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The Measurement of Sediment Concentrations in Tidal Conditions

by

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Synopsis

Accurate predictions for morphological problems in rivers and estuaries can only be made if the relationship between the local sediment transport and flow conditions is known. In general this knowledge cannot be obtained with sufficient accuracy from transport formulas only. On the contrary, high priority should always be given to field measurements.
In tidal conditions the use of bottle-type samplers is not only impractical because of the handling of a large number of bottles but also not reliable in a statistical sense because of the short sampling times.
Modern instruments like optical and acoustical samplers may also be considered. A major drawback of these instruments, however, is the size-dependent calibration. Consequently, in tidal conditions a large number of water samples is still needed for calibration purposes. It is concluded that in tidal conditions a method is required which enables the sampling and handling of a large volume of water (say 50 liters) to obtain a reliable average value of the concentration. A pump sampler in combination with an instrument for the in-situ separation of water and sediment will satisfy these requirements. Separation methods which can be used, are: the sedimentation method, the filter method, the hydro-cyclone method and the centrifuge method.
This paper evaluates the pump-sampling method and the in-situ separation methods.

Resumé

Dans le cadre des problèmes morphologiques dans les fleuves et les estuaires, des prévisions précises ne peuvent être faites que si la relation entre le transport local de sédiments et les conditions hydrauliques est connue. Ces connaissanees ne peuvent, en général, pas être acquises avec suffisament de précision à l'aide de formules de transport uniquement. La priorité devrait, au contraire, être accordée aux mesures in-situ.
Dans les zones à marée l'emploi de l'échantillonneur du type à bouteille est non seulement peu pratique à cause de la nécessité d'utiliser un grand nombre de bouteilles, mais n'est, de plus, pas fiable dans le sens statisque, du fait des courtes périodes d'échantillonnage.
Des instruments modernes, tels que les échantillonneurs optiques et accoustiques peuvent également être considéres. Un problème majeur est néanmoins le calibrage dépendant de la granulométrie.
On peut donc conclure que dans les zones à marée une méthode est nécessaire qui permit l'échantillonnage et la manipulation d'un grand volume d'eau (50 litres) afin d'obtenir une moyenne fiable de la concentration. Ces conditions peuvent être satisfaites par un échantillonneur à pompe couplé à un instrument de séparation des sédiments de l'eau utilisable in-situ. Les méthodes de séparation utilisables sont: la méthode par sédimentation, la méthode par filtrage, la méthode par hydro-cyclone et la méthode par centrifuge.
Cet article évalue les méthodes d'échantillonnage par pompage et les méthodes de séparations in-situ.

1. Introduction

Accurate prediction of morphological problems like the siltation in dredged channels in rivers and estuaries can only be made if the sediment transport in relation to the flow conditions is known.
In general this knowledge cannot be obtained with sufficient accuracy from sediment transport formulas only. On the contrary, high priority should always be given to field measurements of both the suspended and bed load transport.
In natural conditions the solids in suspension mostly consist of silt particles (smaller than 50 μm) and fine sand particles (50 - 200 μm).
To measure the sediment concentrations, a wide range of instruments has been developed, from simple bottle samplers to sophisticated optical and acoustical samplers. In case of well-mixed suspensions of silt with almost uniform concentration profiles, the use of bottle samplers offers a simple solution. However, in tidal conditions this method will result in the handling of a large number of bottles. Another disadvantage of the bottle method is the short sampling time resulting in an unreliable measurement in a statistical sense [1], while also the accuracy of the measurements will be relatively low due to the small sediment samples.
In tidal conditions also optical samplers based on light transmission or acoustical samplers based on sound transmission may be used, but because the calibration is dependent on the size of the sediment particles in suspension, their use is only practical in combination with local water samples to determine the sediment size.
These considerations lead to the conclusion that for the accurate and reliable measurement of the sediment concentrations in tidal conditions, a method is needed which enables the sampling and handling of a relatively large volume (say 50 liters) of water and sediment, while the sampling time must remain small in comparison with the period in which a large change in flow conditions can be expected. A pump sampler in combination with an in-situ separation of water and sediment will meet these requirements. This paper evaluates the pump-sampling method and the in-situ separation methods.

2. Pump-sampling method and accuracy

To determine the local sediment concentrations and the depth-integrated sediment transport, the sampling method should satisfy the following requirements:

- appropriate intake velocity
  Ideally the intake velocity of water and sediment should be equal to the velocity of the ambient flow. Furthermore, there should be no disturbing influence due to the presence of the sampling unit. Deviations of the intake velocity to that of the ambient flow will result in sampling errors. For example, sampling at a lower velocity than that of the ambient flow will result in a higher sediment concentration than present in the stream due to the diverging of the flow lines which cannot be followed by the sediment particles, being of higher density (Figure 1).
  The magnitude of the error due to incorrect intake velocities has been determined by Nelson and Benedict [2]. Their results show a decreasing error for a decreasing sediment size. For a ratio of the intake velocity and local flow velocity in the range 0.5 - 2.0 a maximum error of about 20% was found.

1. Eyster, G.L. and Mahmood, K.,
   Variation of Suspended Sediment in Sand Bed Channels,
   River Sedimentation, Vol. II, Fort Collins, U.S.A., 1976.

2. Nelson, M.E. and Benedict, P.C.,
   Measurement and Analysis of Suspended Sediment Loads in Streams,
   A.S.C.E., Proceedings Vol. 76, 1950.

Measurements in tidal flow and at different heights above the bed imply different flow velocities. Minimizing the sampling error would lead to a continuous adaptation of the intake velocity. To avoid this procedure, it is preferable to operate the pump system at a fixed discharge and to accept a certain sampling error.

- no settlement of sediment particles in the pump hose
  To keep the sediment particles in suspension during transportation in the hose, the flow velocity in the pump hose must exceed a critical value. Using a hose with a bore diameter of 0.016 m, the critical flow velocity for fine sediment particles (< 300 μm) was experimentally found to be about 1.0 m/s, which results in a minimum flow rate of about 12 liters per minute.

- accurate determination of the sample height above the bed
  In case of concentration profiles with large gradients close to the bed it is extremely important to determine the sampling height with high accuracy, which can be done by means of an echo-sounder on the sampling unit.

- accurate determination of the sample volume
  In practice three methods are available: a propeller-type volume meter, an electro-magnetic volume meter and a calibrated vessel. A propeller-type volume meter is not advisable because field experience has shown that in the long run errors are introduced due to pollution of the propeller.

- simultaneous measurement of the local flow velocity
  Simultaneous measurement of the flow velocity close to the intake nozzle is necessary to determine the sediment transport. In tidal conditions a common propeller-type instrument can be used provided it is not sensitive to a saline and silty environment.

3. In-situ separation of water and sediment

The sampling of a relatively large volume (50 liters) of water and sediment requires an in-situ separation of the sediment particles. Basiccally, four methods can be distinguished: sedimentation method, filter method, hydro-cyclone method and centrifuge method.

- sedimentation method
  The sedimentation method is based on the separation of the sediment particles by gravity forces. For collection and determination of the water volume a calibrated vessel can be used (Photo 1 and Figure 2). By using a conical vessel and vibrating equipment to avoid settlement of sediment on the inside of the vessel, a high separation efficiency can be obtained. In case of a settling (vessel) height of about 1.0 meter the separation time for the (sand) particles larger than 50 microns (μm) will be about five minutes. The sediment particles can be collected in a small calibrated measuring glass at the under side of the vessel to determine the immersed volume of the sediment particles directly. The dry weight of the particles can be determined afterwards in the laboratory.

- filter method
  In case of filtering, the water-sediment sample is pumped through a filter which separates all particles exceeding the mesh size of the filter material [3]. This method cannot be used in environments where large quantities of

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3. Rijn, L.C. van,
   Pump-Filter sampler, Design of an Instrument for Measuring Suspended Sand Concentrations in Tidal Conditions,
   Research Report S 404-I, Delft Hydraulics Laboratory, June 1979.

very fine silt are in suspension. In these conditions the filter material will be blocked rapidly thereby reducing the flow velocity in the pump hose to a value less than the critical velocity needed to transport the sediment particles. Another result of filter blockage will be a reduced sampling time and hence a reduced reliability of the measurements.

- hydro-cyclone method
  The separation of the sediment particles by the hydro-cyclone method is based on centrifugal forces. The hydro-cyclone consists of a hollow conical vessel with tangential inflow of the water-sediment sample at the widest part. There are two outlets, one at the under side of the vessel through which a small under flow with the separated sediment particles is discharged and a second outlet at the centre of the upper part of the vessel for the outflow of clear water.
  The separation efficiency is strongly dependent on the inflow rate and the tube diameter of the cyclone. At a given inflow rate a higher separation efficiency is obtained for a smaller tube diameter.
  Laboratory tests [4] show that a cyclone with a diameter of 0.075 m separates all (sand) particles larger than about 50 µm providing the flow rate exceeds 15 liters per minute. Such a value can be handled by a deck-mounted pump using a hose with a bore diameter of 0.016 m and a maximum length of about 50 m.
  A disadvantage of this method is the required collection of the under flow with the sediment particles which results in the handling and analysis of a number of large bottles.

- centrifuge method
  Like the hydro-cyclone method, the separataion by means of the centrifuge method is based on centrifugal forces. Only now the rotational motion is generated by external energy. The sediment particles are concentrated on the inside wall of a rotating tube, which must be replaced after each measurement. The number of revolutions of the centrifuge is about 20,000 per minute for an inflow rate of about 25 litres per minute, which results in a (very high) separation efficiency of about 100% for all particles larger than 1 micron (µm).
  A major drawback of the centrifuge method is the removal of the sediment particles from the inside wall of the centrifuge tube, which is very laborious, particularly when this method is used to sample areas of high silt concentrations. Furthermore, the cleaning of the centrifuge results in a large quantity of wash water, which must be filtrated to determine the silt content.
  Other disadvantages are the large dimensions and the weight (≈ 250 kg) of the centrifuge, the energy-supply requirements and the relatively large handling time of about 15 minutes (starting, stopping and cleaning).

4. Comparative measurements

For practical application the sedimentation and filter method are preferable because both methods offer a simple and efficient solution for the in-situ separation of water and sediment.
To check the separation efficiency, both methods were tested in laboratory and field conditions. The sedimentation equipment used by the Delft Hydraulics Laboratory, consists of a conical vessel, which is calibrated to determine the volume of the water sample (Photo 1 and Figure 2). To avoid sedimentation of

4. Kiff, R.,
   Evaluation of a Hydro-Cyclone for on-site Sediment Separation,
   Journal of Sediment Petrology, 47, no. 3, 1977.

sediment particles on the inside of the vessel, a vibrator with a frequency of 50 hz was attached to the vessel. The sediment particles were collected in a calibrated measuring glass at the under side of the vessel to determine the immersed volume of the particles directly. The dry weight of each sample was determined afterwards in the laboratory. The filter method consists of filtering by means of a filter of 0.2 m in diameter, (Photo 2 and Figure 3). The water-sediment sample is pumped through the filter. After a suitable volume has been sampled, the filter house is opened and the filter with the sediment particles is removed and returned to the laboratory for drying, weighing and size-analysis. To separate the sand fraction, a filter with a mesh size of 50 µm is used.
The water-sediment samples are collected by means of a pump sampler which consists of an intake nozzle orientated towards the flow direction, a pump hose with a bore diameter of 0.016 m and a pump with a capacity in the range 0 - 40 liters per minute (Photo 3).

Laboratory conditions

Simultaneous concentration measurements were done in a flume using a siphon sampler and a pump sampler in combination with the sedimentation method or the filter method.
The siphon sampler consisted of a short hose connected to an intake nozzle next to the intake nozzle of the pump sampler. Each siphon sample was collected in a calibrated vessel (about 10 liter). After settlement of the sand particles the water was poured off carefully and the sand sample was removed to determine the dry weight.
The intake velocity of the siphon sampler was controlled by varying the height of the hose outlet with regard to the height of the intake nozzle. For the siphon sampler as well as the pump sampler the intake velocity was kept equal to the local flow velocity.
The concentrations determined from the siphon samples were assumed to represent the original concentrations (c_0) at the sampling point. Repeated measurements with the siphon sampler indicated reliable sampling as the highest and lowest concentrations were within 10% of the average value [3].
Two types of sand were used, a very fine sand with a mean diameter (D_{50}) of 90 µm and a medium fine sand with a diameter (D_{50}) of 220 µm.
Figure 4 presents the sampling error in the concentration (c) of the pump-filter equipment and the pump-sedimentation equipment for the 90 µm and 220 µm-sediment. Over the whole range the error is less than 10% which is remarkably good. Also size analysis of the sediment samples showed good agreement for all methods.

Field conditions

In the Oosterschelde, a sandy estuary in the south-western part of Holland, the pump sampler in combination with the filter method was compared with an acoustic-Doppler sampler [3]. The acoustic-Doppler sampling method is based on the scattering of ultra sound from the suspended sediment particles. Velocity, concentration and direction of the particles can be derived from the Doppler shift of the signal [5]. The sampler was calibrated in a laboratory flume.
The pump sampler was operated at a fixed discharge of 12 liters per minute with an intake velocity of about 1.0 m/s. No attempt was made to equalize the intake velocity to the local flow velocity. To obtain a reliable average value, a sampling time of 5 minutes was used.
A sampling unit was used to carry the intake nozzle of the pump sampler, which was installed next to the measuring probe of the acoustic sampler, an echo sounder and a current flow meter (Photo 3).

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5. Jansen, R.H.G.,
The in-situ Measurement of Sediment Transport by means of Ultra-Sound Scattering,
Delft Hydraulics Laboratory, Publication no. 203, July 1978.

The local flow depth varied from 20 - 25 m. Flow velocities were up to 1.3 m/s. The local bed material consisted of sand with a diameter (D_{50}) of about 300 μm. Figure 5 presents the concentrations as a function of time for both instruments. As can be observed, the agreement between the concentrations as well as the flow velocities is remarkably good.
Secondly, attention is paid to concentration measurements in the Nieuwe Waterweg near Rotterdam [6]. At this location a pump sampler in combination with the sedimentation method was compared with a pump sampler in combination with the filter method. The intake nozzles of both instruments were installed next to each other on a sampling unit. The local flow depth varied from 15 - 20 meter. Flow velocities were up to 1.5 m/s. The bed material consisted of fine sand with a diameter (D_{50}) of 200 μm. The sampling time for the pump-sedimentation method was about 3 minutes. The sampling time for the pump-filter method was not more than 1 à 2 minutes because the filter showed signs of blockage in an early stage due to the presence of very fine silt particles.
Figure 6 presents the measured sand concentrations as a function of time for both instruments. The overall agreement is satisfactory. It can be observed that the scatter in the concentrations for the filter method is somewhat larger than for the sedimentation method, which is probably caused by the reduced sampling times. Figure 6 also presents the silt concentrations as a function of time. The silt concentrations were determined from water samples which were tapped from the outflow during emptying of the sedimentation vessel. Size analysis showed that 95% of the sediment particles were smaller than 50 μm.

5. Conclusions

From the experimental results it can be concluded that accurate and reliable sediment concentrations can be determined using a pump sampler in combination with the sedimentation method or the filter method for the in-situ separation of water and sediment. The sedimentation method can be used in silty and sandy environments. The filter method is only practical in sandy environments.

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6. Rijn L.C. van,
Methods for the In-Situ Separation of Water and Sediment,
Delft Hydraulics Laboratory, Research Report S 404-II, 1980.

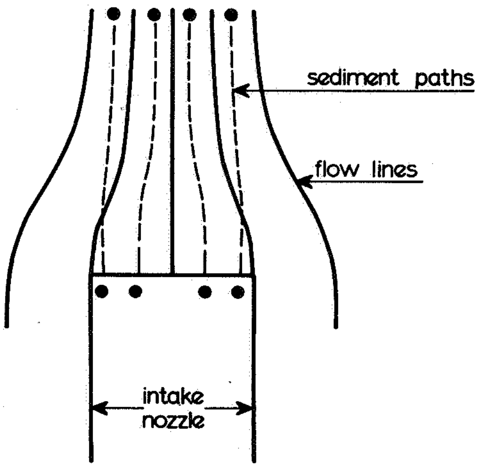

figure 1

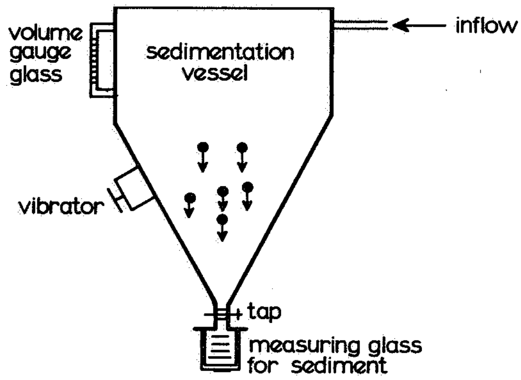

figure 2

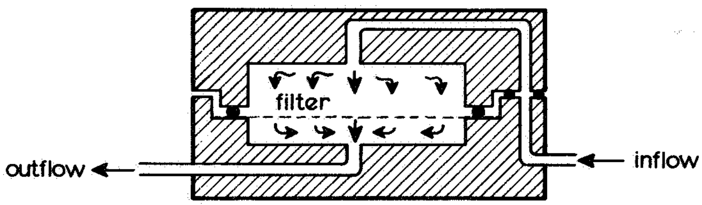

figure 3

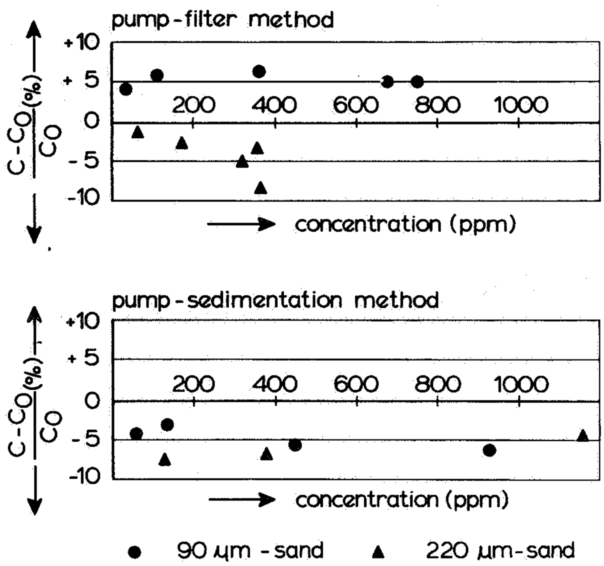

figure 4

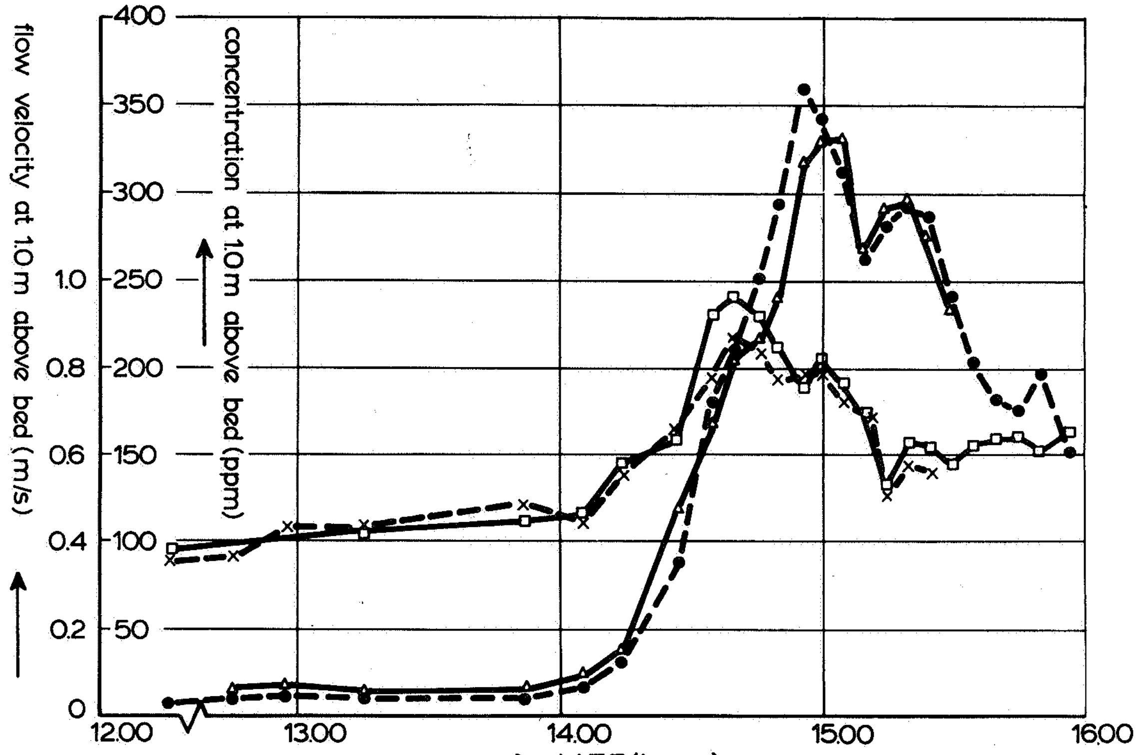

figure 5

flow velocity by impeller - current meter
flow velocity by acoustic - doppler method
concentration by pump - filter method
concentration by acoustic - doppler method

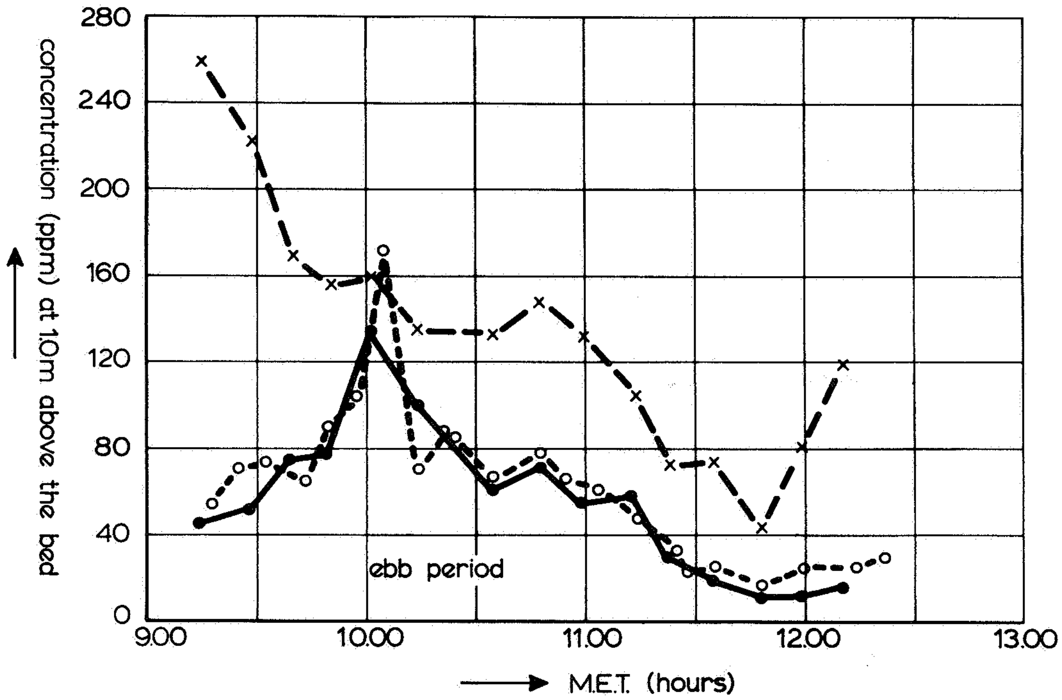

figure 6

sand concentrations (D>50 μm) according to pump-sedimentation method

sand concentrations (D>50 μm) according to pump-filter method

silt concentrations (D<50 μm) according to bottle samples from the sedimentation vessel

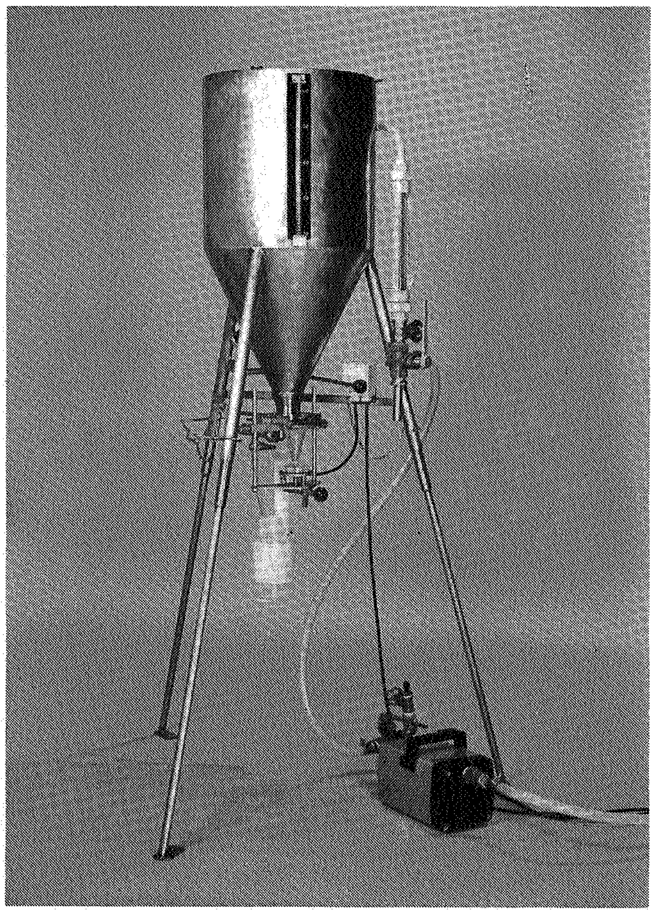

Photo 1

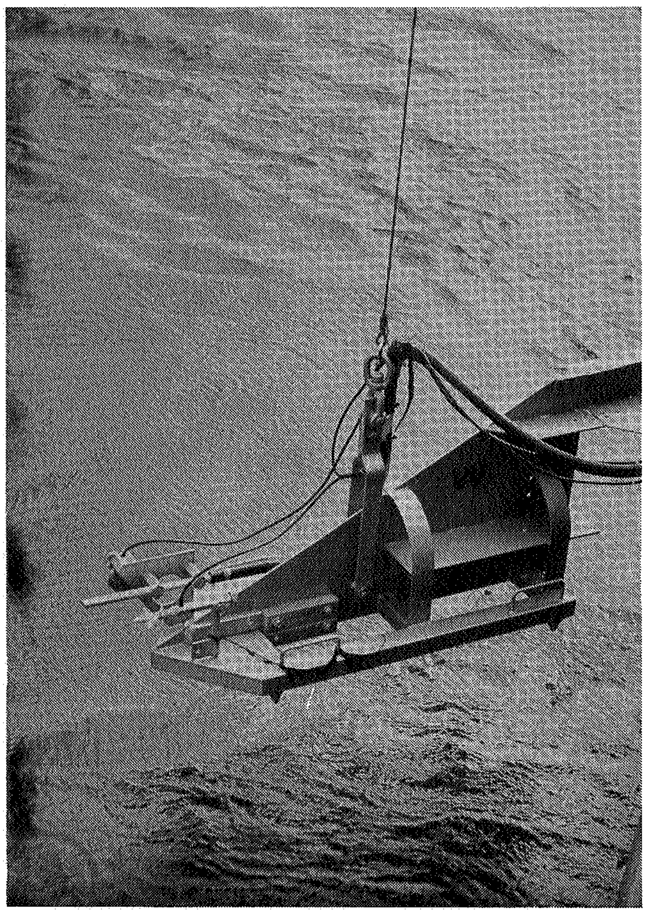

Photo 3

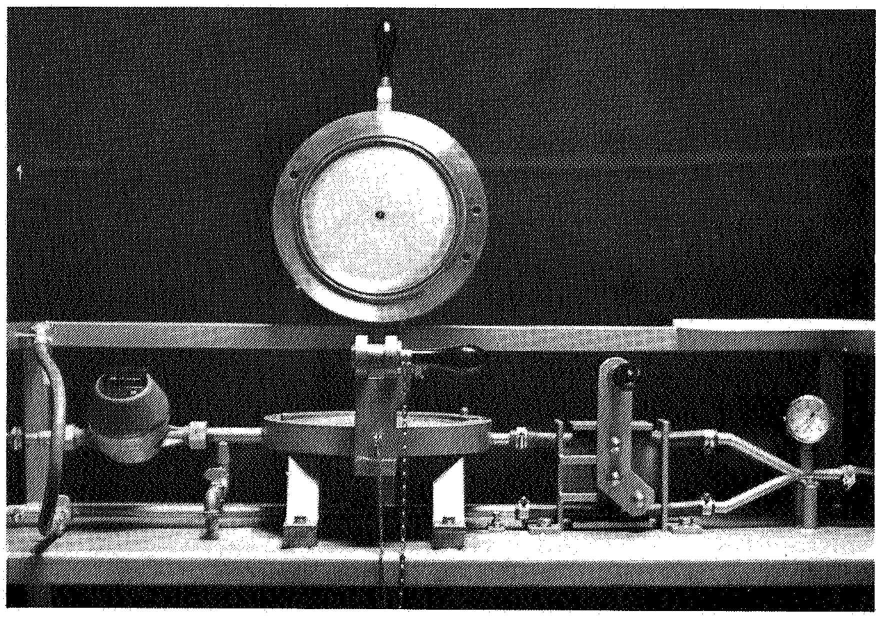

Photo 2