Entrainment and Deposition of Fine-grained Sediments
세립 퇴적물 부상과 퇴적에 관한 연구

해양연구소 해양환경공학실
강 시 환 (姜始桓)

Abstract

Entrainment and deposition experiments were conducted in fresh water on four groups of sediments: three well-defined sediments of uniform composition and narrow-size distribution (1 to 9 μm, 10 to 50 μm, and 50 to 90 μm), and a fourth group which was a mixture of these three sediments.

In the entrainment experiments and at a particular stress, the steady-state suspended sediment concentration of the coarse group was the lowest while the concentrations of the fine and medium groups were higher than that of the coarse group but were similar to each other. Deposition experiments generally showed an exponential decrease of suspended sediment concentration with time with the decay time being a function of particle size and applied stress.

1. INTRODUCTION

Because of the importance of fine-grained sediments in the transport of contaminants, considerable experimental and field work concerned with the entrainment and deposition of these sediments, expecially in rivers and estuaries, has been and is being done. A major difficulty in the interpretation of the results of this work is the fact that sediments consist of a mixture of particles with widely varying size and composition. For example, particle sizes of natural sediments generally vary over three orders of magnitude (Lick, et al, 1984).

In order to understand the effects of particle size on entrainment and deposition, we have performed entrainment and deposition experiments in fresh water on three well-defined, fine-grained sediments of uniform composition (98% silicon dioxide and generally spherical shape), each with a different, narrow-size distribution (1 to 9 μm, 10 to 50 μm, and 50 to 90 μm). This range is typical of the range of particle sizes prevalent in rivers and estuaries. Experiments were also performed on a fourth sediment which was a mixture of these first three sediments.

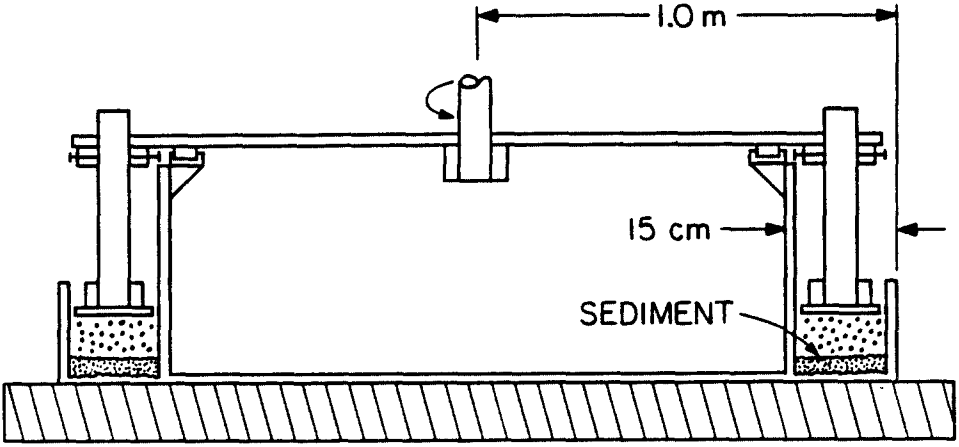

Figure 1. Schematic diagram of flume.

The experiments were conducted in an annular channel, 15 cm wide and 2 m in diameter (Figure 1). A rotating top produced a turbulent flow which in turn exerted a shear stress on the sediment-water interface. Azimuthal turbulent boundary layer velocity profiles were measured using a laser doppler anemometer (DISA 55L 90a) and the law of the wall was used to obtain values of the bottom shear stress for a particular rotation rate (Kang, 1983).

Entrainment experiments (described in section 3) gave information on the effect of particle size on the relation between the applied shear stress and the steady-state concentration of suspended sediment. Deposition experiments were also conducted and the results of these experiments are described in section 4.

2. SETTLING SPEEDS AND PARTICLE SIZES

For each sediment group, settling speeds were determined by the pipette method (Royse, 1970). Effective particle sizes were then determined from Stokes' relation between particle sizes and settling speeds. Particle sizes larger than 63 μm were determined by sieving.

Results of these measurements for each of the three well-defined sediments and for the mixed group are shown in Figure 2. The fine, medium, and coarse groups respectively had median sizes of 3.7 μm, 22 μm, and 78 μm while more than 90% of the particles in the fine, medium, and coarse groups were between 1 and 9 μm, 10 and 50 μm, and 50 and 90 μm respectively. The mixed group, which was a mixture of the three previous groups (almost distinct), had a median size of 17 μm with particles ranging in size from 1 to 90 μm.

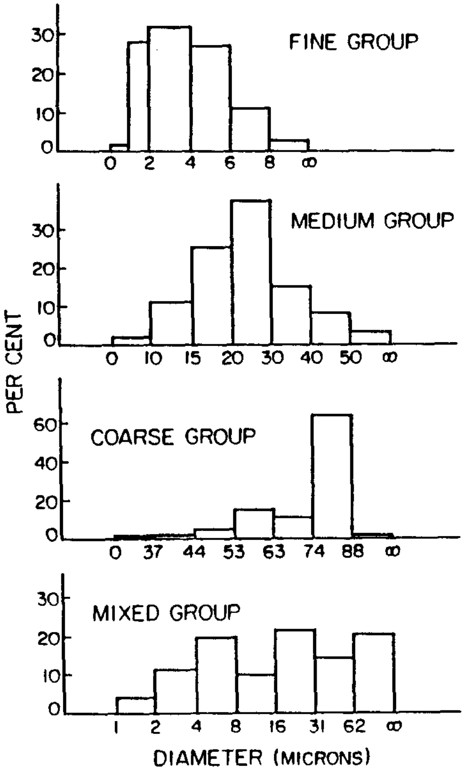

Figure 2. Particle size distributions for the four groups of sediments.

Settling speed measurements were conducted both in tap water and in distilled, deionized water with a dispersant added. In the latter case, the sediments should exist as individual grains with no aggregation into flocs. For the mdeium and coarse groups, no differences between the measurements in the two different media were noticeable. For the fine group, slight deviations were apparent for particles in the 0.5 to 2.0 μm size range indicating that particles in this size range (about 10% of the particles in the group) were moderately flocculated in tap water during settling.

3. ENTRAINMENT

Entrainment experiments were conducted as follows. The sediments in the flume were first thoroughly mixed with the overlying water and then allowed to settle for 24 hours. At this time, the water in the flume was at rest and the sediment concentration in the overlying water (depth of 5 cm) was approximately zero. The lid of the flume was then rotated at a constant speed corresponding to the desired stress. Because of this, the sediments were entrained and the sediment concentration in the overlying water increased, rapidly at first and then more slowly until a steady state was reached. A typical concentration versus time plot is shown in Figure 3.

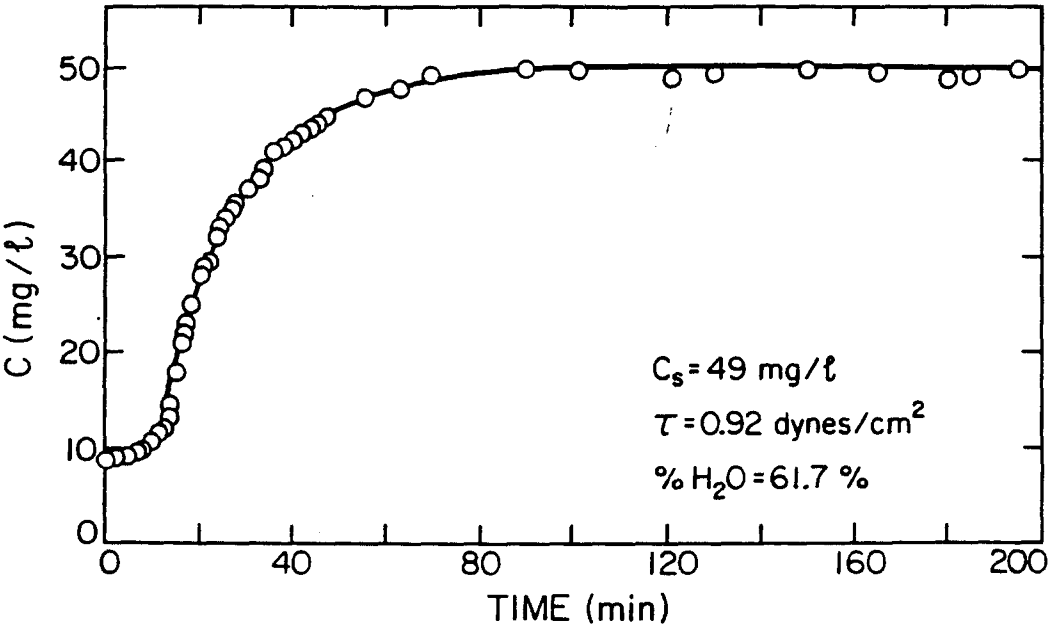

Figure 3. Sediment concentration as a function of time during a typical entrainment experiment.

This steady-state concentration is due to a dynamic equilibrium between entrainment and deposition and depends on (a) the entrainment rate E, which is a function of stress, particle size, and cohesiveness of the bed (amount of sediment available for entrainment at a particular stress) and (b) the deposition rate D, which is a function of particle size and stress. Although in general the dynamics of this steady state are quite complicated, two limiting cases can be described simply. First, if it is assumed that all particles have uniform size and properties and do not compact, the entrainment rate is constant and the deposition rate is $D = \beta C$ where β is a constant. The net flux, defined by $q_s = E - D$, is given in the steady state by

$$q_s = E - \beta C_s = 0$$

where $C_s = E/\beta$ is the steady-state concentration. In the second limiting case, deposition is ignored entirely but the entrainment rate is taken to be dependent on the cohesiveness of the bed and/or possibly particle size, both of which vary with depth. In this latter case, the amount of sediment which can be entrained at a particular stress is generally limited and this amount determines the steady-state concentration.

Note that in the first limiting case, if the overlying water was cleared of sediment, additional sediment would be entrained indefinitely (or at least until the bottom sediments were all entrained or changed character). In the second limiting case, no additional sediment would be entrained.

A plot of these steady-state concentrations as a function of shear stress and size group is given in Figure 4. At each shear stress, the following can be seen: the suspended sediment concentration of the coarse group was the lowest; the concentrations of the fine and medium groups were similar to each other but were higher than that of the coarse group; and the concentration of the mixed group was highest of all.

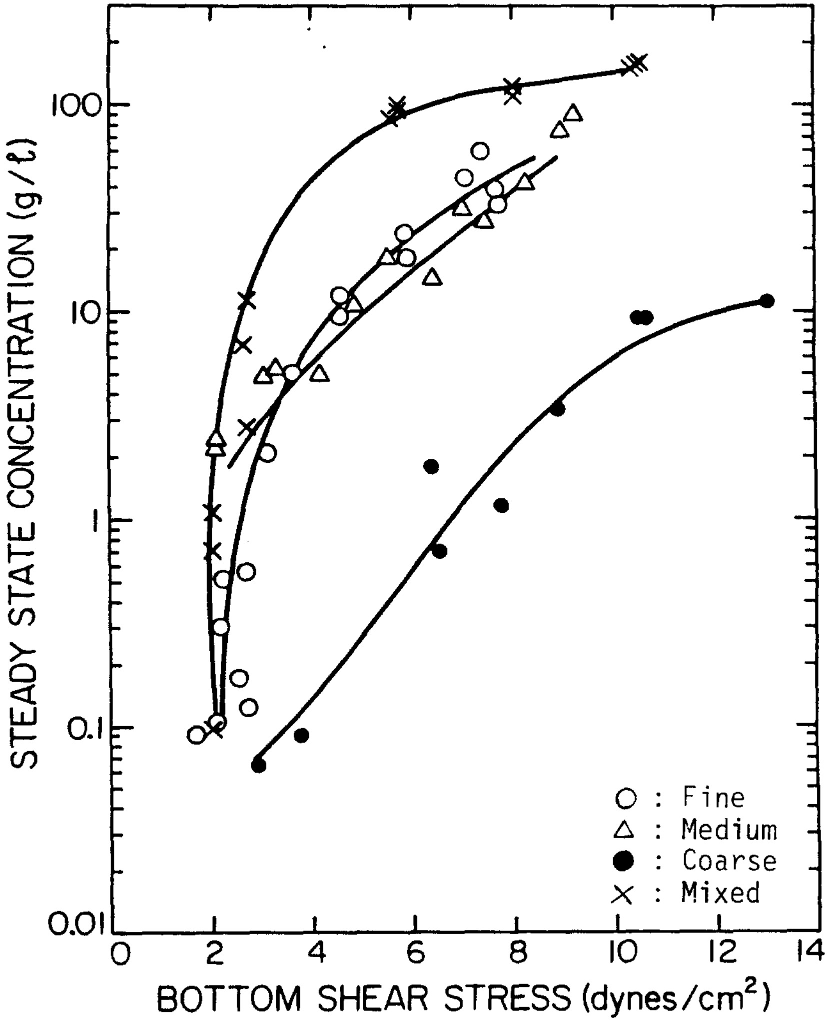

Figure 4. Entrainment experiment. Steady-state concentrations as a function of bottom shear stress for the four groups of sediments.

The coarse group would be expected to have the lowest concentration at a given shear stress since the particles were largest, more difficult to resuspend, and would also settle out more rapidly after resuspension. The medium and fine groups would be expected to have higher concentrations than the coarse group since the particles were smaller. However, the similarity of the fine and medium groups is interesting. The degree of bed compaction was somewhat greater for the fine sediments than for the medium sediments and this implies a smaller entrainment rate for the fine sediments. The smaller particle size of the fine sediments implies a larger entrainment rate. These two factors presumably approximately compensate each other and the net result is that the fine and medium sediment concentrations are approximately the same, at least for the present stresses. Compaction of the bed was not noticeable for the coarse sediments.

The mixed group, which had the highest concentration, consisted of a mixture of fine, medium, and coarse particles which were generally randomly scattered throughout the bed. The larger particles are not cohesive. By being scattered throughout the bed, they tend to separate the fine sediments and reduce the tendency of these latter sediments to aggregate. The end result is a less cohesive bed than if the bed were of uniformly fine sediments and this leads to the large suspended sediment concentrations for the mixed group.

It is interesting to examine the characteristic times necessary to reach the steady state. If the sediments have uniform size and properties and do not compact, the characteristic time can be shown as h/w_s, where h is the depth of the water in the flume (5 cm) and w_s is the settling speed of the particles. For the smaller particles in the coarse, medium, and fine groups, h/w_s is respectively approximately 25 s, 140 s, and 14,000 s. The experimental results indicate characteristic times of approximately 30 s for the coarse group and 150 s for the medium and fine groups. While the coarse and medium groups are reasonably close to the theoretical values, the fine group has a much smaller characteristic time than the theoretical value. This is again due to the aggregation and strong compaction of the bed with depth when fine sediments are present. Because of this, less sediments are available for entrainment in this latter case, i.e., the entrainment rate is a function of the depth and rapidly goes to zero.

4. DEPOSITION

Deposition experiments were also conducted and were as follows. Initially the suspended sediment concentration was zero. While the flume was operating at various prescribed stresses, sediments were introduced into the water and allowed to deposit. The suspended sediment concentration was monitored as a function of time.

The range of streses were 1 to 14 dynes/cm². Initial concentrations were approximately 1 gm/ℓ. Experiments were conducted with the fine, medium, and coarse sediments.

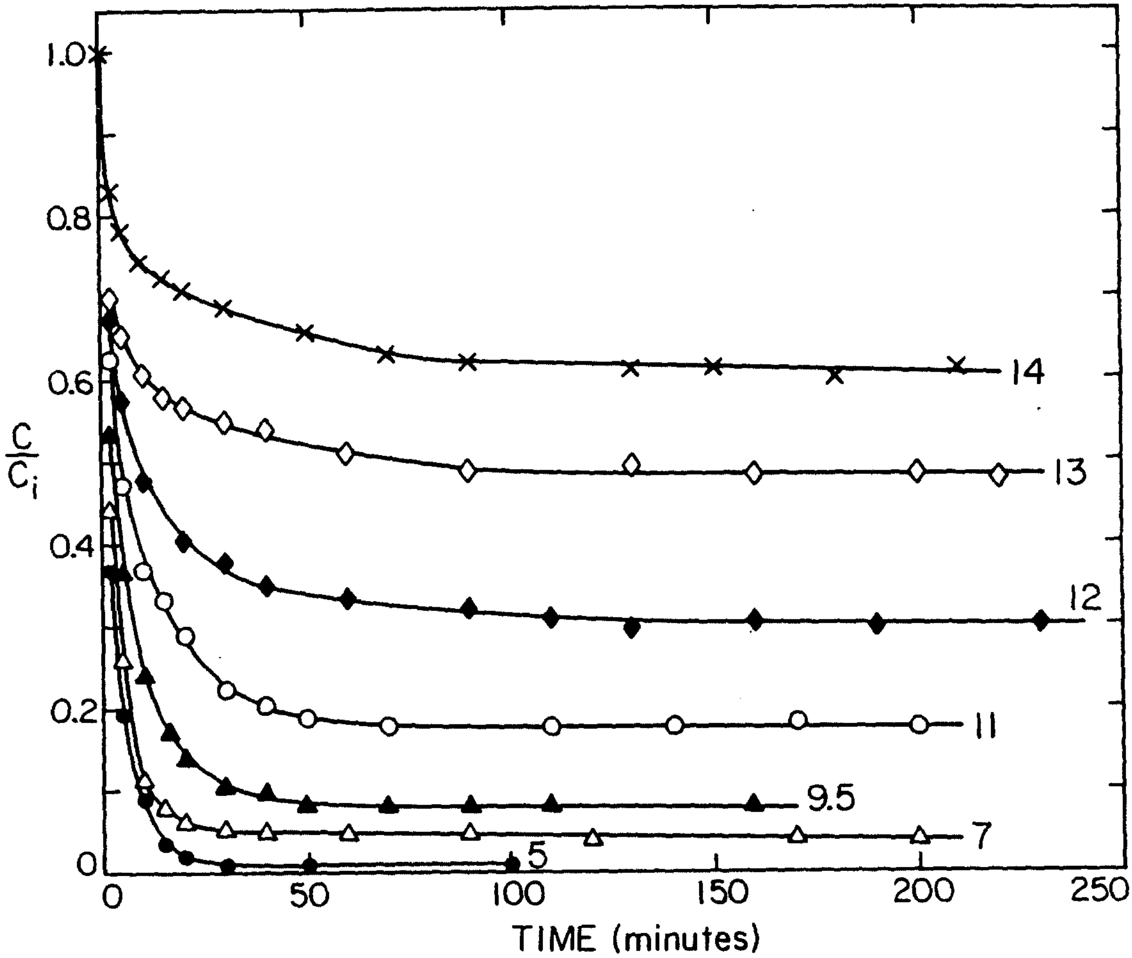

Figure 5. Deposition experiment. Suspended sediment concentration as a function of time for the medium group.

Consider the results for the medium sediments, shown in Figure 5. It can be seen that for each stress the sediment concentration decreased approximately exponentially with time until a steady state was reached. Note that the characteristic decay time increased with stress. For the uniform-size, uniform-property particles with no bed compaction, theoretical decay time of $t_1 = h/w_s$ has values of 1 to 15 minutes for particles of 10 to 50 μm size, approximately in agreement with the observations at least for the lower stresses.

However, the theoretical decay time is independent of stress, at least for particles greater than about 1 μm. In Figure 6, deposition parameter β proposed by Lick (1982) is shown as a function of particle size. In general, the capture efficiency is probably less than one and therefore the effective β, say β^*, is smaller than the ideal β by some factor α where $0 < \alpha < 1$, i.e., $\beta^* = \alpha\beta$. Since the probability of capture by the bed probably decreases as the stress increases, β^* should decrease and the decay time $t_1 = h/\beta^*$ should increase as the stress increases, in agreement with the experimental results for the medium sediments (Figure 5). The same general results are valid for the fine and coarse sediments.

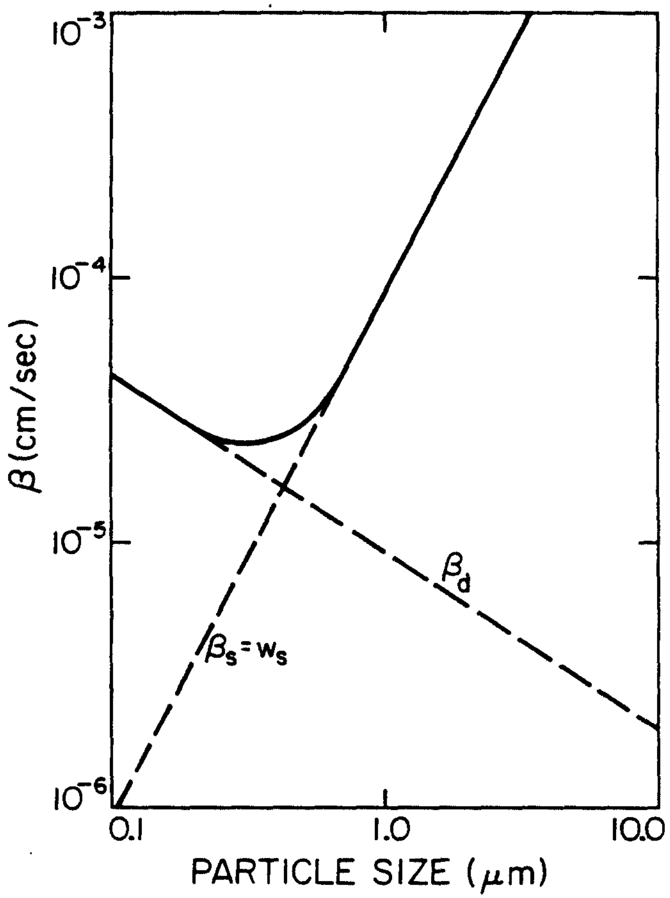

Figure 6. Deposition parameter β as a function of particle size.

5. CONCLUSIONS

The aggregation and compaction of the bed for the fine and medium groups caused these groups to behave similarly in the entrainment experiments. Aggregation was not a factor in the deposition experiments so that the results for these two groups in this latter case were not similar. For cohesive sediments, due to bed compaction with depth, only a finite amount of sediment could be entrained at a particular stress. The deposition experiments showed an approximate exponential decrease of the suspended sediment concentration with time in agreement with the theoretical decay time of h/w_s. This decay time was inversely proportional to the particle size and increased with increasing stress as would be expected if the capture efficiency of the bed decreased with increasing stress.

Real sediments have widely varying composition, both in particle size and mineralogy. Appreciable fractions of a particular sediment may be larger than 100 μm and also smaller than 1 μm. The particles greater than 100 μm should generally be non-cohesive and behave like the coarse group described here. The particles on the order of 1 μm and smaller should generally be cohesive and behave somewhat like the smaller particles in the fine group. As indicated above, real sediments may have quite different characteristics than their median size would indicate. Therefore, in order to predict the entrainment, deposition, and transport properties of real sediments, the distributions of particle size and mineralogy for these sediments must be known.

ACKNOWLEDGMENT

This work was conducted while the author was in the department of mechanical and environmental engineering at the University of California. The author wishes to thank Ms. N.S. Lee for typing of the manuscript.

REFERENCES

Kang, S.W., 1983. Sediment entrainment due to shear flow. J. Ocean Soci. Korea, vol. 18, 21-28.

Lick, W., 1982. Entrainment, deposition, and transport of fine-grained sediments in Lakes, Hydrobiologia 91, 31-40.

Lick, W. and S.W. Kang, 1984. Entrainment of sediments and dredged materials in shallow waters. J. Great Lakes Res. (in press).

Royse, C.F., 1970. An introduction to sediment analysis. Arizona State University Report, Tempe, Arizona.