CHAPTER 95

Inception of Sand Motion around a Large Obstacle

by

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ABSTRACT

To select a material for the top layer of the scour protection in the vicinity of a large-scale offshore structure, it is required to know when the material starts to move as a result of waves and currents. But, inception of the motion of sand particles in a region, where diffraction wave superimposes on incident wave and the water particles depict a resulting orbit of ellipse, differs from that calculated by formulae established in the two dimensional wave field.

This paper reveals the discrepancy in calculation when the conventional formulae were used and the data obtained by model experiment. It makes reference, also, to a possible method for a more accurate evaluation of the inception of motion.

1. Introduction

This paper describes the basic study of the local inception of motion of the sand particles which should provide important information in the design of the scour protection for large scale offshore structures.

Scour prevention work has a long history and has progressed rapidly in couple of decades as result of the demands and encouragement from the field of oil production in the North Sea and similar in the world. Before any further discussion of the subject, let us focus on the involved in the rip-rap type of protection as it has a popular practical application and the results of a study of this particular

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type can be applied to a wide range of other types.

In the design of a scour protection, generally the first to be investigated are the external environmenal forces which cause the bottom sand or material of the protection, usually made of coarse shingles, to move. Then the design features of the protection such as, area, resistance, thickness, durability etc. are to be decided on.

For river structures and jacket members, which are subjected to a steady flow or are small in size compared to the wave length, a considerable amount of expertise concerning the mechanism of local scour and the protection work involved has been collected up to now. However, for a large scale offshore structure, where the diameter of which reaches an order of a wave length or KC number in question is smaller than 0.5, sufficient expertise is not available concerning the protection work nor even the external forces.

Lets confine the problem to the condition of regular waves for the sake of simplicity. The wave field around a large scale structure can be divided roughly into three sections as shown in Fig.1. Firstly, in the front area where the standing wave is dominant, knowledge of the breakwater can be applied to the scouring phenomenon, what Irie(1984) has contributed for example. Secondly, in the sheltered area, there are no problems except for sand deposition. Thirdly, a considerably wide area is covered by the field where the diffraction wave is superimposed on the incident wave. Here on the bottom, the water particle depicts the orbit of ellipse as is shown later in Section 5(see Fig.14). The pure incident wave which is a single plane wave exists only in remote area away from the structure.

The question now remains whether the force which puts the particles in motion at this area is the same as that under the plane wave where the oscillatory flow is just in a single direction. To put the question more concretely, "Is the bottom shear stress the same as predicted by the conventional formulae established in the field of pure sinusoidal wave motion in one direction under two dimensional boundary layers? "

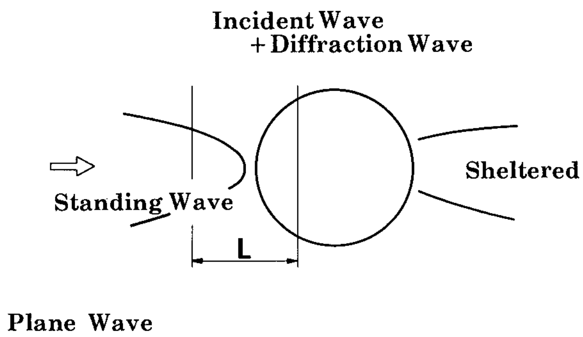


Fig.1 Wave field around a structure

As it is difficult to measure bottom shear directly in the diffraction wave field, so it is difficult to calculate the three dimensional boundary layer equation. Thus the research has begun where a series of model experiments are conducted to see what really happens around a large scale structure under waves. This paper presents a comparison from the observation of the movement of sand particles under plane waves and their movement under diffraction waves.

2. Experiment

The sand movement was investigated where the water depth was constant and the bottom was flat without any ripples. These conditions are plausible for the purpose of looking into the very early stage on particle motion on the top layer of scour protection, which is normally designed and executed flat.

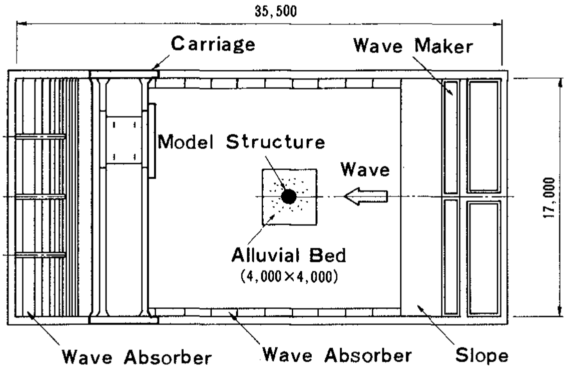
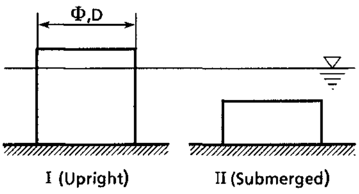


Fig.2 Experimental faciity

Table 1 Conditions of experiment

Sand	Grain Size	$D_{50} = 0.58$ mm
Bathimetry	Water Depth	h = 30 cm
Waves	Period	T = 0.8, 1.0, 1.5, 2.0 s
	Height	H = 6.0~9.0 cm
	Direction	$\theta = 0°, 45°$
Structures	Shape and Size	Circular $\phi = 117$ cm Square D = 117 cm
	Height	I : Upright II : Submerged
	Sketch	

The experiment was carried out in a wave basin 35m×17m(see Fig.2) with the water depth kept a 30cm. The model offshore structures, measuring 117cm, were installed on a sand bed 4m×4m×1cm. The grain size of the sand was chosen as large as D_{50}= 0.58 mm with quite a uniform distribution, with the shingle material to be used in the scour protection in mind, and also giving the sand function as a tracer.

Gravity type oil production platforms being kept in mind, the shapes of the structure were made basically circular, and square to investigate the effect of flow separation at the corner of the square type. A submerged type, as a model of a submerged storage tank, was also investigated .

The water depth and the structure size were scaled down to the 1/66 model from the prototype planned somewhere offshore east of China. The waves were chosen so that the threshold of the inception of motion could be well resolved by observation. The wave condition together with the types of structures are listed in Table 1.

The movement of the sand was observed by a periscope and video camera. The periscope, a simple combination of a plastic pipe, 80 mm in diameter, with a plate of glass at the bottom, was put into the water to a depth of 10 cm to enable the observation of the movement of the bottom sand without the view being disturbed by the up and down movement of the water surface. Fig.3 shows how the observation device was set up. The observation points around a structure were so disposed by 10 cm pitch mostly to cover the region of 1 diameter cylinder by half of it as is displayed in Fig.4. There were a total of 268 observation points.

The observation procedure was as follows; As soon as the wave field became stationary, a computer control in the carriage mounting the observation device started to repeat a stop and go motion to follow the pre-programed paths of the observation points. Observation for one location took only half a minute and the total time took about three hours, during which it was found that the bottom remained almost flat even where the movement of the sand was greatest.

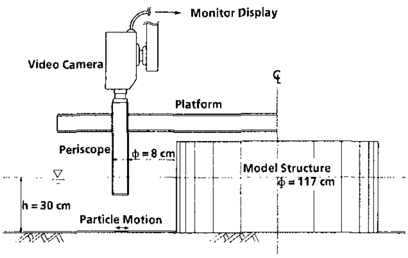


Fig.3 Observation device

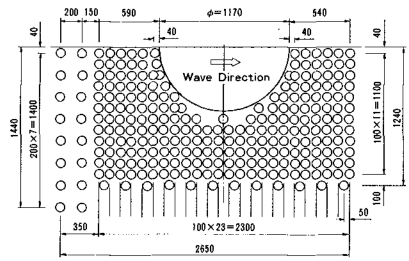


Fig.4 Observation points

3. Theoretical back ground

3.1 Inception of motion of particles under plane wave field

There have been already extensive research contributions in the area of prediction of inception of motion of particles under plane wave field. They are categorized into three approaches which follows;

(1) Critical velocity u_c is evaluated from Eq.(1), originally presented to give critical water depth, with the aid of linear (or nonlinear) wave theory.

$$(H/H_0)^{-1}(\sinh 2\pi h/L)(H_0/L_0) = \alpha(L_0/D)^n \quad , \qquad (1)$$

where H and L are wave height and wave length respectively at water depth h, suffix $_0$ indicates those parameters in the deep sea and D is diameter of sand particles. α and n are constants summarized in a table presented by Noda(1981), which vary with the condition of the boundary layer originally given by, Ishihara·Sawaragi(1960), Sato·Tanaka(1962) Horikawa·Watanabe(1966).

(2) The more direct method of obtaining critical velocity is to use Eq.(2).

$$u_c = \beta \cdot \Delta^{\gamma} \cdot D_{50}{}^{\delta} \cdot T^{\varepsilon} \ , \qquad (2)$$

where Δ is specific gravity of sand particle in water and T is wave period. $\beta, \gamma, \delta, \varepsilon$ are constants given by many researchers such as Bagnold(1946), Goddet(1960), Komar·Miller(1974). The merit of this formula is that it reflects the direct results of the experiments, but the demerit is that those constants vary with the different experiments.

(3) The third approach to calculating the threshold of the movement of sand particles is to use Eq.(3) and Eq.(4).

$$u_*/u_{b0} = \sqrt{f_w/2} = F_1(\,a_b/k_s,\ T\,) \quad , \qquad (3)$$

$$u_{*c} = F_2(u_* D_{50}/\nu) \quad , \qquad (4)$$

where, u_*, u_{*c} is the shear velocity and critical shear velocity respectively, f_w is the friction factor. u_{b0} is the velocity amplitude outside the bottom boundary layer, a_b is the amplitude of the excursion of water particles on the bottom, k_s is the bottom roughness and ν is the kinematic viscosity. The function form F_1 is given by Kajiura(1965), Jonsson(1966), Horikawa·Watanabe(1966), while F_2 is given by Shield's curve for steady flow as an approximation, or by Madsen·Grant(1976) in the oscilatory flow condition.

Eq.(3) gives shear velocity based on the consideration of the boundary layer, while Eq.(4) gives critical shear velocity, which is an experimental parameter. However, it is not certain at present whether these parameters can be applicable under the diffraction wave field where water particle motion is more complicated than with uni-directional oscillation.

3.2 Boundary layer equation under diffraction wave field

So far, the boundary layer equation of the oscillatory flow has been treated on the x-z plane, with x cordinate taken in the direction of the horizontal motion of the water particle induced by single directional wave (plane wave) motion and z in the vertical direction in which the boundary layer develops.

Here, to investigate the bottom shear caused by the multi-directional flow on the bottom where the path is elliptical, the boundary layer should be modeled in the x-y-z region, of which the x-y plane is taken on the bottom. In this respect, Tanaka·Shuto(1981), Fredsφe(1984) developed the models.

Tanaka(1981) treated the flow inside the boundary layer as a wave-current coexistent system. Let $\mathbf{u}=(u_x,u_y)$: the combined velocity inside the boundary layer on the x-y plane, p: water pressure, $\tau=(\tau_x,\tau_y)$: bottom shear stress, ρ: density of water, t : time, then,

$$\partial \mathbf{u} / \partial t = -(1/\rho)\ \nabla p + \partial(\ \tau/\rho)/\partial z \quad . \tag{5}$$

It is assumed that the shear stress can be estimated by the velocity of the oscillatory component u_w by

$$\tau/\ \rho = K_z(\partial u_w/\partial z) \quad , \tag{6}$$

where K_z is given by

$$K_z = \kappa\ u_w^*\ z \quad . \tag{7}$$

u_w^* is the shear velocity under the wave-current coexistent system. With the boundary condition at outside edge of the boundary layer, Tananka derived Bessel's equation and thus obtained the solution for the bottom shear in the wave-current coexistent system.

However, the attempt by the authors to apply his theory to the field where the orbital motion of water is elliptical (without current) failed to bear anything new in evaluating bottom shear. The reason for this was because, with the assumptions of Eqs.(6) and (7), the solution of the bottom shear stress τ_b depicts a complete similar Lissajous figure(ellipse) as the velocity u_b at the outside of the boundary layer, with a constant phase lag. This means there was no change in the maximum shear as is predicted by the two dimensional treatment.

Fredsφe(1984) has started with the same basic equations as Eqs.(5),(6),(7), and has derived the more direct equation to obtain shear stress but with the more simple assumption that the orbital motion is circle and the phase lag between a flow outside the boundary layer and that inside the layer is negligibly small, which is not always the case. His conclusion is that the shear stress with the circle orbit increases by 10~15% more than with the simple oscillatory flow. However, the assumption that the phase lag can be neglected is rather difficult to accept.

4. Experimental result

4.1 Verification for method of experiment

There are some uncertainties when it comes to defining sand particle movement, which has caused some deviations in the data obtained by various researches so far. There was a fear that the presence of the periscope disturbed the bottom flow. To judge whether the observation was correctly carried out and to compare the criteria of movement defined by the authors with that of established results, the verification experiment was carried out for the plane wave.

Fig.5 shows the result. The symbols in the figure show the rank of movement. The curves are also drawn using Eq.(1) to Eq.(4) for the sake of comparison. Dashed lines represent the initial movement obtained by Isihara·Sawaragi and Jonnson+Shields. The solid lines indicate the severe movement shown by Horikawa-Watanabe and Sato-Tanaka. The lines of Komar-Miller and Goddet fall firmly on these solid lines. The result of the experiment is in good agreement with the calculation lines, except for the small deviations. This means that the observation method was correct.

4.2 Inception of sand motion around a large structure

In Fig.6 shows the result of the observation on the movement of sand

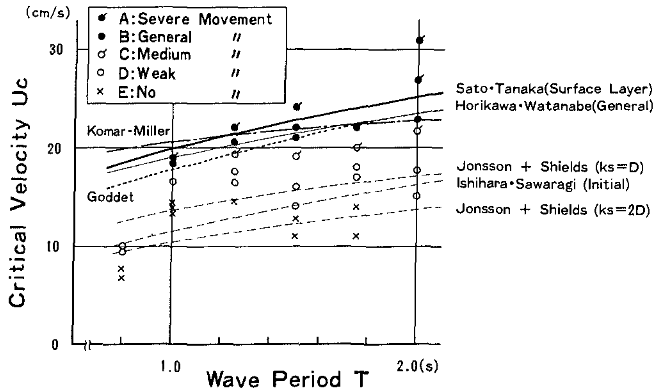


Fig.5 Critical velocity under plane waves

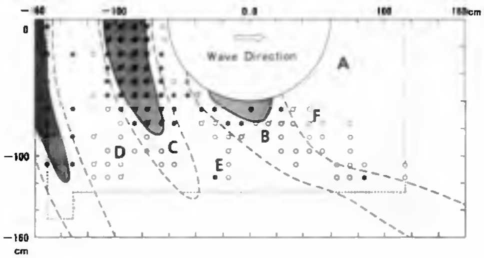


Fig.6 Particle movement(Circular-I, T=1.0s, H=8.0cm)

particles around a large scale circular cylinder. The observation area is enclosed by dotted lines and is somewhat rectangular in shape. The symbols have the same meanings as in Fig.5, while, for simplicity no symbols inside the observation area indicate no movement. The curves in Fig.6 are drawn by the method explained in Section 3.1. First, the bottom velocity field around a cylinder was calculated using potential wave theory, then it was compared with the threshold data obtained from the experiment for verification under plane waves explained in Section 4.1(see Fig.5). The data read from Fig.5 as follows; u_c= 0.15 m/s for the initial movement for T=1.0-2.0s, u_c=0.175,0.205,0.225 m/s for the general movement for T= 1.0,1.5,2.0s respectively. The light gray zones, enclosed by dashed lines, are for the initial movement, while dark zones, enclosed by solid lines, are for the severe movement. No color indicates no movement theoretically.

The general impression of the comparison of the state of movement between the experiment and the calculation is that they agree quite well. As for the initial movement, the sheltered area noted by character A in the figure agrees well, while in B and C where the particles were expected to move, they actually didn't move, and in D, E and F where no motion was expected some movement in fact occurred. As for the general movement, the agreement is fairly good.

The pattern of the sand movement in front of the cylinder ("front" here means the area facing the direct wave attack, and "lee" means the sheltered area, the opposite side of the front area), generally corresponds to that of the diffraction wave height. Severe movement occurred at the node, no movement or weak movement occurred at the antinode.

To summarize, even in the region of diffractive wave, the front side of the cylinder where the long crested standing wave was dominant, hence wave motion was rather two dimensional, as well as in the sheltered lee side where only small amplitude diffraction waves with their long crests penetrated, inception of motion agreed well with the conventional motion criteria. In other regions, such as to the side of the front of the cylinder where the orbit of the bottom water particles was circle or ellipse, the conventional formulae for inception were no longer valid, in the strict sense.

When the wave height decreases by only 1 cm, the pattern of the movement exhibits quite a significant change, as is shown in Fig.7. In this case, the calculations predict the general trend of movement well, but, the agreement does not reach the same extent as in the previous case. Especially to the side of the front area, the agreement becomes less. The prediction of the weak movement in this region by conventional formulae becomes more difficult than in the case of single plane waves.

The change of the wave period also changes the pattern of the movement. Fig.8 and Fig.9 show the case of T=1.5s and 2.0s respectively. The same comment as the above is drawn about the agreement. The longer the wave period, the more lee side the severe

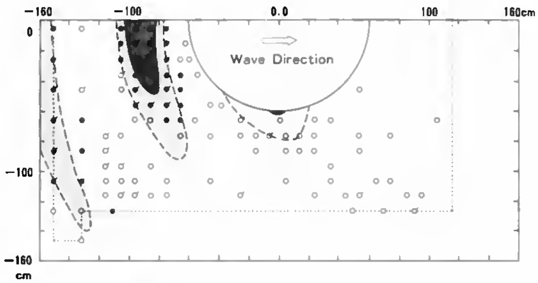


Fig.7 Particle movement(Circular-I, T=1.0s, H=7.0cm)

Fig.8 Particle movement(Circular-I, T=1.5s, H=6.0cm)

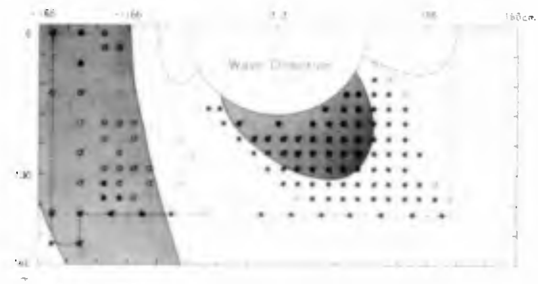


Fig.9 Particle movement(Circular-I, T=2.0s, H=8.0cm)

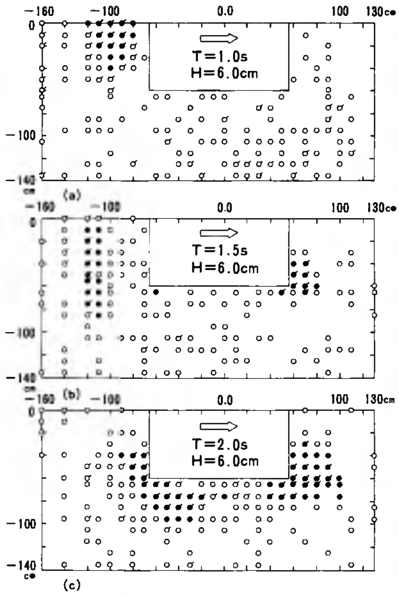


Fig.10 Particle movement (Square-I, θ=0°)

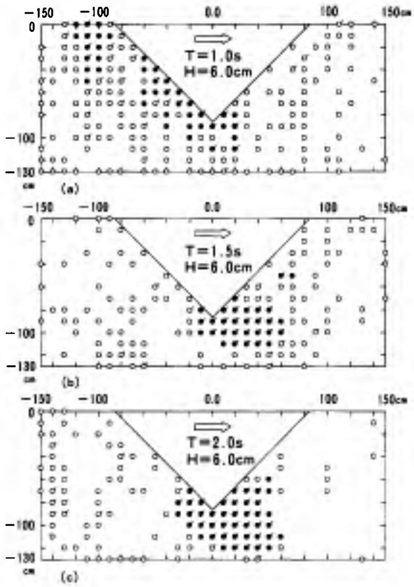


Fig.11 Particle movement (Square-I, θ= 45°)

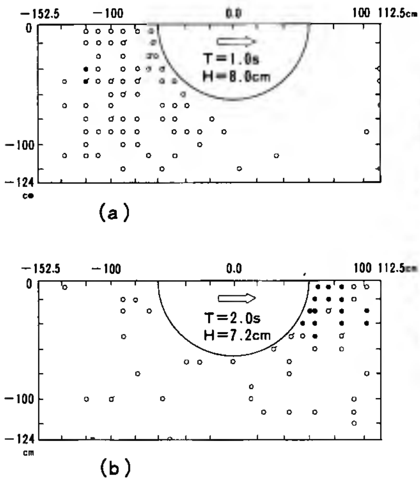
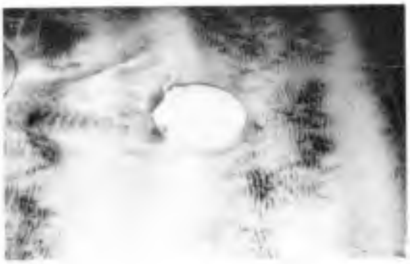


Fig.12 Particle movement (Circular -II)



Photograph 1 Wave breaking on the top of a submerged cylinder (Circular -II)

movement area shifted. The agreement of the calculation and the experimental result is generally good. However, again, the disagreement to the side of the front region is not negligibly small.

Fig.10 and Fig.11 show the cases of the square cylinder, in which wave directions are $\theta = 0°$ and $45°$ respectively. Square cylinders generally give a similar pattern of movement to that of the circular one. Again, the longer the period, at the side of the region further back the more severe the movement becomes. A characteristic of the square type is the accelerated motion at the corners. This trend is emphasized when the corner locates where the water velocity becomes most accelerated as in the case where $\theta = 45°$, shown in Fig.11.

The movement patterns of shown so far are generally similar to the scour patterns obtained in the model experiment done by the authors(Toue ·Katsui 1985), as well as in one conducted by Rance (1980).

There is less impact at the bottom of a submerged structure as shown in Fig.12(a). However, it sometimes helps wave breaking at the top of the body, hence the particles in the lee side are easy to move even in the sheltered area(see Fig.12(b)). Photograph-1 shows how a wave breaks on the top of a submerged circular cylinder.

4.3 Ripple formation around a structure

The bottom configuration was also measured with the thicker layer(depth:30cm) of finer sand(D_{50}=0.15 mm), which was easier to move. Photograph-2 and Fig.13 show two examples of the results, which give a general view of the scour pattern around a circular type cylinder and a square type cylinder respectively. The pattern of erosion and deposition in the front area corresponded to that of severe motion. Erosion occurred to the side at the front and in the lee side.

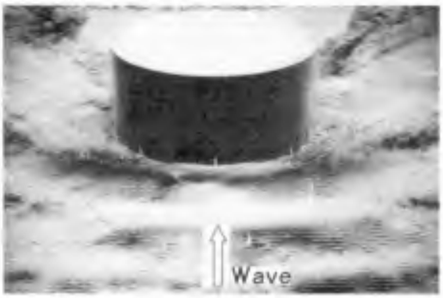
Laboratory experiment on the morphology of the bottom, however, has its limitations. Whenever the data, such as the scour hole depth or scouring area, are translated to the case of the prototype or to the design procedure, special care should be taken with the scale effect. But, the pattern of the ripple formation around a structure is quite typical in the region to the side of the front where diffraction waves dominate as can be clearly seen in Photograph-3. This fact may give some clues in understanding the mechanism of bottom shear or presumable special flow.

5. Possible approaches to understanding the phenomena

It was confirmed that the inception of sand particle motion in the region where waves from different directions are superimposed on each other differs from what is calculated by conventional two dimensional formulae. This phenomenon could be considered inherent, too, in front

Fig.13 Bird's eye view of measured bottom change
(Square-I, θ=0°, T=1.0s, H=10.0cm, t=120min)

Photograph 2 Bottom change around a cylinder
(Cicular-I, T=1.0s, H=11.0cm, t=120min)



Photograph 3 Ripple pattern to the side of the front of a cylinder

of a breakwater when waves come obliquely to the normal direction of the breakwater and thus making a short crested standing wave field.

The phenomenon should be fully understood for the proper design of the scour protection around a structure. The reasonings can be accounted for in several possible ways; the measurement error, the nonlinearity of the bottom velocity (the velocity was estimated by linear wave theory), the special transformation of the bottom shear caused by the the elliptical orbital motion of the water particles or the induced flow around a structure.

As for the first possibility, there might have been, to some extent, wave reflection from the other end of the wave basin, inhomogeneity of the incident wave and the ambiguous judgement of sand movement despite the efforts to avoid them. The use of the linear wave theory to obtain the bottom velocity proved not to influence the accuracy. However, most of the above suspicions are cleared up with the veification test for the plane wave field already stated at Section 3.1.

Secondly, it would be natural to consider that the development of the boundary layer is influenced by the elliptical orbital motion of the water particles. Fig.14 shows the elliptical Lissarjous figure of the velocity vector, which is typical in the region to the side of the front of the cylinder. Even though the attempt by the authors failed to introduce theoretically the special development of the boundary layer there, the bottom shear, hypothetically, may be distorted both in amplitude and in phase lag from those in the two dimensional flow field, as Fredsφe(1984) partially has introduced the bottom shear where the orbital motion was circle.

The third possibility is the formation of the flow. In the experiment, the flow was also observed using dye from the point of view of directional flow not quantity of flow. There was a steady flow from the side of the cylinder to its lee side with a magnitude of a few cm's per second. It can be understood to a certain degree with the help of Fig.15, which shows a flow pattern of mass transport velocity around a circular cylinder inside the boundary layer. The figure was calculated after Mei(1983). But, in front of the cylinder, the flow

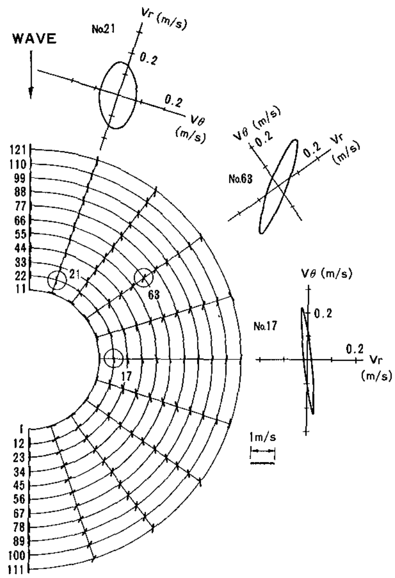


Fig.14 Lissajous figures of bottom velocity vector around a cylinder(Circular -I)

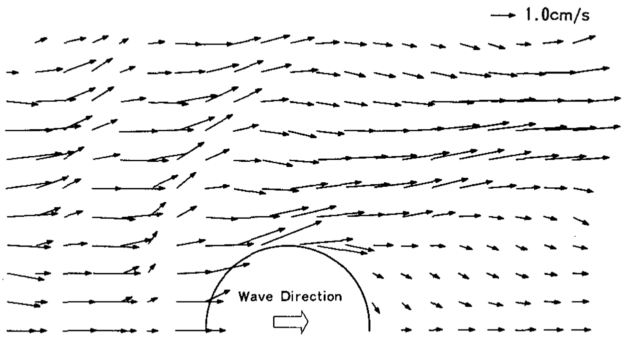


Fig.15 Mass transport velocity around a circular cylinder
(Circular -I, T=1.0cm, H=10cm)

was observed to be in the offshore direction (against the direction of the wave incidence), with a magnitude of the same or a little stronger than that of the side flow. Thus in the area to the side of the front of the cylinder there was a kind of dead space with respect to the steady flow, in which the dye stayed for a considerably long time creating a circulation with the concentration of the dye color being faded at this particular place. Fig.15 cannot account for this kind of flow pattern. This fact indicates that there should be some other mechanism which creates the flow around the structure, something which may be caused by the gradient of radiation stress as is the case in the surf zone.

6. Conclusion

The basic, or preliminary, study of the inception of sand particle motion around a structure using the model experiment was carried out, as well as a simple application of the formulae established in plane wave motion. Through this study, it was confirmed that at the area where the wave motion is more two dimensional, areas like front area or sheltered area, the conventional formulae are applicable, but in the area where the wave field is more complex that the orbital motion of water particles depict circlular or elliptical path, there are discrepancies between such formulae and the experimental results.

The reasons of the discrepancies can be ascribed to two kinds of phenomena. One possibility is the flow induced by mass transport inside the boundary layer and/or by a flow which is presumably caused by the gradient of radiation stress around a structure. The second reason could be that the boundary layer, hypothetically, may develop in a more complex manner such as with some distortion in three dimensional space in the area where water particle figures the elliptical Lissajous.

Further research is required both on the theoretical treatment and to obtain a more precise measurement data concerning the flow in the region where multi-directonal waves are superimposed themselves.

Acknowledgement

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