An Experimental Evaluation of Oil Slick Movement Caused by Waves[1]

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ABSTRACT

The wave-induced movement of oil lenses and other floats was studied by using mechanically generated gravity waves in a water tank. The measured surface drift velocities were in all cases higher than those predicted by the Stokes theory of deep water waves. For wave conditions at which the Stokes velocity is higher than 2 cm sec $^{-1}$, the measured surface velocities were 35–150% higher than the Stokes velocity. The drift velocity was insensitive to float size when the float length was larger than one wavelength. Thin, flexible, plastic floats were found to have the same drift speed as similarly sized oil lenses. A discussion of the movement of oil spills on the open ocean is included.

1. Introduction

The frequent occurrence of oil spillage into the ocean is a pollution problem of increasing magnitude. The oil spills occur most frequently when oil tankers run aground, collide, or discharge their oily ballast water overboard. Once an oil spill is discovered, the ability to accurately predict its subsequent path is necessary for determining the pollution potential for shorelines and for effectively mobilizing available clean-up equipment. Conversely, in the event that no party admits to spilling the oil, the predictive ability could be used to determine where the oil came from and perhaps who spilled it.

Several investigators have made efforts to correlate oil spill movements solely with local wind conditions. Smith (1968) reports that for the Torrey Canyon spill a correlation was obtained by assuming that the oil moves in the direction of the wind with 3.41% of its velocity. Similarly, Tomczak (1964) obtained a 4.2% correlation for the Gerd Maersk oil spill. In the latter case, the wind speed was measured about 10 m above the sea. Although these correlations provide useful approximations to the oil speed and path, more accurate correlations are needed.

For the Torrey Canyon oil spill, the observed oil path and the wind speed correlation path repeatedly cross each other and then separate from each other (Smith, 1968). Moreover, the deviations occur somewhat regularly and with a period of from 2–5 days. This type of deviation would not be caused by tidal currents or permanent ocean currents but may well have been caused by the influence of waves.

2. Existing analyses of wave-induced drift

The wave theory of Stokes (1847) predicts a net mass transport in the direction of a wave propagation. When the water depth d is at least half as large as the wavelength L, the expression given by Stokes for the mass transport velocity at the water surface is within 0.5% of

$$V=C(\pi H/L)^2, \tag{1}$$

where H is the wave height and C the wave speed.

The typical magnitude of the Stokes velocity on the open ocean can be estimated by consulting published data of typical sea conditions. Based on empirical data, Bigelow and Edmonson (1947) indicate that the age of a wave, expressed as the wave velocity divided by the wind velocity U, influences the wave steepness H/L as shown in the first two columns of Table 1. Using these values of H/L as a function of C/U, Stokes theory [Eq. (1)] gives the transport velocities shown in the third column of Table 1. It can be seen that one obtains Stokes velocities as high as 2.9% of the wind velocity producing the waves. This magnitude is large enough to account for the deviation found in the wind speed correlations reported by Smith for the Torrey Canyon spill.

Stokes' analysis is based on an inviscid irrotational wave field. Longuet-Higgins (1953) has analyzed the effect of viscosity on drift profiles in closed wave channels of finite depth. Unfortunately, his solution was not developed for deep water waves. As the product of the water depth d and the wavenumber, $k=2\pi/L$, becomes much larger than unity, the Longuet-Higgins surface transport velocity becomes unbounded. This fact is reported by Huang (1970).

Chang (1969) analyzed the influence of viscosity for deep water conditions ($kd\gg1$) and found that although

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TABLE 1. Correlation between wave age, wave steepness and the Stokes velocity. (First two columns taken from Bigelow and Edmonson, 1947.)

Age of wave, expressed as wave velocity divided by wind velocity (C/U)	Steepness of wave (H/L)	$\frac{\text{Stokes velocity}}{\text{wind velocity}} \times 100\%$
0.1–0.5	0.076	0.57–2.85
0.6	0.070	2.90
0.7	0.061	2.56
0.8	0.053	2.20
0.9	0.046	1.86
1.0	0.040	1.58
1.1	0.035	1.19
1.2	0.031	1.12
1.3	0.028	1.01
1.4	0.025	0.82

the drift profiles are influenced by viscous effects, the surface transport velocity is essentially the same as given by Stokes. Huang (1970) then included viscous effects for arbitrary values of kd and for either a clean or dirty water surface. In both cases Huang's surface velocity is near the Stokes velocity for values of $kd > 2$.

The works of Longuet-Higgins (1953) and of Huang (1970) are from the Eulerian point of view, while Chang (1969) used a Lagrangian description. More recently Ünlüata and Mei (1970) used a Lagrangian approach closely following that of Chang, but for arbitrary values of kd. Ünlüata and Mei find that as kd becomes large, the surface transport becomes unbounded. This conclusion disagrees with the result of Chang (1969), which is puzzling, because the two investigations are so similar in their approach. In addition, Ünlüata and Mei raise doubts about Huang's (1970) solution by pointing out an error in the free surface boundary condition which was used by him. It is apparent that for deep water conditions, none of the available theories adequately accounts for the influence of viscosity.

3. Previous experiments

Mitchim (1940), Russell and Osorio (1957), and Chang (1969) measured wave-induced surface drifts in wave tanks. In all cases where $kd > 2$, the measured surface drift correlated reasonably well with the Stokes velocity. The following differences between these experiments and ocean oil spills should however be pointed out:

First, in all cases the surface drifts were measured with small floats or neutrally buoyant particles designed to follow the movement of the water itself. An oil layer, however, might conceivably move at a somewhat different velocity than the water beneath it. Also, the presence of even a very thin oil layer might influence the movement of the water itself.

Second, the existence of a backflow beneath the water surface is reported by both Mitchim (1940) and by Russell and Osorio (1957). These experiments were conducted in long, narrow wave tanks equipped with a mechanical wave generator at one end and a sloping beach at the other end to suppress wave reflections. Data were taken when the wave generator had been running for an hour or more. In this steady-state condition, the net mass flux across any vertical transverse cross section of the tank must be zero. Thus, forward flow near the water surface produces a backward flow near the bottom of the tank as Mitchim (1940) reported, or at the center depth of the tank, as Russell and Osorio (1957) reported. Moreover, the magnitude of the backflow current is not small compared to the surface drift. Indeed, the backflow velocities reported by Russell and Osorio (1957) are always larger than 12% of the forward surface drift velocity. Ünlüata and Mei (1970) indicate that the time required for the backflow current to develop after the wave generator is turned on is of the order of T/V where T is the tank length and V the Stokes surface drift velocity [Eq. (1)]. Thus, on the open ocean, the subsurface backflow current might never develop. Moreover, the large water depth of the open ocean would allow the condition of zero net horizontal mass flux to be satisfied with a backflow current that is infinitesimally small. It thus appears that the existing experiments may not be applicable to open ocean conditions. Moreover, it is difficult to see how the existing theories can be used to interpret these experiments, because of the inherent deficiencies in all the theories, as noted above.

4. Description of the experiment

Oil slicks were made by placing various amounts of paraffin oil onto a water surface. This oil does not continuously spread on water but rather forms lenses of stable diameter. In addition to the oil floats, thin, flexible plastic floats of various sizes up to 64.0 cm long were also used. The experiments were conducted in a wave tank 0.61 m deep by 0.30 m wide by 6.1 m long (Fig. 1). The tank was equipped with a mechanical wave generator at one end and a sloping beach at the other.

The following experimental procedure was used. The water in the tank was allowed to become quiescent, and the oil float (or plastic float) was carefully laid on the

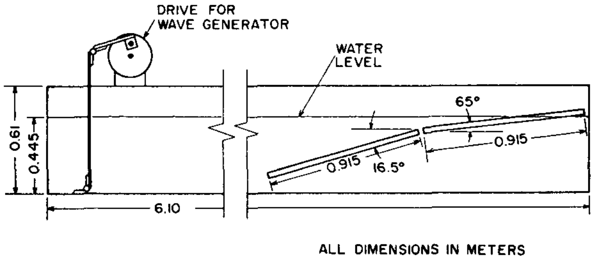

FIG. 1. Schematic of wave tank.

water surface about 30 cm upstream of the test section, which was 61 cm long, and located 218 cm from the wave generator. The wave generator was then turned on, and the float moved into the test section under the wave action. The time required for the float to travel through the 61 cm long test section was then measured. This measurement completed the data run. In each data run, the wave generator was on for no longer than 4 min.

One of the reasons for adopting the above test procedure was to avoid the backflow current described above. Numerous time-exposure photographs of chalk dust particles sprinkled into the water indicate that no backflow occurred in the tank when the above procedure was followed. This is as expected because the wave generator was not on long enough for the current to develop. (The value of the quantity T/V discussed above is always less than 75 sec for the present experiments.) The chalk dust photographs did indicate, however, that the generator was on long enough for the wave conditions to be steady. This is shown by the fact that the chalk dust particles had the same orbit diameter and forward orbital displacement for all the photographs taken during any one run. It is important to note that the chalk dust particles also indicated that during the experiments the non-uniform conditions near the beach and near the wave generator did not approach within 1 m of the test section.

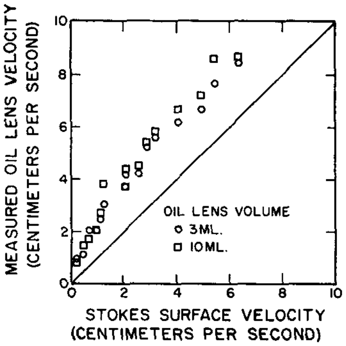

Fig. 2. Comparison of oil lens velocity with the Stokes velocity.

Another reason for adopting the above test procedure was to avoid the influence of surface contaminants. Thus, it was found that when the wave generator had been running for longer periods of time, say 20 min, surface contaminants concentrated at the beach end of the tank. When the float encountered this densely packed layer of contaminants, it would slow down or stop. Then when the wave generator was turned off, the layer of contaminants would spread back toward the wave generator. In the above test procedure, there is not sufficient time for the surface contaminants to become densely packed, and the contaminants do not influence the float movement. This conclusion was reached after noting that changing the water in the tank and scrubbing the tank walls did not alter the float velocities. It should be mentioned that the water surface was skimmed after each data run. The skimming was accomplished by flowing air across the water surface to concentrate the contaminants at the beach end of the tank, where the surface water was removed by opening several drains located at the water level.

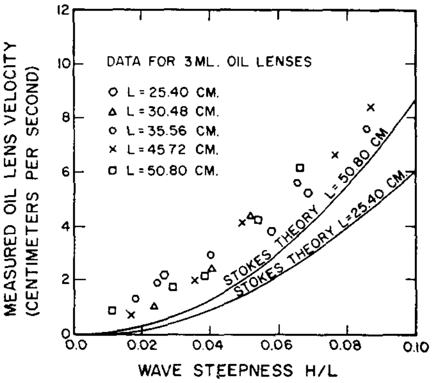

Fig. 3. Wave conditions for the 3-ml oil lens data.

Finally, the above procedure is the only one that gave repeatable results. This is because, with the present wave tank, only an unsteady backflow current could be obtained. Russel and Osorio (1957) reported a similar result when they generated waves longer than about 10 m in their 55 m long tank. Perhaps the present tank would give a steady backflow current for very short wavelengths, but waves shorter than 25 cm were found to be unsuitable because they decayed rapidly in height as they moved down the tank.

5. Experimental results and discussion

Fig. 2 shows data for oil lens velocity vs Stokes velocity. It can be seen that the oil lens velocity is always higher than the Stokes velocity. It can also be seen that in most cases the 10-ml oil lens (7 cm diameter) traveled faster than the 3-ml oil lens (5 cm diameter.)

The wave conditions for the data shown in Fig. 2 are presented in Figs. 3 and 4 for the 3- and 10-ml oil lenses,

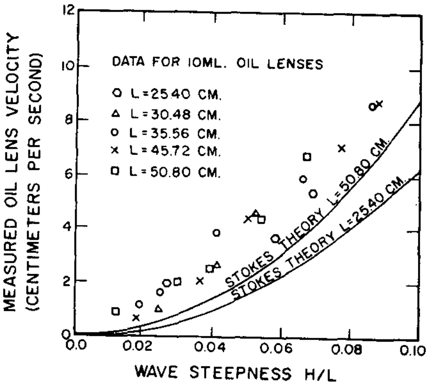

Fig. 4. Wave conditions for the 10-ml oil lens data.

respectively. The wave steepness is plotted on the abscissa, and the oil lens velocity is plotted on the ordinate for the various families of wavelengths indicated. Unfortunately, the range of wavelength covered by the data is not sufficient to cause a significant variation in the Stokes velocity. This fact is evident from an inspection of the solid lines in Figs. 3 and 4. These lines represent the Stokes velocities for 25.4- and 50.8-cm waves (the wavelength range covered by the data). Waves with a wavelength <25.4 cm could be generated in the tank, but as mentioned above they decayed rapidly as they moved down the tank, so thay were unsuitable for this investigation. Waves longer than 50.8 cm were likewise unsuitable because they would not be deep water waves for the water depth (44.5 cm) used.

Fig. 5 is a plot of measured float velocity vs the length of the float, with data for both oil lenses and plastic floats. Since the range of oil lens diameter covered in Fig. 5 is much larger than in Fig. 2, the influence of lens diameter on lens speed is more clearly evident. Fig. 5 indicates that for a wavelength of 25.4 cm and for lens diameters between 2.4 and 13.2 cm, the lens speed increases with lens diameter.

The next question is, at what lens diameter does lens speed become insensitive to lens size? This question could not be answered by using larger oil lenses, because the tank was too narrow; therefore, long but narrow plastic floats were prepared. The floats were all 2.5 cm wide, but the lengths varied between 4.8 and 64.0 cm. They were always placed longitudinally in the tank.

The plastic floats were made of thin, flexible sheets of quilted plastic. This material is commercially available for wrapping food and consists of two sheets of plastic, bonded together such that air cells are formed between the two sheets. These square cells of air measure 0.7 cm on a side and the thickness of the total quilted material is 0.015 cm.

It can be seen from the plastic float data shown in Fig. 5 that the float velocity becomes insensitive to float size when the float length is larger than the length of the waves used (25.4 cm). This suggests that the wavelength is the critical parameter. This conclusion is strengthened by similar data obtained for a different wavelength (50.8 cm) and shown in Fig. 6.

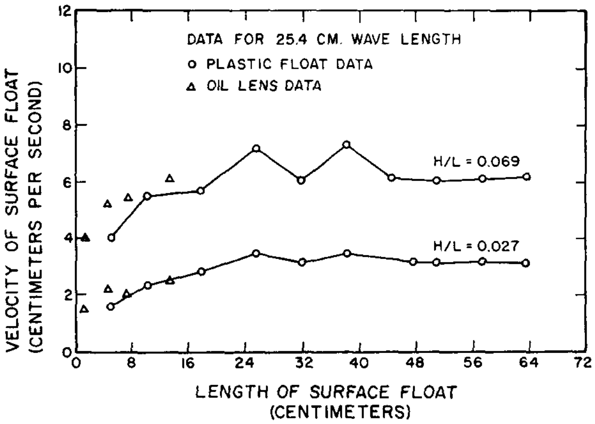

FIG. 5. The influence of float material and float size at 25.4 cm wavelength.

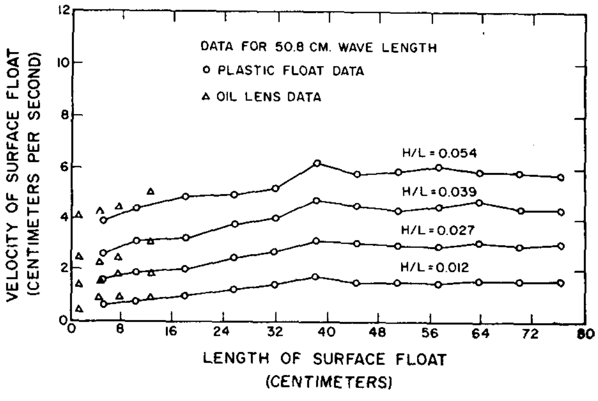

FIG. 6. The influence of float material and float size at 50.8 cm wavelength.

It can also be seen from Figs. 5 and 6 that the oil lenses had the same velocity as similarly sized plastic floats. This suggests that the float velocity is relatively insensitive to float material, as long as the float material is flexible and as long as the float does not penetrate very deeply into the water.

6. Summary and conclusions

A positive conclusion drawn from the experiments is that float speed becomes independent of float size when the float length is larger than one wavelength. The experiments also indicate that float speed is relatively insensitive to float material if the float is flexible and rides lightly on the water. These two observations would not be expected to arise from either the transient procedure or the shortness of the wave tank.

The measured values of the wave-induced surface drift were in all cases higher than those predicted by the Stokes theory of deep water waves. For wave conditions at which the Stokes velocity is higher than 2 cm sec^{-1}, the measured surface velocities were 35–150% higher than the Stokes velocity. Previous investigators have reported closer agreement with the Stokes theory, but they also report large subsurface backflow current in their wave tanks. The procedure used in the present work avoided the backflow and thus may be more representative of open-ocean conditions.

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