = H_o/T/\sqrt{(\rho_s/\rho-1)gd_{50}}$ becomes large, net on-offshore sediment transport decays fast regardless of their direction.

3) The non-dimensional height of upper limit of beach deformation h_o/H_o increases with increasing $\xi = i/\sqrt{H_o/L_o}$ and N_s. And the non-dimensional depth of lower limit of beach deformation h_m/L_o can be expressed by Eq.(6).

4) The maximum net offshore sediment transport takes place in the offshore region and the maximum onshore sediment transport takes place in the surf and swash zones. Time-variation of the maximum sediment transport rate can be approximated by Eq.(1). And its maximum can be expressed by Eqs.(12) and (13).

5) When $N_{sr} > 1200$, time-averaged bed load surpasses time-averaged suspended load, and main beach deformation seems to be created by bed load.

6) When $N_{sr} < 640$, time-averaged suspended load surpasses time-averaged bed load, and beach deformation seems to be caused by both bed load and suspended load.

7) Suspended load becomes equivalent in amount to bed load when $u_*/w_0 = 0.8$.

References

Battjes,J.A., Surf Similarity, Proc. 14th International Conf. Coastal
    Engg. pp 466–480, 1974.
Bowen,A.J., Simple Models of Near Shore Sedimentation ; Beach Profiles
    and Longshore Bars, Proc. Coastaline of Canada Conf., in press,
    1979.
Dingler,J.R., Wave-formed Ripples in Near Shore Sands, Ph.d. Disserta-
    tion, Dept. of Oceanography, University of Carifornia, San Diego,
    1975.
Goda,Y., A Synthesis of Breaker Indices, Proc. of JSCE, No.180, pp 339–
    350, 1970. (in Japanese)
Hallermeier,R.J., Calculating a Yearly Limit Depth to the Active Beach
    Profiles, CERC Ft. Belvoir, Va., Tech. Paper 77-9, 1977.
Horikawa,K., T. Sunamura and H. Kondo, A Study of Beach Deformation by
    Wave Action, Proc. 21st Japaneae Conf. Coastal Engg. pp 193–199,
    1974. (in Japanese)
Inman,D.L. and A.J.Bowen, Flume Experiment on Sand Transport by Waves
    and Currents, Proc. 8th International Conf. Coastal Engg. pp 137–
    150, 1963.
Madsen,O.S. and W.D.Grant, Quantitative Description of Sand Transport
    by Waves, Proc.15th International Conf. Coastal Engg. pp 1093–
    1112, 1976.
Nakamura,M., H. Shiraishi and Y. Sakai, Wave Decaying due to Breaking,
    Proc. 10th International Conf. Coastal Engg. pp 234-253, 1966.
Rector,R.L., Laboratory Study of Equilibrium Beach Profiles, BEB Wash-
    ington D.C., TM-41, Aug. 1954.
Sato,S. and N. Tanaka, Sand Movement due to Wave Action on a Horizontal
    bed, Proc. 9th Japanese Conf. Coastal Engg. pp 95-100, 1962.
    (in Japanese)
Saville,T., Scale Effects in Two Dimensional Beach Study, Proc. 7th
    IAHR, pp A3-1 – A3-10, 1957.
Sawaragi,T. and I. Deguchi, Distribution of Sand Transport rate Across
    a Surf Zone, Proc. 16th International Conf. Coastal Engg. pp 1596–
    1613, 1978.
Swart,D.H., A Shematization of On-offshore Transport, Proc. 14th
    International Conf. Coastal Engg. pp 884-900, 1974.
Tanaka,N. and O. Shinbo, The Propaties of Coal Grains as Bed Material
    in the Model Beach Experiment on Littoral Drift, Report of the Port
    and Harbour Research Institute, Ministry of Transport, Vol.12,
    No.1, pp 3-58, March, 1973. (in Japanese)