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Beach Profile Change and Equilibrium due to Irregular Waves in the Nearshore Region
淺海 不規則波에 依한 海濱變形 및 平衡

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Abstract □ The skewness of near-bottom velocity distribution caused by the nonlinear interaction of the second order waves proposed by Wells (1967) has been re-evaluated. The direction of cross-shore sediment transport was related to the sign of the third moment (skewness) of velocity distribution, and a new concept of neutral depth which can explain the recovery of beach equilibrium after a disturbance is suggested. The seasonal change of beach profile due to the change of wave condition (storm-swell profile) is interpreted in terms of nonlinear interaction of the waves rather than the conventional wave steepness. The beach is eroded (storm profile) when the nonlinear interaction of the waves is strong (storm wave), whereas the beach is accreted (swell profile) when the nonlinear interaction is weak (swell wave).

要 旨: Wells (1967)에 의해 제안된 2nd order 파랑들의 비선형 상호작용에 의한 바닥 부근에서의 유속분포에 대한 왜도 (skewness)를 다시 계산하고 재평가하였다. 해안선에 수직한 방향의 퇴적물 이동 방향을 그 유속의 3차 모멘트 (왜도)의 부호에 따라 알 수 있음을 보였고, 해빈이 어떤 교란을 받은 후에도 원래의 평형을 회복할 수 있는 새로운 개념의 중립수심을 제안하였다. 또한 계절적인 파랑조건의 변화에 따른 해빈단면의 변화 (폭풍-너울 단면)도 종래의 단순한 파랑구배에 의한 구분보다는 파랑의 비선형 상호작용으로 설명되었다. 즉, 파랑의 비선형 작용이 강한 때에는 (폭풍파) 해빈은 침식을 받으며, 반면에 비선형작용이 약할 때에는 (너울파) 해빈은 퇴적됨을 보였다.

1. INTRODUCTION

The sediment transport by waves in the beaches and nearshore regions occurs largely in two directions, one in shore-parallel and another in cross-shore direction. The transport in shore-parallel direction is generally a surf zone process, which is caused by the longshore currents generated by the breaking waves. The longshore current is a quasi-steady phenomenon compared to the time-varying wave orbital velocities. The longshore drift is mostly responsible for the change of shoreline configuration. On the other hand the transport in cross-shore direction is caused by the wave orbital velocities and mass transport, and thus the effect is not confined within the surf zone but is extended to the nearshore region where the wave motion affects the bottom. The net effect of the time varying cross-shore sediment transport causes the change of beach profile across the nearshore region (Komar, 1976).

Beachface is eroded or accreted by the on-offshore movement of sediments caused by the wave orbital velocities near the bottom, and the beach profile adjusts itself to the characteristic wave conditions until it reaches an equilibrium. The equilibrium profile of the beaches has been manifested in terms of either the

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storm and swell profiles (Shepard, 1950; Bascom, 1954; Komar, 1976) or the null point equilibrium (Ippen and Eagleson, 1955; Eagleson et al., 1958; Eagleson and Dean, 1961). However, none of the models could adequately explain the change of beach profile either in the field or in the laboratory (Eagleson et al., 1963; Komar, 1976; Noda and Matsubara, 1978; Seymour and King, 1982; Seymour and Castel, 1989).

Wells (1967) considered the skewness of velocity distribution caused by the nonlinear interaction of second order Stokes waves solved for by Bi sel (1952), and also suggested the existence of a neutral depth similar to the null point, where the sediment moved neither onshore nor offshore. However, the calculation by Wells (1967) had a slight mistake, and thus the field test by Seymour and King (1982) was also not so successful even though Kang (1987) could predict the profile change after a beach fill between a groin compartment using the same equation of Bi sel (1952).

The present paper corrects the calculation of the skewness proposed by Wells (1976), and re-evaluates the direction of sediment movement and the concept of neutral depth according to the change of skewness with depth. The change of beach profile according to the change of wave conditions is also examined in terms of nonlinear interaction of the waves.

2. NONLINEAR INTERACTION OF THE WAVES AND THE SKEWNESS OF VELOCITY DISTRIBUTION

Nonlinear interaction of a finite number of ocean waves modulates the amplitude of surface fluctuation with the sum and difference frequencies of each component waves (Phillips, 1977), which makes the waves of the ocean look quite irregular. Bi sel (1952) solved for the nonlinear interaction of the second order Stokes waves of a finite number N, and the horizontal component of the wave orbital velocity u at the Eulerian frame was given as

$$u = \sum_{i=1}^{N} (A_i \cos\theta_i + B_i cos 2\theta_i)$$

$$+ \sum_{i=1}^{N} \sum_{j=1}^{i-1} \{ S_{ij} \cos(\theta_i + \theta_j) + D_{ij} \cos(\theta_i - \theta_j) \} \qquad (1)$$

where $\theta_i = k_i x - \sigma_i t$, the wave number $k_i = 2\pi/L_i$, the angular frequency $\sigma_i = 2\pi/T_i$, in which L_i and T_i are the wavelength and the period of each component wave, respectively. The coefficients A_i, B_i, S_{ij}, and D_{ij} are given in the Appendix, and the dispersion relationship of each wave train is given as

$$\sigma_i^k = g k_i \tanh k_i h \qquad (2)$$

where g is the acceleration of gravity and h is the water depth.

Wells (1967) evaluated the skewness (β) of the velocity distribution given by the equation (1) as

$$\beta = \frac{\mu_3}{(\mu_2)^{3/2}} \qquad (3)$$

where μ_2 and μ_3 are the second and third moments of the velocity distribution, respectively. The second and third moments for the waves given as the Eq. (1) can be calculated as

$$\mu_2 = \frac{1}{2} \sum_{i=1}^{N} (A_i^2 + B_i^2) + \frac{1}{2} \sum_{i=1}^{N} \sum_{j=1}^{i-1} (S_{ij}^2 + D_{ij}^2) \qquad (4)$$

$$\mu_3 = \frac{3}{4} \sum_{i=1}^{N} A_i^2 B_i^2 + \frac{3}{2} \sum_{i=1}^{N} \sum_{j-1}^{i-1} (A_i A_j S_{ij} + A_i A_j D_{ij}$$
$$+ B_i S_{ij} D_{ij}) \qquad (5)$$

Wells (1967) miscalculated the above Eq. (5) and obtained a result that the skewness was always positive at the shallow region and negative at the deep region of a beach, which is contrary to the correct calculation.

3. SEDIMENT TRANSPORT AND THE SKEWNESS

Calculation of the instantaneous sediment transport rate by the wave orbital velocities could yield the exact amount and direction of cross-shore movement of the sands (Madsen and Grant, 1976; Bailard and Inman, 1981; Bailard, 1982). However, the model of Madsen and Grant (1976) considered the transport by the linear waves which could not produce a net transport in one direction. The models of Bailard and Inman (1981) and Bailard (1982) incorporate many coefficients to be evaluated before using the model, and were also not very successful in the field test (Seymour and King, 1982; Seymour and Castel, 1989).

The rate of sediment transport by waves is usually considered to be proportional to the third power (Bagnold, 1963, Bailard, 1982) or to the sixth power (Madsen and Grant, 1976) of the instantaneous velocities. For the exact calculation of the sediment transport rate the effect of bottom slope and threshold velocity should also be included (Madsen and Grant, 1976; Bailard, 1982). However, even though the skewness itself is a representation of the degree of asymmetry of the probability distribution curve of the velocities, it can be regarded as a semi-quantitative representation of the direction and magnitude of the sediment transport rate by waves, since the skewness is calculated as the ensemble average of the third power of the velocities normalized by its variance.

The skewness also tells the existence of the asymmetrical positive or negative peak velocities within the velocity distribution. If we consider that the threshold velocity to initiate the movement of sediment grains masks the role of low velocities and that the rate of sediment transport is proportional to the third to sixth power of the velocities, the importance of the peak velocities of the wave orbital velocity is more signified. Thus the skewness itself can be adequately related to the sediment transport by waves, especially to the direction of net sediment transport.

Fig. 1 shows the change of skewness with the change of depth by the interaction of two waves. It shows that the direction of sediment movement at a depth changes according to the degree of nonlinear interaction of waves. It is obvious from the Eq. (2), (3), and (4) that a monochromatic swell train has always positive skewness, and thus the waves generally move the sediment onshore at all depths. However, it shows that the sediment at the shallower depths is moved offshore, whereas the sediment is moved onshore from the deeper part of the beach, as the height of the interacting wave is increased. When the heights of the interacting waves are about the same, the sediment is moved offshore at all depths.

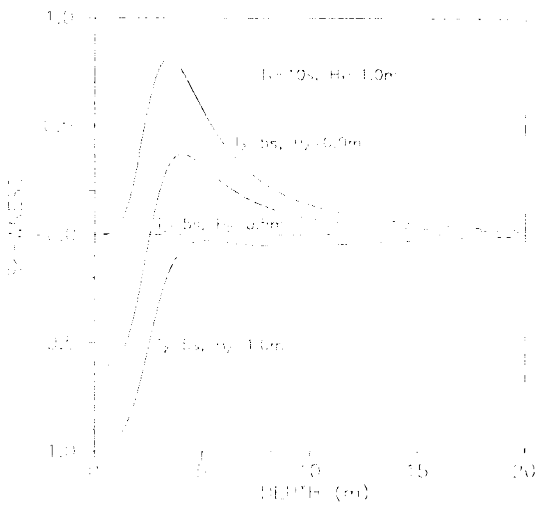

Fig. 1. Change of skewness with depth and height by the nonlinear interaction of two waves.

Therefore it is suggested that the direction of sediment movement is determined by the nonlinear interaction of the waves, and the sediment can be moved either offshore or onshore at all depths, or converge to a depth where the skewness becomes zero where the beach can attain an equilibrium according to the wave conditions.

4. NEUTRAL DEPTH AND BEACH EQUILIBRIUM

The hypothesis of null point equilibrium also has been used to explain the equilibrium beach profile. The hypothesis explains the equilibrium beach slope as the result of force balance between the gravity force and the drag force acting on each grain on a sloping bottom (Ippen and Eagleson, 1955; Eagleson et al., 1958; Eagleson and Dean, 1961).

The models attributed the onshore drag force to the onshore mass transport near the bottom caused by the waves proposed by Longuet-Higgins (1953) which becomes larger as the water depth decreases. The result was that the coarser grains should move offshore if a mixed-size sediments were placed at a place, which was inconsistent with the findings of Bagnold (1940). Eagleson et al. (1963) also failed to predict the change of beach profile based on the model of Ippen and Eagleson (1955). This conventional null point hypothesis has its own drawback in that the model only considers a static equilibrium rather than a dynamic equilibrium of the beach, and thus the beach cannot recover an equilibrium after a slight disturbance caused by an temporal event (Komar, 1976; Sleath, 1984; Kang, 1987). These models also cannot explain the cyclic change of the storm and swell profiles caused by the change of seasonal wave conditions.

Wells (1967) also proposed the existence of a neutral depth, where the skewness becomes zero and thus the sediment moves neither onshore nor offshore. Based on the analysis of the skewness of velocity distribution, Wells (1967) suggested that the sediment grain always moved onshore in the regions shoreward and offshore in the regions seaward of the neutral depth. In this concept of neutral depth, the sediment is also divergent from the neutral depth and thus the beach cannot attain an equilibrium after a disturbance. Once a beach in equilibrium with the characteristic wave condition of the beach has been deepened by a catastrophic event, the beach cannot recover the original equilibrium depth since the sediment should be carried offshore. Similar argument can also be applied to the case when the beach has become shallower by any event.

However, Fig. 1 shows that the neutral depth does not always exist, and Fig. 2 shows that the sediment always moves offshore from shallower region and onshore from deeper region towards the neutral depth when a neutral depth exists, which is contrary to the result of Wells (1967). Fig. 2 also shows that the neutral depth becomes deeper and thus the beach near the shoreline is more erosive as the wave height increases.

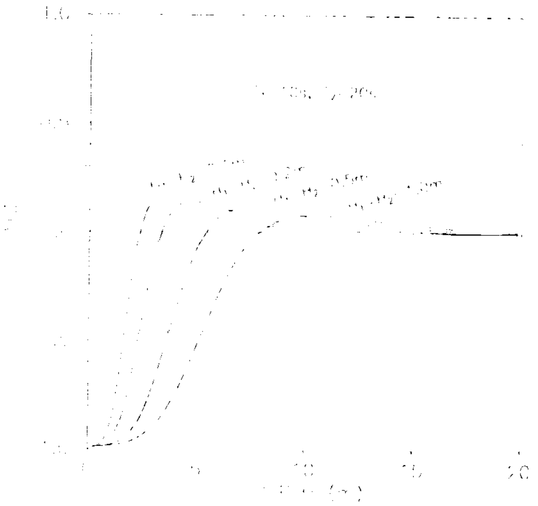

Fig. 2. Deepening of neutral depth with the increase of wave heights.

According to the neutral depth shown in Fig. 2 sediment is converging towards the neutral depth, and this convergent-type neutral depth can easily explain the recovery of the beach profile after any chaotic disturbance. If a beach in equilibrium with the neutral depth on the average by mild waves is attacked by a train of higher waves, the sediments are carried farther offshore and the equilibrium beach becomes deeper. However, the beach becomes shallower again and recovers the original equilibrium because the sediments are carried onshore from the deeper region when the original mild wave condition returns. If the stronger waves comes again, the sediments in the shallow region are carried offshore and the beach in equilibrium with the waves becomes deeper again (Fig. 2). This kind of cyclic change of the beach profile is well documented in the nature (Shepard, 1950; Komar, 1976).

5. BEACH CYCLE

The onshore movement of sand causes accretion of the beach resulting in a wide berm and steep slope of the beach face, and the offshore movement of sand usually causes erosion of the beach resulting in a narrow berm with gentle beach slope. The eroded beach material is carried offshore and forms the typical offshore bar and trough morphology (Shepard, 1950, Komar, 1976).

The accretional feature of the wide berm has been called as the summer profile, normal profile, post-storm profile, or the swell profile. The erosional feature of the berm and the construction of the offshore bar and trough has been called as the winter profile or the storm profile (Johnson, 1949; Shepard, 1950; Bascom, 1954). The cyclic change of the beach profile according to the seasonal change of the wave conditions has been known as the beach cycle (Shepard, 1950; Komar, 1976). All the nomenclatures relate the beach profile to the characteristic seasonal harsh or mild wave conditions, and thus Komar (1976) suggested the use of storm and swell profiles to clarify the role of the waves to the change of beach profile.

However, the distinction between the storm and swell waves is not very clear, and it is often simply related to the wave steepness (the ratio of wave height to wavelength). The storm wave is usually characterized by the irregular fluctuation of water surface with a relatively high steepness. On the other hand the swell wave shows a relatively simple sinusoidal wave form with a relatively low wave steepness (Komar, 1976). The storm waves cause the erosion of the beach producing the offshore bars and troughs (storm profile). The swell waves make a wide berm carrying the sediment from the deep offshore (swell profile) (Johnson, 1949; King and Williams, 1949; Shepard, 1950; Bascom, 1954).

Even though the models considering the wave steepness with some modifications showed a very limited success in predicting the storm and swell profiles (Johnson, 1949; Iwagaki and Noda, 1963; Dean, 1973; Hattori and Kawamata, 1980; Dalrymple, 1992), those generally showed a case-specific success and were not very successful either in the field (Seymour and King, 1982; Seymour and Castel, 1989) or in the laboratory experiment (Noda and Matsubara, 1978; Dalrymple, 1992). Moreover, those models could not explain the mechanism of the on-offshore sediment movement due to the changing condition of the waves.

Wave steepness can be changed either by increasing the wave period or by decreasing the wave height. However, as discussed before, a monochromatic swell wave, however steep it may be, always carry the sediment onshore. Fig. 3, 4, and 5 also show that the changing wave steepness alone is not enough to change the direction of net sediment movement at a depth. Even though Fig. 2 showed that the more sand was carried offshore and the equilibrium depth became deeper as the wave height increased, Fig. 3 shows the case that more sand is carried onshore from the deep region and the equilibrium depth becomes shallower with the increase of wave height. Fig. 4 shows that the

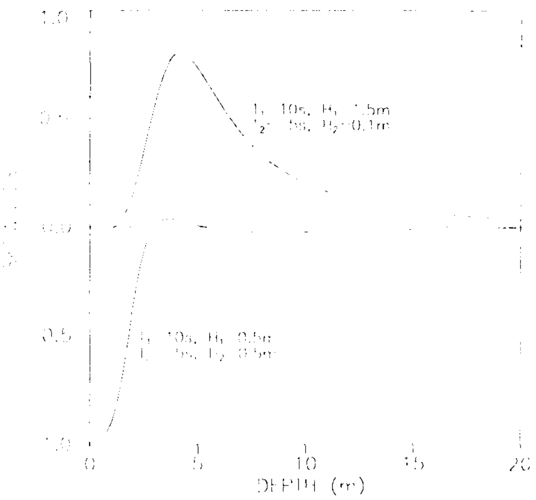

Fig. 3. Shallowing of neutral depth with the increase of wave heights.

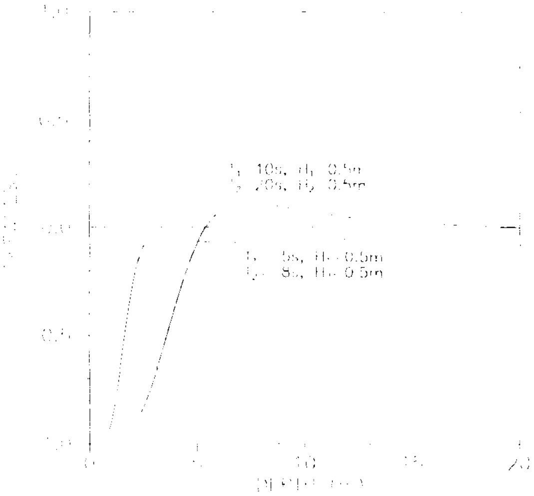

Fig. 4. Shallowing of neutral depth with the increase of wave periods.

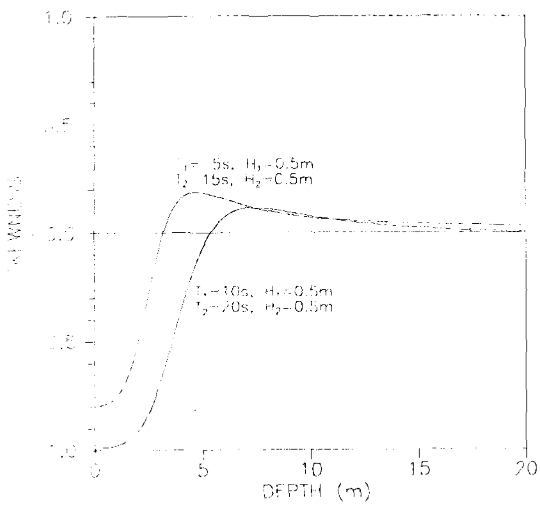

Fig. 5. Deepening of neutral depth with the increase of wave periods.

increase of average period causes more onshore movement of sediment. However, Fig. 5 also shows that the increase of period alone causes more offshore movement of sediment making the beach deeper. Komar (1976) also implies the minor role of the period in the direction of sediment movement. Offshore movement of beach material by the increased wave period was also reported by Shepard and Lafond (1940).

As a result it was shown that the direction of sediment movement can be adequately determined by the nonlinearity or the irregularity of the waves rather than the simple wave steepness. A strong nonlinear interaction of waves, which means the nonlinear interaction among waves of about equal energy, causes the erosion of beach and the sediments are carried farther offshore resulting in bars and troughs. On the other hand, a weak nonlinear interaction, which means that small waves interact with a large swell wave and thus the wave train can be well defined by a simple swell wave, causes the accretion of the beach carrying the sediment from the deep offshore (Fig. 6).

6. CONCLUSION

The skewness of velocity distribution near the bottom caused by the nonlinear interaction of waves changes with depth, and the sign of the skewness can be related to the direction of movement of the bottom sediment at a beach. The sediment moves onshore when the velocity distribution is positively skewed and vice versa.

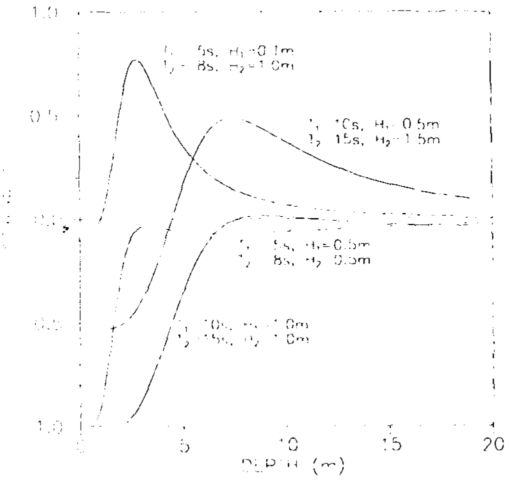

Fig. 6. Change of skewness by the strong and weak interactions of the waves.

If the nonlinear interaction of waves is weak and thus the wave train can be well defined by a swell wave, the skewness is positive at all depths and the beach is accreted, whereas the skewness is negative at all depths and the beach is eroded if the nonlinear interaction is strong. For the intermediate case the skewness is negative in the shallow region and positive in the deep region, and thus the sediment is converging towards the neutral depth where the skewness is zero and no net movement of sediment occurs. The neutral depth is the depth of equilibrium of a beach, which becomes deeper or shallower as the nonlinearity of the waves becomes stronger or weaker, respectively.

The concept of convergent-type neutral depth suggested in this paper can well explain the dynamic equilibrium at a beach and the cyclic change of beach profile due to the seasonal change of wave conditions, which is a common phenomenon in the nature. It is also suggested that the storm or swell profiles, which represent the erosional or accretional feature of the beach, respectively, should be determined by the nonlinear interaction of the waves in the wave spectrum at a beach instead of using the simple wave steepness.

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