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A NEW APPROACH TO BEACH MORPHOLOGY WITH THE FOCUS ON SUSPENDED SEDIMENT TRANPSORT

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ABSTRACT: An assessment of the roles of various modes of sediment motions on longshore transport is presented. Then a literature survey is made for overviewing the research efforts on longshore sediment transport problems with a focus on suspended load. The past efforts with the emphasis on bed load transport are said to have the roots in pioneering works by Einstein and Bagnold. However, many field measurements on suspended sediment concentration have demonstrated the importance of suspended sediment in the analysis and prediction of longshore sediment transport. A macroscopic model for estimating sediment pickup rate by random breaking waves is introduced with its extension to the prediction of beach morphological changes.

1. Introduction

Beach morphology has been puzzling people since old days. Shorelines advance and/or retreat beyond the expectation of local people. Excessive retreat of shorelines or beach erosion endangers the living of people there. Unexpected deposit of sand on a beach may cause shoaling of a harbor nearby that leads to the loss of function to accommodate ships in the harbor.

Scientific studies of sediment transport that causes morphological changes of beaches began in the 1940s. More than half a century has elapsed in our efforts to understand the phenomenon of sediment transport by waves and currents. Although thousands of papers and reports have been published in the past, we are still unable to predict the shoreline changes with confidence. The author believes that the main reason of our incapability is our failure in correctly evaluating the role of suspended sediment energized by breaking waves in the surf zone.

Table 1 lists an assessment on the roles of various modes of sediment motions on longshore transport, which causes the morphological changes of beaches in the time span of months, seasons, and years. The cross-shore movement of sediment that causes beach profile changes in a few days is not discussed in the present paper, because the onshore and offshore transports tend to cancel out in a long time span. The assessment of the relative importance of the modes of various sediment motions represents the personal view of the author, in the situation that quantitative data making such an assessment is insufficient. The author would welcome the comments of other scientists and engineers on this assessment from different viewpoints.

The sediment transport in rivers and coasts has two modes: i.e., bed load and suspended load transports. The bed load transport occurs in the mode of either individual particles motions or

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sheet flow movement. Presently the mechanism of the former mode including formation of sand ripples has been well clarified by many research efforts, while the phenomenon of sheet flow of sediment has become somewhat known. The extent of their contributions to the longshore transport needs to be scrutinized, however. Probably they are playing a major role in cross-shore sediment transport, but individual sediment particles in the transport mode of bed load would not contribute much to the longshore sediment transport. The sheet flow mode may exercise a medium influence on longshore transport.

Table 1. Tentative assessment of the roles of longshore sediment transport modes

Mode		Present state	Total contribution
Bed load:	particles	almost known	small
	sheet flow	somewhat known	medium
Suspension:	from sand ripples	almost known	little
	by breakers	unknown	dominant

Sediment particles are put in suspension by two driving forces. One is the shear stress of oscillating flows acting on the bed layer, and the other is the vertical momentum of water jets produced by breaking waves. Sediment suspension from the crests of sand ripples is a typical example of the former, and it has been studied quite well. However, the total quantity of longshore transport of this type of suspended sediment is thought to be very small compared with that of sediment suspended by breaking waves. The importance of sediment suspension by breaking waves is readily understood when we look down the sea surface from a pier extending through the surf zone; we can observe a burst of sediment cloud rising up in the water after a plunging breaker movers out toward the beach. The sediment cloud slowly moves alongshore within the surf zone, carrying a large amount of suspended load.

There are some reports that suspended sediment rather than bed load dominates longshore transport, especially during stormy conditions. Nevertheless, quantitative analysis of sediment suspension by breaking waves has not succeeded yet because of the complexity of phenomena involved. The majority of studies on sediment transport problems have mainly addressed to the topics of bed load and sediment suspension from sand ripples, by detouring the tough assignment of solving the mystery of sediment suspension by breaking waves. It is now the time to focus our research efforts on the above task so that we can make a breakthrough in the riddle of beach morphology.

In the present paper, an overview of the past research efforts on sediment transport problems will be made from the viewpoint why the phenomenon of sediment suspension by breaking waves has not been paid due attention. Then a macroscopic model by Katayama and Goda (1999, 2000) will be introduced with its extension to the prediction of beach morphological changes.

2. Overview of Past Research Efforts on Sediment Transport Problems

2.1 EARLY STAGE STUDIES WITH METHODOLOGY OF RIVER SEDIMENT ANALYSIS

The problem of beach erosion occurred at many places in the world from time to time, but American people seem to have the keenest concern on conservation of beaches for summer resort. Upon the demand of many people, the U.S. Army Corps of Engineers created the Beach Erosion

Board in the early 1930s to deal with severe beach erosion problems along the American coastline. After World War II, the U.S. Navy also found interests in wave-related problems. For one of the projects commissioned to University of California, Berkeley, Einstein (1948) gave a suggestion for the direction of approach to be taken for the study on beach sand movements by waves, saying that the concept of river sediment transport can be extended to beach sand movements even though a river flows in one direction while beach sands are exposed to oscillatory flows of wave orbital motions.

Einstein had established his famous formula on bed load transport in rivers in 1942. His formula was based on statistical concept with dimensional analysis. Later Kalinske (1947) augmented the Einstein formula by giving more physical reasoning. Both of them had recognized the necessity to include the suspended load into the total transport, but they analyzed the bed load transport only, probably because of difficulty in deriving any generalized conclusion on the amount of suspended load.

In the U.K., Bagnold (1946) initiated investigations on the motion of sand by waves; he had been famous for his experiments on impulsive breaking wave force on a vertical wall as well as his pioneering work on blown sand. He immersed a swinging, arc-shaped cradle, hanged from the ceiling, in a water tank. By changing the amplitude and frequency of swinging motion of the cradle, he created oscillating water flows relative to the surface of cradle. Bagnold then placed a layer of sand on the cradle and observed the motion of sand particles by oscillating water flows. The threshold velocities for initiation of particle motions, formation of sand ripples, and suspension of sand particles from sand ripples were thus measured and recorded. Another method of creating oscillating flows relative to a sand layer is to reciprocate a horizontal plate with sand on top of it in a water tank through a piston-motion mechanism. This method was used by Manohar (1955) for the study of threshold velocities of sand motions in a manner similar as Bagnold’s study.

An early laboratory study of sand movement by waves was reported by Scott (1954), who carried out many tests at University of California, Berkeley. A few years later, a group of researchers at the Massachusetts Institute of Technology began a series of detailed measurements on the wave-induced motion of particles on slopes. Eagleson and Dean (1961) summarized their findings on the vertical distribution of net velocity near the bed, the drag coefficient of sediment particles on bed, etc.

2.2 MECHANISMS OF SAND MOTIONS UNDER WAVE ACTIONS

2.2.1 Incipient Motions of Sediment Particles by Oscillating Flows

Studies on sand particle motions in the early stage stimulated interests of researchers on the incipient motions of sediment particles by oscillating flows. To facilitate the laboratory experiments, Lungren and Sorensen (1957) invented a pulsating water tunnel, which later became favorite equipment in many coastal engineering laboratories in the world.

The threshold of incipient motions of sediment particles is mostly expressed in terms of the Shields number, which normalizes the critical shear stress for driving particles into reciprocating motions. The so-called Shields curve, i.e., plotting of the threshold Shields number against the Reynolds number (defined by the shear velocity and the particle diameter), has been applied by many researchers to their laboratory data. Furthermore, Larsen et al. (1981) reported the results of ocean measurements in which the threshold of fine sediment suspension from the sea bottom of 75 to 90 m deep by wave actions was well described by the Shields curve.

However, Hallermeier (1980) analyzed ten sets of laboratory data by various investigators and concluded that the Shields curve is not suitable for describing the threshold of incipient sediment motions by oscillating flows. Instead, he proposed two empirical formulas for the critical orbital velocity, one for fine grains under high-frequency oscillations and the other for coarse grains under relatively low-frequency oscillations. A recent paper by You (2000) also discusses the threshold wave orbital velocity for initiation of sand particle motions in a similar fashion.

2.2.2 Sediment Suspension by Shear Stress from Bed Layer

As the shear stress acting on sediment particles by wave motions increases, ripples appear on the surface of sand layer on the bottom. With a further increase in the shear stress or orbital velocity, sediment particles are put into suspension from the crests of sand ripples. Then suspended sediment is moved upward by turbulence while being pulled down by gravity. The sediment concentration is densest near the bed and thinnest near the surface. The time-averaged vertical distribution of sediment concentration is governed by the strength of turbulent eddy viscosity and the settling velocity of sediment in suspension.

There have been many studies on the concentration of sediment suspended by wave actions; some made detailed experiments in oscillating water tunnels as well as in wave flumes, while others measured sediment concentrations in the sea. Das (1972) gave a review of early studies on suspended sediment, the amount of which was mostly measured from water samples taken by suction. Sleath (1982) is one of earlier investigators who made use of phototransistors to measure the concentration of sediment. Nowadays, many optical backscatter sensors and acoustic sensors are employed to monitor temporal variations of sediment concentrations, even though some researchers favor the method of water sampling by suction. Nielsen (1984) used a specially devised water sampler for his field measurements in the nearshore zone. Black and Rosenberg (1994) compared optical and pump-sampling techniques with conclusions that the efficiency of pump in trapping sediment may be affected by the strength of ambient turbulent eddies and the response of optical backscatter sensors is strongly dependent on grain size.

The suspended sediment concentration near the bed is in the order of 1 g/*l* and decreases rapidly to the order of 0.001 g/*l* as the height from the bed increases, when no wave breaking takes place; e.g., Van Rijn et al. (1993). Nielsen (1986) gave a formula for the concentration at the sea bottom as being proportional to the cube of a Shields parameter. The vertical distribution of suspended sediment concentration in waves can be calculated by solving the diffusion equation. Fredsoe et al. (1985) demonstrated several results of numerical calculations that fit quite well to laboratory data. Suspension of sediment from the crests of sand ripples can now be simulated numerically. Asp Hansen et al. (1994) has presented a successful example using a discrete vortex model.

Several field measurements have revealed the phenomenon of rapid rises of suspended sediment concentration near the seabed, especially when conspicuous wave grouping is present; e.g., Hanes and Huntley (1986), and Williams et al. (1996). The transport of suspended sediment is the product of concentration and flow velocity. Because the concentration fluctuates in correlation with the flow components of wave motions, long-period motions, and mean currents, the cross-shore transport rate must be calculated by integrating the instantaneous product of concentration and velocity instead of the product of the mean concentration and the mean velocity, as demonstrated in the field data analysis by Osborne and Greenwood (1992). In the case of longshore sediment transport rate, however, Jaffe and Sallenger (1992) found no clear correlation between the suspended sediment concentration and the longshore current velocity so that the longshore transport rate can be calculated with the product of their means.

2.2.3 Sheet Flow of Sediment on Seabed

In the inner surf zone where intensive wave breaking is taking place, sand ripples on the seabed disappear and sediment particles move en masse. This is called the sheet flow of sediment. Ribberink and Al-Salem (1995) reported quite detailed measurements of sediment concentration in the sheet flow layer in a large oscillating water tunnel. They devised a special sheet flow sensor using an electro-resistance probe, and measured the temporal variation of sediment concentration. Within the layer of several millimeters below the surface, sediment particles are fluidized from their static state of deposition and then return to the static state with the phases of wave motions; their concentration periodically varies in the range of 800 to 1600 g/*l*. Above the sheet flow layer, the sediment moves in suspended state. Its concentration rapidly decreased from about 10 to 100 g/*l* on the bottom to 0.1 g/*l* or less at the height of about 5 cm.

2.3 SEDIMENT SUSPENSION IN THE SURF ZONE

2.3.1 Field Measurement of Suspended Sediment in the Surf Zone

The suspended sediment by nonbreaking waves exists only near the seabed with little concentration in the water column as a whole. When waves break, however, suspended sediment of high concentration rises up in mid-water and near the surface.

Field measurements of suspended sediment concentration had been made in many countries since the 1950s. Among them, Fairchild (1972) succeeded in obtaining more than 800 data in the surf zone at various elevations from the seabed to mid-depth. He moved a tractor-mounted pump sampler along a pier extending from the shore; he utilized one pier at Ventnor in New Jersey and another at Nags Head in North Carolina. The maximum concentrations ranged up to 2.6 g/*l* at Ventnor and 4.0 g/*l* at Nags Head. The median diameter of suspended sediment was in the range of 0.12 to 0.20 mm. While the data by Fairchild gave an overall view of suspended sediment in the surf zone, they were not well correlated with wave data and no simultaneous current measurements were taken.

Since the 1970s, many field campaigns have been conducted in a more systematic way. Kana and Ward (1980) reported the first systematic measurements of sediment concentrations and current velocities along the CERC pier at Duck. They commented “the sediment concentrations ranged over $3\text{-}^{1}/_{2}$ orders of magnitude from approximately 0.05 g/*l* to over 10.0 g/*l* with highest concentrations in the inner surf zone and near the bed.” Then with introduction of optical backscatter sensors, it became clear that bursts of suspended sediment occur intermittently with the peak concentration more than 20 g/*l*. Beach and Sternberg (1988) reported that such suspension events are correlated with infragravity waves of 30 to 300 s in period. Nadaoka et al. (1988a) attributed suspension events to the three-dimensional large-scale eddies that were produced by plunging breakers. Nadaoka et al. (1988b) further reported field measurements of such eddies and their relationship with sediment suspension. Jaffe and Sallenger (1992) observed that suspension events occurred in every 1 to 2 minutes with the concentration being one order of magnitude greater than the rest of time. Although the suspension events occupied less than 10% of the observation time, they contributed to the increase of mean concentration by 15% to 55%. Black et al. (1995) presented several records of the suspended sediment of high-density clouds with explanation how they moved back and forth around the sensors in relation with the wave motions. Miller (1999) also demonstrates records of suspension events with high-concentration sediment reaching to near the water surface.

2.3.2 Large-Scale Laboratory Measurements of Suspended Sediment in the Surf Zone

Sediment suspension by breaking waves has also been investigated in very large wave flumes with $H_{1/3}$ exceeding 1.0 m. Dette and Ulizcka (1986) presented the earliest results of large-scale tests. Dally and Barkaszi (1994), Roelvink and Reniers (1995), and Shimizu et al. (1996) reported the test results of similar magnitude. A recent report by Peters and Dette (1999) expresses the vertical distribution of suspended sediment concentration in an exponential decay function as an approximation, i.e.,

$$c(z) = c_0 e^{-az} \tag{1}$$

where $c(z)$ is the time-averaged concentration, c_0 denotes the reference concentration on the bed, and a represents the decay parameter. According to Peters and Dette (1999), c_0 is around 10 g/l and the value of a comes down to 2 m^{-1} in the inner surf zone, indicating nearly uniform distributions.

Suspension events are evidently caused by breaking waves as demonstrated by Nadaoka et al. (1988a, 1988b). The role of breaking waves in sediment suspension has also been exhibited in numerical simulations by Pedersen et al. (1995), who used a discrete vortex model in analyzing the velocity field in the surf zone. They obtained a good agreement of sediment concentration with the measurement by Dette and Ulizcka (1986).

2.4 LONGSHORE SEDIMENT TRANSPORT FORMULAS

2.4.1 CERC Formula

Our capability in predicting beach changes solely depends on the reliability of sediment transport formula. In the early days, the amount of total longshore sediment transport was estimated from the volumetric change of beach and berm in the coast where longshore sediment transport was impounded by some barrier such as a jetty or others. The longshore transport rate was then correlated with the longshore component of wave energy flux during the period in which the amount of longshore sediment transport was estimated. Through accumulation of many data at various coasts, the so-called CERC formula (USACE 1984) was evolved. Its volumetric expression is as follows:

$$q_{total} = \frac{K H_b^2 (c_g)_b}{8s(1-\lambda)} \sin\alpha_b \cos\alpha_b \tag{2}$$

where K denotes the constant of the CERC formula being 0.385 on the average, H denotes the significant wave height $H_{1/3}$, c_g is the group velocity, α stands for the wave angle, the subscript b denotes the value at the breaking point, s is the density ratio of sediment to water $\left(s = \rho_s / \rho\right)$, and λ represents the void ratio of sediment in situ being about 0.4. When the root-mean-square wave height H_{rms} is used, then the constant K takes the value 0.77.

The reliability of the CERC formula for making prediction of beach morphology has been discussed over many years. Greer and Madsen (1978) is one of early reviewers, who recommended the formula to be used for the order estimate only. The focus of discussion is the value of constant K. While K is thought to be affected by the grain size, Komar (1988) could not find a clear relationship because of large scatter of field data. However, Del Valle et al. (1993) supported the grain-size dependency of K with the field data of coarse sand coast with the grain size up to 1.5 mm, and presented the following empirical relationship:

$$K = 0.8\exp[-2.5d] \tag{3}$$

where d is the grain size in millimeters. Schooness and Theron (1994) calculated the K value for many field data by grouping them with grain size. For the group with grain size smaller than 1 mm, the mean of K was 0.41, but for the group with grain size larger than 1 mm the mean was 0.01, although the effect of grain size could not be revealed within the two groups. A recent paper by Van Wellen et al. (2000) also used the K value of 0.07 to fit the data on shingle beaches in their assessment of various longshore transport formulas.

In addition to the CERC formula, several formulas have been proposed to evaluate the total rate of longshore transport across the shore. The formula by Kamphuis (1991) is a representative example. Schooness and Theron (1996) calibrated 52 formulas with 273 data points and concluded the Kamphuis formula being the most reliable, although Van Wellen et al. (2000) disagree with them, saying that their field database is biased towards a certain group of environmental parameters.

2.4.2 Energetics Model by Bailard

Many sediment transport formulas are dedicated to predict the local transport rate. When combined with the longshore current prediction and/or measurements, they yield the estimates of total longshore sediment transport rate. Bayran et al. (2000) calibrated six sediment transport formulas with the field measurement data of longshore currents and suspended sediment concentrations at various elevations along the CERC Field Research Facility (pier) at Duck. The data of three experiments named DUCK 85, SUPERDUCK, and SANDYDUCK were analyzed to yield the cross-shore distribution of longshore transport rate. The local transport rate formulas include those by Bijker (1971), Bailard (1981), Watanabe (1992) and others. These formulas comprise the bed load and suspended sediment transports evaluated mostly with the concept of shear stress acting on the seabed.

Comparison between the field data and predictions was made of the cross-shore profiles of local longshore transport rate as well as the whole data points. Most of predictions were in the range of 1/5 to 5 times the measurements, but some data were outside this range and the fraction of outside data among the whole was 4% to 38% depending on the formulas and wave conditions; thus the performance of the prediction formulas was only fair.

Among the six formulas, the Bailard formula deserves explanations because it is based on the energetics concept proposed by Bagnold (1963, 1966), who recommended use of the fluid power rather than the shear stress as the driving force of sediment transport. According to Bayram et al. (2000), the Bailard equation is expressed as follows:

$$q = 0.5\rho f_w u_0^3 \frac{e_b}{(\rho_s - \rho) g \tan\gamma} \left(\frac{\delta_V}{2} + \delta_V^3 \right) + 0.5\rho f_w u_0^4 \frac{e_s}{(\rho_s - \rho) g w_f} \delta_V u_3^* \tag{4}$$

The notations in Eq. 4 are defined as follows: e_b and e_s denotes the bed load and suspended load efficiency factors (fraction of energy dissipation spent to sediment transport), respectively, f_w is the wave friction factor, g is the acceleration of gravity, u_0 represents the amplitude of wave orbital velocity at the bed, u_3^* is the cubic velocity moment, w_f stands for the sediment settling velocity, δ_V expresses the ratio of longshore current velocity to u_0, γ is the wave height parameter, and ρ and ρ_s are the densities of water and sediment, respectively. Equation 4 is a simplified version of the original equation by Bailard, who used the internal angle of friction of the sediment ϕ instead of the parameter γ in the denominator of the first term in the right-hand side of Eq. 4.

As for the constant values, Bailard (1981) gave the least squares estimates of e_b and e_s as 0.21 and 0.025, respectively, but later recommended the values of $e_b = 0.13$ and $e_s = 0.032$ (Bailard, 1984) when he proposed Eq. 5 below. In the reference by Bayram et al. (2000), however, they listed the values of $e_b = 0.1$, $e_s = 0.025$, and $\tan\gamma = 0.63$.

Bailard (1984) applied his formula to examine the parameters involved in the K value of the CERC formula. By finding the coefficient values best fitting to field and laboratory data, he derived the following equation; the original constant values are halved because of the use of significant wave height in Eq. 4:

$$K = 0.025 + 1.3\sin^2 2\alpha_b + 0.0035 u_{0b} / w_f \tag{5}$$

This is an explicit inclusion of the grain size effect (settling velocity) into the longshore sediment transport formulas. The settling velocity of sediment can be estimated with the formula derived by Rubey (1933) who worked on the problems of sediment motion on riverbeds, i.e.,

$$w_f = \sqrt{(s-1)gd}\left[\sqrt{\frac{2}{3} + \frac{36\nu^2}{(s-1)gd^3}} - \sqrt{\frac{36\nu^2}{(s-1)gd^3}}\right] \tag{6}$$

where ν denotes the kinetic viscosity of water.

2.5 BEACH MORPHOLOGICAL MODELS WITH SUSPENDED SEDIMENT

2.5.1 Field Measurements of Suspended Sediment and Comparison with CERC Formula

Equation 5 by Bailard (1984) for the K value of the CERC formula suggests the enhanced role of suspended sediment on longshore transport. His revision of the coefficient value for the bed load efficiency factor e_b from 0.21 to 0.12 and that of suspended load efficiency factor e_s from 0.025 to 0.032, when he derived Eq. 5, indicates an increased role of suspended sediment. If one assumes the condition of $\alpha_b = 10$ degrees, H_b = 3.0 m at the depth h_b = 4.0 m, and the mean diameter of d = 0.2 mm (w_f = 2.4 cm/s), the sum of the first two terms in the right-hand side of Eq. 5 becomes 0.18 and the third term has the value of 0.29 (u_b is assumed equal to $\sqrt{gh_b}$). If the former is regarded to represent the contribution of the bed load and the latter as that of suspended load, it is evident that the suspended load becomes dominant in the longshore transport of fine sediment for most of storm conditions.

Direct comparison between the contributions by the bed load and by the suspended load across the beach is difficult, because the field measurement of bed load transport is almost impossible. Although tracer investigations provide the data of local longshore transport rate, we cannot tell whether tracers were transported by the bed load mode or suspended mode. What we can do is to estimate the amount of suspended sediment transport rate by integrating the measured data of sediment concentrations and current velocities across the surf zone and to compare the result with an estimate of total sediment transport rate.

The objective of field measurements by Kana and Ward (1980) was to estimate the sediment