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Development and flume calibration of a new type of near-streambed suspended load sampler

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Abstract Using a conventional suspended load sampler, it is generally impossible to measure the layer of high sediment concentration near the streambed. As a result, the accuracy and value of the collected data are greatly reduced. In this paper, a new type of near-streambed suspended load sampler is described. Its reliability and value have been verified by flume calibration. A feasible means of solving the problem of total load measurement in large rivers is therefore provided.

Mise au point et étalonnage d'un nouvel appareil de prise d'échantillon de débit solide en suspension au voisinage du fond du lit de rivière

Résumé Pour un appareil conventionnel de prise d'échantillon de débit solide en suspension, il est impossible de mesurer d'ordinaire la couche riche en sables près du fond du lit de la rivière, donc, l'exactitude de ses résultats et la valeur pratique sont largement réduites. Dans cette communication un nouveau type d'appareil de prise d'échantillons de débit solide en suspension près du fond du lit de rivière est proposé, et sa sûreté et sa valeur pratique ont été prouvées par les données de l'échantillonnage des jaugeurs type Parshal, c'est ainsi qu'un moyen de résoudre le problème de mesure du transport total de sables a été trouvé pour les grandes rivières.

INTRODUCTION

There are two theories relating to the vertical distribution of suspended sediment concentrations, namely, diffusion theory and gravity theory. However, both can only be used to calculate the relative sediment concentration at points in the vertical. To calculate the absolute sediment concentration at a certain point, we must first know the sediment concentration near the streambed (Sa is usually used to denote the sediment concentration at a point located at a distance a from the streambed, where a represents the thickness of the bed surface layer). The measurement of sediment concentration near the streambed is therefore an important task in sediment investigations. In suspended load measurement, the commonly used devices are depth-integrating and point-integrating samplers. With these samplers, the distance from the intake nozzle of the sampler to the streambed will be at least 15–20 cm or more. In the rivers of mountain and hilly areas, the variation of sediment concentration in the vertical is far more marked than in lowland rivers transporting mainly fine material. A highly concentrated layer of sediment occurs near the streambed, and it is this layer of high sediment concentration that the conventional suspended load sampler fails to sample. This will result in underestimation of both the quantity and the size distribution by the measured suspended load, which is therefore reduced in accuracy and value. To solve this problem work on developing and calibrating the NBS-84 type near-streambed suspended load sampler (Fig. 1) commenced in 1980. Test measurements on the Mingjang River carried out over a four year period from 1984 to 1987 provided satisfactory results (Wang, 1987) and in May 1987, the sampler passed a technology appraisal by the Provincial Committee of Science and Technology.

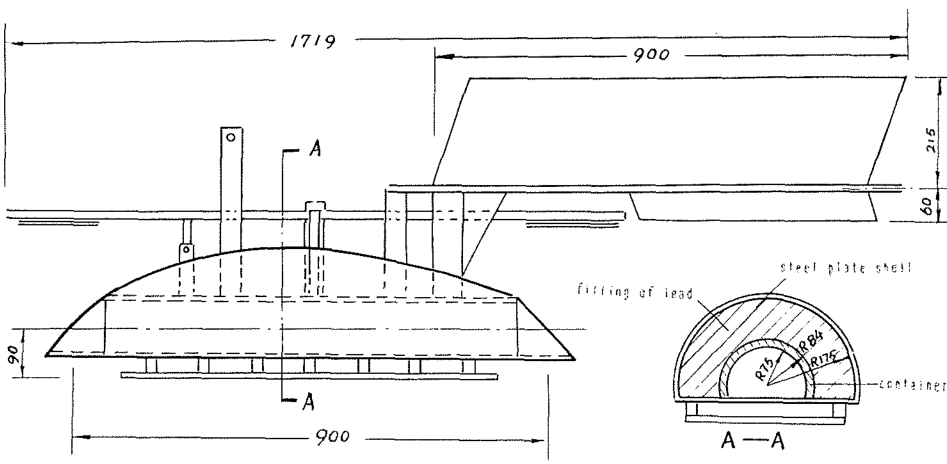

Fig. 1 The NBS-84 near-streambed suspended load sampler.

THE DEVELOPMENT OF THE NBS-84 NEAR-STREAMBED SUSPENDED LOAD SAMPLER

The NBS-84 type sampler may be classified as an instantaneous suspended load sampler. Development work started in 1980 and was completed in 1984. Several design improvements were made during this period (Fang & Wang, 1986). The original design had the following advantages. Firstly, it had a large intake nozzle which reduced the possibility of clogging. Secondly, the volume of its container (about 10 000 ml) was much greater than that of standard time-integrating and bottle-type samplers. Even under conditions of low sediment concentration, a single sample is enough for particle size distribution analysis of the sediment. Thirdly, it can be used in high velocity flows and its underwater orientation can be easily controlled, so as to keep *he axis of its body parallel to the direction of flow. Fourthly, it is also easy to operate and maintain. Conversely, in order to increase the sampler's weight and therefore its stability underwater, a pair of streamlined casting had been fixed to the two sides of the upper part of the sampler. This produced a complicated shape and caused a major increase in the disturbance of the flow. In addition, because the streamlined castings were placed on the upper part of the sampler, this resulted in a higher centre of gravity and decreased the stability of the sampler underwater. In order to counter the above weakness, several design improvements were introduced to produce the final version. These included:

(a) Combining the sample container and the streamlined castings into a single unit. The outline of the sampler has been streamlined so as to minimize disturbance of the flow. The centre of gravity of the sampler has also been lowered to increase its stability underwater.

(b) Adding a horizontal tail vane to improve the smoothness of the sampler entry into the water and to provide sensitive direction control. Most of the vertical tail vane on the original model was retained. An experimental relationship provided by the Beijing General Hydrometric Station was used to determine the total area of the tail vane, namely,

$$S_h = 2D$$

$$S_v = 1.58D$$

(where S_h and S_v denote the areas of the horizontal and vertical tail vanes of the streamlined castings respectively, and D is the maximum diameter of the streamlined casting).

(c) Modifying the leading edge of the intake to the sample container to provide a sharp-edged form which improved the hydraulic conditions at the sampler intake.

(d) Improving the reliability of the sampler by replacing the original push-pull switch by a rotary switch.

The main characteristics of the improved sampler are as follows: length: 1719 mm; width: 350 mm; height: 578 mm.

The length of the sample container is 90 cm, the centre of the flow cross section is 9 cm from the streambed, the lowest point of the sampler container is 4.6 cm from the streambed, the design sampling capacity is 8000 ml, and the design weight is 300 kg.

MODE OF OPERATION

The stay line is used to increase the stability and to help to increase the effectiveness of the sampler. When the sampler has been moved to the predetermined sampling point along the electric cableway, the electro-magnetic switch installed on the river bank is used to close the lids on the two ends of the sampling container and collect the sample.

CALIBRATION TESTS

Aims and methods

Because of the disturbance caused by the presence of the apparatus, convergence or divergence of the streamlines will occur in the vicinity of the entrance to the sampler. This will result in a corresponding acceleration or deceleration of the flow. Because the specific gravity of the sediment particle is greater than that of the water, the inertia of the former is greater than that of the latter. The sediment and water will therefore be separated from each other under conditions of acceleration or deceleration, resulting in a sampling error. When the intake velocity of the sampler is greater than that of the natural flow, the measured sediment concentration will be lower, and the size distribution will be a little finer, than the actual values, and *vice versa* (Guy & Norman, 1976; Xia, 1958). A fundamental requirement for all suspended load samplers (including the near-streambed suspended load sampler) is that the intake velocity coefficient should be as close as possible to 1. The aim of the calibration tests was to determine the hydraulic characteristics of the sampler by observation of the intake velocity coefficient K_v and the velocity distributions inside and outside the sampler. In addition, we also aimed to observe the flow pattern and the underwater orientation and stability of the sampler, in order to assess the reliability of the data collected using this sampler, and, if possible, to identify means of further improvement.

In the calibration tests, a model scale of 1:3 was used for the sampler. The tests were carried out in a glass-walled flume 1.5 m wide, 1.25 m high and 64 m long with a recirculating water supply capacity of 1.2 $m^3\ s^{-1}$, located in the Sedimentation Laboratory of Chengdu University of Science and Technology. The bed of the flume was floored with sand and gravel according to the model scale and the original bed material size distribution. The slope of the bed was 0.25%. In the test, conditions were strictly controlled to ensure that the flow in the test segment was uniform. Discharge was controlled by a sharp-crested weir. A specially calibrated pitot tube was used to measure the velocity. Its inner and outer diameters were 1.5 mm and 3 mm respectively.

The range of hydraulic conditions used in the calibration tests were:
Discharge (Q) = 0.229–0.704 $m^3\ s^{-1}$;
Depth (H) = 18.61–39.28 cm;
Average velocity (V) = 0.82–1.19 m s^{-1};
Slope of the flume bed (i) = 0.25%.

Calibration method and results

Entrance velocity calibration tests The sampler was placed in the test position and the velocities were measured at the points shown in Figs 2 and 3. The sampler was then removed and the natural flow velocities were measured at the corresponding points in the flume. The average velocity of the flow in the intake cross section V_s and the average velocity of the natural

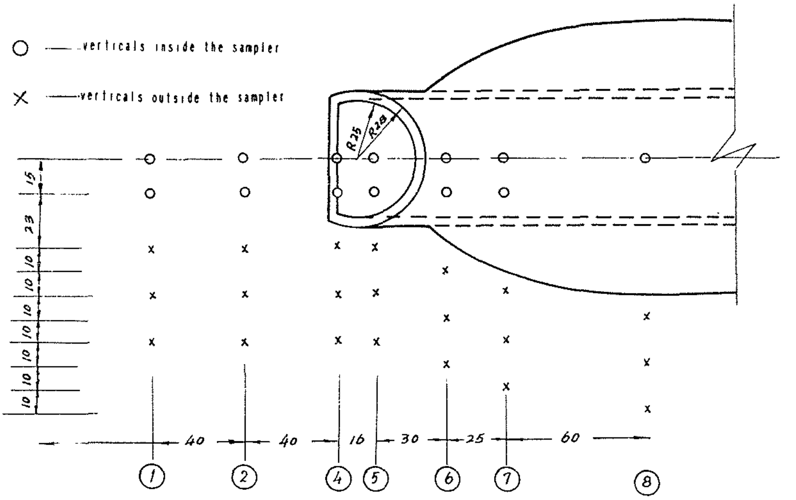

Fig. 2 Plan of the layout of the points for velocity measurements around the sampler (all dimensions are in mm).

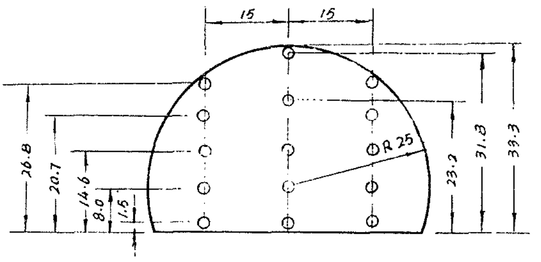

Fig. 3 Sectional drawing of the layout of the points for velocity measurement inside the sampler container (all dimensions are in mm).

flow in the corresponding section V_o were calculated. Using these data, the intake velocity coefficient of the sampler K_v is determined as:

$$K_v = V_s/V_o$$

The results are shown in Table 1. The intake velocity coefficient is a comprehensive index of the hydraulic character of the sampler. It directly affects the accuracy of the sediment measurements. As stated above, the intake velocity coefficient of an ideal sampler should approach 1 as closely as possible. At present, the general design criterion for a sampler is to set the confidence limit of K_v being within a certain range. For the instantaneous type of near-streambed sampler, it is stipulated that the confidence limit of $K_v \geqslant 0.9$ should be no less than 75%. The test results indicate that K_v = 0.953–0.985 (see Table 1), showing that the intake velocity coefficient of the sampler meets this requirements.

Table 1 Results of the determinations of the intake velocity coefficient

Test	Depth H (m)	Discharge Q ($m^3\ s^{-1}$)	Entrance section average velocity V_s($m\ s^{-1}$)	Natural flow average velocity V_s ($m\ s^{-1}$)	Entrance velocity coefficient K_v
1	0.1861	0.229	0.680	0.705	0.965
2	0.2234	0.307	0.724	0.754	0.960
3	0.3023	0.524	0.902	0.916	0.985
4	0.3928	0.704	0.905	0.950	0.953

Characteristics of the velocity distribution of the intake section of the sampler Figure 4 shows, for different conditions of water level and discharge, the distribution of the ratio K_r for the intake velocities (ratio of measured velocity inside the sampler to natural velocity at that point) in a vertical direction inside the sampler. These curves indicate that the velocity distribution of the intake section of the sampler is far from uniform because of the resistance effect of the sample container. For the points near the top of the container, because of the resistance effect exerted by the container wall, the velocity inside the sampling container is far less than the corresponding natural velocity, whether the point is on the central vertical or on the side vertical. This causes the velocity ratio K_r at that point to be less than 1; while at the points near the bottom of the container, the corresponding values of K_r approach 1 or a little more than 1. Explicitly, this is because, under natural conditions, these points are within the near-streambed zone and are therefore affected by the streambed roughness. In addition, the effects of the wall drag are also shown by the fact that the value K_r for a point on the side vertical is less than that of the corresponding point on the central vertical. Finally, at the points with a height of h (where h = the height from the bottom to the centre of the cross section of the container), the K_r values are all greater than 1. The distribution of K_r clearly

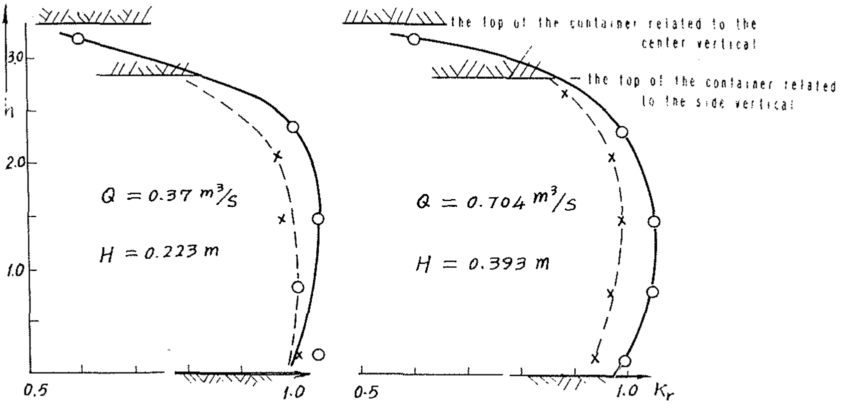

Fig. 4 Distribution character of velocities of the sampler container.

shows that in the design and development of the sampler, the inner wall of the container should be made as smooth as possible to increase the value of the intake velocity coefficient.

Test to investigate a possible means of increasing the intake velocity coefficient According to the results of the existing study, the intake velocity should increase if the cross section of the sampling container is expanded in the direction of flow. In the calibration, two model sampling containers made of plexiglass had been provided. One had a cylindrical shape, while the other was cone-like, with the degree of expansion d_2/d_1 being 1.10 (where d_1 and d_2 denote the areas of cross sections in the entrance and the exit of the container respectively). Using the velocity data obtained for the comparison tests, the intake velocity coefficients were calculated using the above method (see Table 2).

Table 2 Comparison of the intake velocity coefficients for sampling containers with different cross sections

Test	*Discharge* $Q(m^3 s^{-1})$	*Intake velocity coefficient* K_v: *for cylinder*	*for cone*
1	0.510	0.946	1.03
2	0.704	0.953	1.04

The results given in Table 2 indicate that the intake velocity coefficient can be effectively increased by changing the form of the sampling container from a cylinder to a cone. With a degree of expanding of 1.10, K_v can be increased from 0.95 to 1.04.

Observation of the flow patterns When the water flows around the sampler, the resistance force of the passing flow will be apparent. It consists of two components, i.e. the friction force along the surface of the sampler and the form drag resulting from the pressure difference produced as the flow passes through the sampler. For a sampler, the latter is the main component. Under certain conditions of flow turbulence, the friction force is related to the surface roughness of the sampler, while the form drag is controlled mainly by the shape of the outline of the sampler.

To permit observation of the character of the passing flow, red coloured water obtained using potassium permanganate was used as an indicator to observe the flow pattern. The red liquid was injected at predetermined points into the flow through an injection needle with a diameter of 0.3 mm. We can therefore judge whether the design of the outline and the size of the sampler are reasonable according to the flow-route, deformation, diffusion and mixing in different parts of the coloured streamline. Observations showed that the streamlines of coloured water passed smoothly over the surface of the sampler. Separation of the boundary layer within the region of 2–4 cm at the rear of the streamlined casting will occur only when the discharge and turbulence of the flow are increased. Because the separation occurred near the rear of the sampler, the corresponding region of wake flow is quite limited. This is extremely important for reducing the vibration of the sampler and increasing its sensitivity of orientation and stability. The flow pattern observations also indicated that the lid placed horizontally above the entrance, the switch controlling components and the horizontal tail vane at the rear of the sampler all cause considerable disturbance to the water flow, deforming and bending the surrounding streamline. A vortex could also be seen occasionally immediately under the front part of the tail vane through the observation of the coloured water flow.

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