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INSTITUT NATIONAL de RECHERCHE sur les EAUX

ON THE VERTICAL TRANSIT METHOD OF DETERMINING THE MEAN VELOCITY IN OPEN CHANNEL FLOW

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MANAGEMENT PERSPECTIVE

The standard procedure for measuring river discharge is the velocity - area method. Velocity measurements are made with the assumption that vertical velocity profiles of the flow are logarithmic. As long as this is true, velocities obtained as the average of the values obtained at the 0.2 and 0.8 depth, give results that are within about 1 to 2 % of the true mean velocity. Such accuracies, however, may not be attainable in large, deep rivers because the logarithmic velocity profile is based on the " law of the wall " and its validity can be expected to diminish with distance from the bed. Additional problems can be expected in channels affected by vegetation, irregular roughness, constrictions, partial ice dams upstream of the measuring cross-section and tidal influence. Under such circumstances, a possible alternative approach is a vertical integration of the velocity profile by raising the current meter from the bed to the water surface at a constant rate.

Dr. J. Lawrence
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PERSPECTIVE DE GESTION

La méthode ordinairement utilisée pour la mesure du débit des cours d'eau est celle de l'aire-vitesse. Les mesures de la vitesse sont effectuées suivant l'hypothèse que les profils verticaux de la vitesse de l'écoulement sont logarithmiques. Tant que cette hypothèse est valable, les vitesses obtenues comme étant la moyenne des valeurs mesurées aux profondeurs 0,2 et de 0,8 se situent à moins d'environ 1 ou 2 % de la vitesse moyenne réelle. De telles précisions peuvent cependant ne pas être atteintes dans le cas des grands cours d'eau profonds parce que le profil logarithmique de la vitesse est basé sur la "loi de la paroi" et on peut s'attendre à ce que la validité de ce profil diminue en fonction de la distance au lit. On peut s'attendre à des problèmes additionnels dans le cas des chenaux influencés par la végétation, une rugosité irrégulière, des étranglements, des barrages partiels par la glace à l'amont de la coupe transversale de mesure et par les marées. Dans ces situations, une intégration suivant la verticale du profil des vitesses, obtenue en soulevant le moulinet depuis le fond jusqu'à la surface à une vitesse constante constitue une méthode de remplacement possible.

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SUMMARY

Theoretical and dimensional analysis were used to examine the factors that must be considered in the integration of a vertical velocity profile of an open channel flow to obtain the mean velocity. The results show, that for logarithmic profiles, the mean velocity obtained by vertical integration is slightly larger than the true value and that this discrepancy is primarily a function of the ratio a/h (h = depth of the flow, a = the distance between the meter rotor and the bed when the sounding weight is resting on the bed). A correction coefficient can be determined for velocity profiles of known shape and is equal to unity if a/h = 0. For general application, methods must be devised which eliminate the effect of a/h. This can be achieved by making changes to the instrumentation and its suspension or devising analytical procedures which account for the area of the profile along the vertical length "a".

Results from limited tests in a laboratory flume with a Price " Pygmy " meter indicate that for a given flow rate and flow depth, there is a critical transit time (total time to raise the meter from the bottom to the surface) below which the meter should not be used. Further tests conducted on vertical velocity profiles of deep rivers, using a full sized Price meter should be conducted to compare the vertical transit method with the conventional 0.2 and 0.8 depth method, to determine the minimum possible transit time. The effect of the vertical transit speed (rate at which the meter is raised from the bed to the water surface) on the response of the current meter should be investigated in a towing tank.

RÉSUMÉ

Les analyses théorique et dimensionnelle ont été utilisées pour examiner les facteurs qui doivent être pris en considération lors de l'intégration d'un profil vertical de vitesses dans un chenal à écoulement à surface libre afin d'obtenir la vitesse moyenne. Les résultats montrent que, pour les profils logarithmiques, la vitesse moyenne obtenue par intégration verticale est légèrement supérieure à la valeur réelle de la vitesse et que cet écart est principalement fonction du rapport a/h (h = profondeur de l'écoulement, a = distance entre le rotor du moulinet et le lit du cours d'eau lorsque le saumon repose sur le fond). Un coefficient de correction peut être déterminé pour les profils de vitesses de forme connue et il est égal à un si a/h = 0. Pour l'application générale, des méthodes permettant d'éliminer l'effet de a/h doivent être conçues. Cet effet peut être éliminé en modifiant les instruments et leur suspension ou par des méthodes analytiques tenant compte de la surface du profil le long de la longueur verticale "a".

Les résultats obtenus lors d'essais limités en canal de laboratoire avec un moulinet "Pygmé" Price indiquent que pour une vitesse et une profondeur données de l'écoulement, il y a un intervalle de transit (durée totale nécessaire pour remonter le moulinet du fond jusqu'à la surface) critique en decà duquel le moulinet ne devrait pas être utilisé. D'autres essais devraient être effectués pour les profils verticaux de vitesses dans des cours d'eau profonds avec un moulinet Price de dimensions normales pour comparer la méthode du transit vertical à la méthode classique des 0,2 et 0,8 afin de déterminer la durée de l'intervalle minimal de transit. L'effet de la vitesse verticale de transit (vitesse à laquelle le saumon est remonté du fond à la surface de l'eau) sur la réponse du moulinet devrait être étudié en bassin d'essai de carènes.

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1.0 INTRODUCTION

The standard procedure for measuring the discharge of a river is the velocity-area method. The total area of the cross-section is divided into small sections and the area and mean velocity of each are determined separately. The small sections are each bounded by the stream bed, the free surface and two imaginary vertical lines called verticals as shown in Figure 1. Each vertical, being a common dimension for two adjoining sections, fixes the point at which observations of depth and velocity are made. The methods of determining the mean velocity at a given vertical generally used by the Water Survey of Canada (WSC) and the United States Geological Survey (USGS) are the two point and the six-tenth depth methods. In the two point method, observations are made in each vertical at 0.2 and 0.8 depth below the free water surface. The average of those two observations is then taken as the mean velocity in the vertical. In the six-tenth method, an observation of velocity made in the vertical at 0.6 depth below the surface is used as the mean velocity in the vertical. The six-tenth method is normally used where flow depth are less than 0.75 metres.

The point velocity method is based on observations in natural channels and is in close agreement with the logarithmic distribution for a wide channel. Rouse (1950) has shown that the use of the two point and six-tenth depth methods yield results less than 2% higher than the logarithmic relationship regardless of relative roughness and Reynolds number. Intensive investigation by Anderson (1961) using data from 100 different streams revealed that the two point method gave results which were within about 3% of the true mean velocity 95% of the time. Results from Hulsing et al (1966) showed that the mean velocity obtained with the two point method and the six-tenth method differed from the actual mean velocity by about 1% and 2% respectively. Carter (1970) reports that the shape of a vertical velocity distribution actually varies from instant to instant because of turbulent fluctuations of the flow. However, in spite of this variability, the velocity at the six-tenth depth and the average of the 0.2 and 0.8 depth velocities closely approximated the actual mean.

The experimental observations suggest that good results can be obtained with the operationally convenient point velocity methods. The reason for this is that, as long as the flow is in a wide channel, the velocity profile can be expected to be logarithmic (Yalin, 1971) and for this distribution the 0.6 depth and the two point method have been found to be valid as demonstrated by Rouse (1950) and Yalin (1977). However, there are cases where velocity profiles may not be completely logarithmic. In deep rivers, because the logarithmic profile is based on the " law of the wall ", its validity can be expected to diminish with large distances from the bed. Other conditions that distort the velocity profile are channels affected by vegetation, irregular roughness, constrictions, partial ice dams upstream of the measuring cross-section, tidal cycles, etc.. Under these conditions, a more effective approach may be a vertical integration of the flow to obtain the mean velocity directly. The process of integration would arrive at the mean velocity regardless of the shape of the velocity profile.

The vertical integration method, in spite of its advantages, has found only limited use in North America because the flow measuring instrument of choice is the Price current meter which, because of its vertical axis of rotation, is affected by vertical velocities (Kallio, 1966; Rantz, 1982). The method is more popular in European countries where propeller type meters are preferred (Lambie, 1978; Rantz, 1982). In this report, theoretical and experimental methods are used to examine depth integration, hereafter referred to as the vertical transit method, applied to flows with logarithmic velocity profiles. In addition, the practicality of using the Price meter for depth integration is considered.

This study is part of an overall quality assurance program presently being conducted by the WSC, with active participation of the Hydraulics project at the National Water Research Institute (NWRI), in an effort to improve standards and update measuring equipment. The work was conducted at the hydraulics laboratory of NWRI in support of WSC.

2.0 THEORETICAL CONSIDERATION

2.1 Basic Equation for the Vertical Transit Method

In the vertical transit method, the current meter and its suspension is lowered to the bed of the stream and then raised to the surface at a uniform rate. Generally, such integration traverses are made with the meter suspended by a cable and suitable sounding weight. In the case of the Price meter, Columbus type sounding weights are used as shown schematically in Figure 2.

For any arbitrary vertical velocity distribution, the determination of the mean velocity by vertical integration with the current meter is equivalent to the summing of very small elements of area under the velocity curve which can be expressed by writing

$$V_t = \frac{1}{h} \sum_{i=1}^{n} V_i \; \Delta y_i \qquad (1)$$

where V_t = the mean velocity of the vertical velocity profile, V_i = the velocity at the ith elevation y_i, Δy_i = the incremental width of the ith element of area, n = the number of elements of area under the velocity curve being summed between the end limits and h = the total depth of the flow. During the vertical transit the current meter is moved at a constant speed and therefore, it follows that the elemental width Δy_i is constant. As a result one obtains

$$\Delta y_i = \frac{h}{n} \qquad (2)$$

Substituting equation (2) into equation (1) results in

$$V_t = \frac{1}{n} \sum_{i=1}^{n} V_i \qquad (3)$$

The velocity of flow is measured by recording the rate of rotation of the rotor of the current meter. The relationship between the linear flow velocity and the rate of rotation of the rotor is normally determined from calibrations in a towing tank. As a result one may say that flow velocity is proportional to the rate of rotation of the current meter rotor. Therefore one may write

$$V_t \propto \frac{1}{n} \sum_{i=1}^{n} N_i \qquad (4)$$

where N_i is the rate of rotation of the rotor at the ith position and $\propto$ denotes the proportionality. Also, the rate of rotation N_i can be written as

$$N_i = \frac{R_i}{t_i} \qquad (5)$$

where t_i is the sampling time at the ith position and R_i = the number of revolutions of the rotor. Considering once again that the vertical velocity sampling is conducted at a constant vertical transit speed, the total transit time can be written as

$$t_* = nt_i \qquad (6)$$

where t_* is the total transit time. Finally, substituting equation (5) and (6) into equation (4) results in

$$V_t \propto \frac{1}{t_*} \sum_{i=1}^{n} R_i \propto \frac{R_*}{t_*} \qquad (7)$$

where R_* = the total number of revolutions accumulated during the vertical transit of the current meter. Equation (7) states that the mean velocity of a vertical velocity distribution can be obtained by dividing the total revolutions of the current meter rotor by the total transit time.

One of the difficulties with the vertical transit method is that, because of the presence of the sounding weight, the bottom velocities over the distance between the meter and the bottom of the weight cannot be measured. In addition, velocities near the surface should not be measured because the meter is affected by the free surface (Rantz, 1982). As a result the velocity profile is integrated only between the practical limits shown schematically in Figure 3.

The effect of not including the vertical distance "a" near the bed and "b" near the free surface can be expected to depend on the shape of the velocity profile. For example, for a rectangular velocity distribution, although a very unlikely case, the integrated mean velocity is always equal to the actual mean velocity regardless of the values of a and b. In reality, the velocity is known to increase with distance from the bed in some way which depends on the bed roughness, the energy gradient, the flow depth and the properties of the fluid. For a uniform flow in a wide channel it is known that the vertical velocity distribution is logarithmic. Therefore, as a first step in examining the vertical transit method, considerations are given to uniform flow conditions for which the vertical velocity profile is known to be logarithmic. This will make it possible to determine the relative effects of "a" and "b", the effect of the current meter and to compare the results with those obtained by the traditional 0.2 and 0.8 depth method under controlled conditions.

2.2 Vertical Transit Method Applied to Logarithmic Velocity Profiles

The logarithmic vertical velocity profile can be expressed as

$$V = 2.5\, U_* \ln \left(A_s \frac{y}{k_s} \right) \tag{8}$$

where U_* = the shear velocity, k_s = the equivalent sand grain roughness height and A_s = a coefficient which is constant in the rough turbulent flow regime and is equal to exp(0.4*8.5) as shown by Yalin (1977). The true mean velocity is obtained by integrating the complete velocity profile over the limits from k_s to h as shown in Figure 3, which results in

$$V_a = 2.5\, U_* \left\{ \ln \left(\frac{A_s}{e}\right) + \frac{\ln (h/k_s)}{(1 - k_s/h)} \right\} \tag{9}$$

where V_a = the actual mean velocity, e = the base of natural logarithms. The depth integration with the vertical transit method is equivalent to an integration of the vertical velocity profile between the limits $(a + k_s)$ and $(h - b)$. Integration of equation (8) yields

$$V_t = 2.5\, U* \frac{\left\{\left[1-\frac{b}{a}\cdot\frac{a}{h}-\left(\frac{a}{h}+\frac{k_s}{h}\right)\right]\ln\left(\frac{A_s}{e}\right)+\left(1-\frac{b}{a}\cdot\frac{a}{h}\right)\ln\left[\left(1-\frac{b}{a}\cdot\frac{a}{h}\right)\frac{h}{k_s}\right]-\left(\frac{a}{h}+\frac{k_s}{h}\right)\ln\left[\left(\frac{a}{h}+\frac{k_s}{h}\right)\frac{h}{k_s}\right]\right\}}{\left[1-\frac{b}{a}\cdot\frac{a}{h}-\left(\frac{a}{h}+\frac{k_s}{h}\right)\right]} \tag{10}$$

where V_t = the mean velocity obtained with the depth integration method. Combining equations (9) and (10) results in the velocity ratio

$$\frac{V_t}{V_a} = (1-k_s/h) \frac{\left\{\left[1-\frac{b}{a}\cdot\frac{a}{h}-\left(\frac{a}{h}+\frac{k_s}{h}\right)\right]\ln\left(\frac{A_s}{e}\right)+\left(1-\frac{b}{a}\cdot\frac{a}{h}\right)\ln\left[\left(1-\frac{b}{a}\cdot\frac{a}{h}\right)\frac{h}{k_s}\right]-\left(\frac{a}{h}+\frac{k_s}{h}\right)\ln\left[\left(\frac{a}{h}+\frac{k_s}{h}\right)\frac{h}{k_s}\right]\right\}}{\left[1-\frac{b}{a}\cdot\frac{a}{h}-\left(\frac{a}{h}+\frac{k_s}{h}\right)\right]\left\{\left(1-\frac{k_s}{h}\right)\ln\left(\frac{A_s}{e}\right)+\ln\left(\frac{h}{k_s}\right)\right\}} \tag{11}$$

Equation (11) is completely dimensionless and shows that the velocity ratio is a function of a/h, b/a and h/k_s. When a/h = 0 and b/a = 0, it is clear that for any value of h/k_s, the ratio of $V_t/V_a = 1.0$. Values of the velocity ratio were computed for different values of a/h, b/h and h/k_s in order to determine the effect of these independent variables.

The effect of the relative flow depth h/k_s is revealed by plotting curves of V_t/V_a versus h/k_s with a/h as a parameter for values of b/a = 0, 1.0 and 2.5 in Figures 4,5 and 6 respectively. The plots show that V_t/V_a is totally independent of h/k_s when a/h = 0 and b/a = 0. For a given value of b/a, V_t/V_a becomes increasingly dependent on h/k_s, as a/h increases. The greatest dependence of V_t/V_a on h/k_s is observed when b/a = 0 as shown in Figure 4. In this case, when a/h > 0, values of V_t/V_a initially increase as h/k_s increases from its lowest value of 10, until a maximum value of V_t/V_a is reached. Thereafter, values of the velocity ratio decrease as h/k_s increases, with the rate of change increasing as a/h increases. The value of h/k_s for which the value of V_t/V_a is a maximum, decreases as a/h increases.

The curves in Figure 5 show that, when b/a = 1.0, values of the velocity ratio at a given value of h/k_s and the rate of change of V_t/V_a with h/k_s are notably less than those observed in Figure 4 over the same range of a/h and h/k_s. The maximum value of V_t/V_a, when a/h = 0.1, has been reduced from a value of about 1.033 when b/a = 0 to a value of about 1.02 when b/a = 1.0. In addition, values of h/k_s at which maximum values of V_t/V_a occur for a given value of a/h have increased.

Examination of Figure 6 reveals a continuation of the trend established in Figures 4 and 5 for $h/k_s > 200$. In this range, as b/a is increased to 2.5, values of the velocity ratio and its rate of change with increasing h/k_s have been further reduced. Indeed, for values of $h/k_s > 200$ and $0 < a/h < 0.1$, the ratio V_t/V_a is only weakly dependent on the relative depth h/k_s. It is particularly interesting to note that V_t/V_a is confined to values between 1.00 and 1.004, with values initially increasing as a/h increases from 0 to 0.04 and then decreasing as a/h increases further to its largest value of 0.1. For values of h/k_s < 200, the dependency of V_t/V_a on h/k_s increases as h/k_s decreases from about 200 to 10. The rate of increase in V_t/V_a as h/k_s increases, also increases for values of a/h from 0 to 0.1. In addition, for values of h/k_s < 200, values of V_t/V_a decrease as a/h increases reaching its lowest value of 0.987 at $h/k_s = 10$.

The effect of changing the ratio b/a on the velocity ratio can be more directly shown by plotting V_t/V_a versus b/a with a/h as a parameter for fixed values of h/k_s. Curves for the case of h/k_s = 10, 100, and 1000 are given in Figures 7,8 and 9 respectively. In all three cases the curves clearly show that V_t/V_a steadily decreases as b/a increases and the rate of change becomes greater as a/h increases. As a result, for each value of a/h, a value of b/a is reached at which the value of V_t/V_a at a given a/h is less than values of V_t/V_a at lower values of a/h. It can also be seen that for a given h/k_s, there is a value of b/a at which V_t/V_a changes from values greater than 1.00 to values smaller than 1.00. The values of b/a for which V_t/V_a =1.00, decrease as a/h increases as shown in Figure 10. The curves in Figure 10 show that the rate of decrease in b/a as a/h increases depends on the value of h/k_s. As h/k_s increases, the rate of reduction in b/a increases as a/h increases from 0 to 0.1. The reason for this can be explained as follows: The omission of the top portion of the velocity profile over the vertical distance "b" compensates for the omission of the part of the velocity profile omitted over the vertical distance "a". The velocity near the bed varies significantly with changes in vertical position. As a/h increases the change in proportion of velocity profile omitted near the bed during the integration decreases. As a result less compensation (smaller b/a) is required to offset the discrepancy in the mean velocity. This effect becomes more pronounced as h/k_s increases.

2.3 Comparison with the 0.2 and 0.8 Depth Method

Flows, for which the depth integration method is potentially useful, are of depths greater than 0.75m. For such flows, the mean velocity of the vertical velocity profile is determined from velocity measurements at the 0.2 and 0.8 depth. This method is based on the premise that the vertical velocity distribution is logarithmic, which is usually the case for near uniform flow in wide channels. For fully rough turbulent flow (usually the case for rivers) the two point velocities can then be expressed as

$$V_{0.2} = 2.5\ U_* \ln\ (0.2\ A_s h/k_s) \tag{12}$$

and

$$V_{0.8} = 8.5\ U_* \ln\ (0.8\ A_s h/k_s) \tag{13}$$

where $V_{0.2}$ = the velocity at the 0.2 depth level from the bed, $V_{0.8}$ = the velocity at the 0.8 depth level from the bed and the other variables have already been defined. The mean velocity is determined from the relationship

$$V_c \doteq \tfrac{1}{2}\ (V_{0.2} + V_{0.8}) \tag{14}$$

where V_c is the average velocity obtained with the two point method. In order to compare the vertical transit method with the two point method, it is convenient to determine the ratio V_c/V_a by combining equations (12), (13), (14) and (9) to obtain, after some re-arranging of terms, the relationship

$$\frac{V_c}{V_a} = \frac{\ln\left(\frac{A_s}{e}\right) + \ln\left(\frac{h}{k_s}\right) + 0.084}{\ln\left(\frac{A_s}{e}\right) + \frac{1}{(1-k_s/h)}\ln\left(\frac{h}{k_s}\right)} \qquad (15)$$

Examination of equation (15) shows that V_c/V_a is a function of h/k_s only, since A_s/e is constant with a value of 11 (Engel, 1983). The curve of equation (15), plotted as V_c/V_a versus h/k_s, is given in Figure 11. The curve shows that V_c/V_a increases from a value of 0.987 to about 1.0082, with the rate of change decreasing as h/k_s increases from 20 to about 400. For values of $h/k_s > 400$, values of V_c/V_a decrease marginally to a value of 1.0070 when $h/k_s = 10{,}000$.

Comparison of the results obtained with the vertical integration and the two point method clearly show that, for a given logarithmic velocity profile and proper choice of b/a, the vertical integration will always give better results except when h/k_s has a value of about 45 for which the velocity ratio obtained with the two point method is also 1.0. For values of $h/k_s < 45$ the error in the mean velocity obtained with the two point method increases from 0 at $h/k_s = 45$ to - 3.5% at $h/k_s = 10$. For values of $h/k_s > 45$, the error reaches a maximum value of about 0.8%.

The better results obtained with the integration method are primarily due to the fact that for a given flow condition and current meter assembly, the proper value of b/a can be selected from a curve in Figure 10. Therefore, the effect of the free surface on the current meter performance as reported by Rantz (1982) need not be a deterrent to the use of the vertical transit method at least for normal velocity profiles. Indeed, under these conditions, the limitations of restricted bottom velocity measurements due to the presence of the meter suspension assembly as shown in Figure 2, need also not be a deterrent to using the vertical transit method. All that is required is the value of "a", which yields a value of $a/h < 0.1$ and the value of "b" giving a value of b/a for which mean velocity determined with the vertical integration is equal to the true mean velocity for the given value of h/k_s. Unfortunately, similar considerations may not apply to irregular velocity profile because their shape is not known. In this case, the only alternative is to devise an instrument for which the size of "a" is negligibly small.

3.0 PRELIMINARY TESTS

In addition to the three variables a/h, b/a and h/k_s, identified by theoretical methods, it is necessary to determine the importance of the length of traversing time, t_*, for a given set of conditions. For a given flow depth, the transit time dictates the rate at which the current meter is raised toward the surface. The vertical transit rate is important because, depending on the streamwise velocities, it may significantly affect the meter rotor response, thereby introducing an error in the velocity measurement. Preliminary tests were conducted to examine the effect of transit time, t_*, on the current meter.

The experiments were conducted in a tilting flume, 20 m long, 2.0 m wide and approximately 76 cm deep. The flow depth was controlled by a vertical set of louvers located at the downstream end of the flume. Water was supplied to the flume from a large constant head tank, through a 40 cm (16") pipe which was terminated by a diffuser in the head box of the flume. Baffles placed in the head box ensured a uniform, two dimensional velocity distribution in the central 1/3 of the flume. The water levels in the flume were measured with point gauges having a resolution of about 0.1 mm.

Velocities were measured with a Price "Pygmy" type current meter attached to a standard rod suspension. The revolutions of the meter rotor were counted and accumulated on a mechanical counter which could be engaged and stopped simultaneously with an electronic clock. The vertical transit measurements were made using a variable speed motor with ratchet and pinion drive which permitted the raising of the meter at selected constant speeds. The vertical transit apparatus and current meter setup is shown in Figure 12.

Tests were conducted for three different flow conditions, having flow depth of 30.7 cm, 45.0 cm and 60.5 cm respectively. In all cases the bed roughness was taken as the natural roughness of the flume bed. The flume bed consisted of a rough, oxidized metal surface and as a result the test flow was expected to be in the upper, transitional flow regime and values of h/k_s were not determined. This roughness was chosen to minimize the boundary effect on the current meter rotor which has been shown to under-register when placed closer to the bed than 9 cm (Rantz, 1982). Reynolds numbers, expressed as $V_c h/\nu$ were quite large and therefore the data should correctly reflect the effect of the transit time on the current meter.

At each flow depth, the vertical velocity profile was defined by making velocity measurements at fixed points along the vertical at 3 cm intervals beginning at 2 cm above the bed. The starting position of 2 cm was the smallest distance from the bed attainable because of the rod suspension of the meter. Effects of the bed on the rotor are expected to be small. At each flow depth, vertical transit measurements were made over the available range of vertical transit speeds, the total number of meter rotor revolutions R_* noted and the mean velocities V_t computed. The velocity profiles are plotted in Figures 13, 14 and 15. The data from the vertical transit tests are given in Table 1.

4.0 DATA ANALYSIS

4.1 The Reference Mean Velocity

The true mean velocity for each vertical velocity profile was taken to be the value obtained with the 0.2 and 0.8 depth method determined from Figures

13, 14 and 15. The velocities at the 0.6 depth were also obtained from the velocity profiles for comparison with the two point method. Comparison of the mean velocities obtained with the two point method and the 0.6 depth method showed very good agreement, with the absolute difference not exceeding 2.3 %. This indicates that the velocity profiles are sufficiently logarithmic. Therefore, the velocity V_c was taken to be the true reference mean velocity for each velocity profile.

4.2 Mean Velocity from Vertical Profile Integration

The vertical integration requires the selection of an appropriate value of "b" relative to "a" expressed as the ratio b/a. Because of the rod suspension and current meter design, the smallest possible value of "a" was 2 cm. A value of b/a = 2.5 was selected and the values of "a" and "b" were plotted on the velocity profiles as a/h and b/h to conform with the co-ordinates of Figures 13, 14 and 15. The area under each curve between the limits of a/h and (1 - b/h) were then determined with a planimeter and the mean velocity V_D computed. The velocity V_D was then compared with the reference mean velocity V_c obtained with the two point method by expressing the velocities as the ratio V_D/V_c. The velocity ratios are given in Table 2. Examination of the velocity ratios shows that the values are very close to the ideal value of 1.0 with the deviation not exceeding 0.5%. These results suggest that the value of b/a is satisfactory for the present test conditions.

4.3 Effect of Vertical Transit on the Current Meter

The vertical movement of the current meter relative to the stream flow may affect the rate of rotation of the meter rotor. The mean rate of rotation of the rotor for a particular vertical transit of the velocity profile, should depend on the mean velocity of the flow, the depth of the flow, the vertical transit time, the roughness of the bed, the parameters "a" and "b" as defined earlier and the properties of the fluid. This may be expressed by the functional relationship

$$N_* = f_3 \; [V_c, t_*, h, a, b, k_s, \rho, \mu] \tag{16}$$

where f_3 denotes a function, N_* = the rate of rotation of the meter rotor, ρ = the density of the fluid and μ = the dynamic viscosity of the fluid. Taking h, V_c and ρ as the characteristic variables, dimensional considerations yield

$$\frac{N_* h}{V_c} = f_4 \left[\frac{t_* V_c}{h}, \frac{a}{h}, \frac{b}{a}, \frac{h}{k_s}, \frac{V_c h \rho}{\mu} \right] \tag{17}$$

where f_4 denotes another function. Equation (17) shows that $N_* h/V_c$ is a function of the dimensionless variables a/h, b/a and h/k_s as observed for the velocity ratio in equation (11). However, equation (17) has the additional variables $t_* V_c/h$ and $V_c h\rho/\mu$. The variable $t_* V_c/h$ is important because it accounts for the effect of the vertical transit motion of the current meter and its assembly through the transit time t_*. It represents the ratio of V_c and the vertical transit speed h/t_*. The values of the Reynolds numbers are given in Table 2 and are considered to be large enough so that viscous effects are expected to be very small. In addition, for the present tests, b/a is taken to be constant at 2.5 and is not a variable quantity. Finally, the bed roughness was kept constant and therefore the variable h/k should also not contribute to any consistent variability in the dependent variable of equation (17) for the present data set. As a result, the Reynolds number, b/a and h/k can be omitted from equation (17) to give

$$\frac{N_* h}{V_c} = f_5 \left[\frac{t_* V_c}{h}, \frac{a}{h} \right] \qquad (18)$$

where f_5 denotes a function. The data in Table 1 were used to compute the dimensionless variables in equation (18) and these are also given in Table 2.

Values of $N_* h/V_c$ were plotted versus $t_* V_c/h$ with a/h as a parameter in Figure 16. The plots show that for all three values of a/h, $N_* h/V_c$ is independent of $t_* V_c/h$ when the latter is greater than about 80. This implies that there is a critical value of $(t_* V_c/h)$, say T_{cr} (the subscript "cr" denotes the critical value). If this is true, than it does not matter what transit time is used, as long as $t_* V_c/h > T_{cr} > 80$. By the same token, for values of $T_{cr} <$ 80, the vertical transit method should not be used. In this range $N_* h/V_c$ tends to increase as $t_* V_c/h$ decreases and this may be because the current meter is affected by the vertical motion of the meter.

The critical value T_{cr} implies a minimum transit time for a given average velocity and flow depth in the vertical. For a river vertical with a depth of 5 m and an average velocity of 2 m/s, a critical value of T_{cr} = 80 means that t_* must not be less than 200 seconds (3.33 min.). This translates into a vertical traversing speed of about 2.5 cm/s. In more general terms the vertical traversing speed can be expressed as

$$V_v = \frac{80}{V_c} \qquad (19)$$

where V_v = the vertical rate of ascend of the meter and its assembly. Clearly, the maximum allowable rate of ascent depends on the average velocity of the flow. As the flow velocity increases, the rate at which the current meter can be raised to the surface increases. It appears that for most flow conditions, provisions must be made to ensure that constant, slow rates of ascent can be maintained during the flow measurement. Alternately, faster rates of ascent may be possible if the effect of the vertical transit velocity on the current meter can be identified.

The fact that $N_* h/V_c$ is independent of $t_* V_c/h$ for values of the latter greater than 80, indicates that for the flow conditions tested, the meter was not significantly affected by the vertical transit motion in this range. The data in Figure 16 were obtained in a flume over limited flow depth with a Price "Pygmy" type current meter which is a miniature version of the Price 622 AA current meter. The latter type is used for river flow measurements and its response characteristics may be somewhat different. Further tests for a wide range of flow conditions in river cross-sections should be conducted to determine if there is indeed a single value of T_{cr} or if it too is a function of other variables. In additions tests should be conducted in a towing tank to determine the effect of vertical transit speed on the standard Price current meter with cable suspension.

4.4 Mean Velocity Obtained with Vertical Transit Method

Smooth curves were fitted to the plotted data in Figure 16 for values of $t_* V_c/h > 80$. This resulted in values of $N_* h/V_c$ = 1.04, 1.51 and 2.02 for values of a/h = 0.065, 0.044 and 0.033 respectively. Using these values of $N_* h/V_c$, values of the mean velocities V_t were computed and these are given in Table 3. Finally, the velocities V_t were compared with the reference velocity V_c by computing the ratios V_t/V_c and these are also given in Table 3. The results in Table 3 show that the mean velocity determined with the vertical transit method agrees within 0.5% of the reference velocity. These results are encouraging. However, the data are too limited to determine if there are any trends between the percent error and other variables. Such information should be obtained from further measurements in river cross-sections.

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

5.1.1 It has been shown that, when a current meter positioned at a given vertical in a river cross-section is raised vertically and slowly through the flow from the bed to the surface at a constant rate, the mean velocity is proportional to total count of revolutions of the meter rotor divided by the total vertical transit time.

5.1.2 Theoretical analysis of logarithmic vertical velocity profiles has shown that the accuracy of determining the mean velocity depends on the ratios a/h, b/a and h/k_s, assuming that there are no effects due to the current meter itself. For a given value of a/h, a value of b/a can be selected so that the mean velocity determined with the vertical transit method is equal to the true mean velocity. This value of b/a depends on the value of h/k_s and applies only to logarithmic velocity profiles.

5.1.3 Theoretical analysis has shown that the mean velocity in the vertical obtained with the 0.2 and 0.8 depth method tends to overestimate the true mean velocity for values of $h/k_s > 45$ and underestimate the true mean velocity when $h/k_s < 45$. The maximum overestimation is about 0.8% when h/k_s has a value of about 400. The underestimation increases as h/k_s decreases and reaches a discrepancy of about - 3.5% when h/k_s has a value of 10.

5.1.4 It has been shown through dimensional analysis, that the performance of the meter rotor should depend on a dimensionless parameter t_*V_c/h. Experimental data indicate that a critical value of this dimensionless parameter may exist. For values less than the critical value, the meter appears to be affected by the vertical rate of transit. For values greater than the critical value, the response of the meter is unaffected by the vertical transit speed. The critical value of t_*V_c/h represents the minimum value of t_* that can be used without affecting the current meter.

5.1.5 Analysis indicates that the vertical transit method should be ideally suited for flows having large depths. Changes in instrument configurations are required to apply the vertical transit method in flows with non-logarithmic velocity profiles in order to eliminate the need for adjustment coefficients.

5.2 Recommendations

5.2.1 It is recommended to conduct a series of tests at carefully selected river cross-sections. Careful measurements should be made to obtain vertical velocity profiles and these should be used to test the results obtained with the vertical transit method. Sites should be chosen to cover a wide range of flow depth and bed roughness.

5.2.2 Tests on the 622 AA Price type current meter with its conventional sounding weight suspensions should be conducted in a towing tank to determine the effect of vertical transit speed on the performance of the meter. Efforts should be concentrated on the effect of varying the vertical transit speed at specific towing carriage speeds.

ACKNOWLEDGEMENT

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TABLE 1

EXPERIMENTAL DATA FROM VERTICAL TRANSIT TESTS

h cm	R_* rev	t_* s	N_* rev/s	V_t cm/s
30.7	268	151.3	1.771	52.43
	227	128.1	1.772	52.46
	184	103.0	1.786	52.86
	168	93.8	1.791	53.01
	91	51.5	1.767	52.31
	80	43.1	1.856	54.89
	57	31.2	1.827	54.05
	313	177.7	1.761	52.14
	232	130.6	1.776	52.58
	190	106.7	1.781	52.72
	133	75.1	1.771	52.43
	98	55.2	1.775	52.55
45.0	363	201.9	1.798	53.21
	204	113.1	1.804	53.39
	125	68.7	1.820	53.85
	84	46.0	1.826	54.02
	62	33.5	1.851	54.75
	302	165.8	1.822	53.91
	372	204.3	1.821	53.88
	341	189.1	1.803	53.36
	239	130.1	1.837	54.34
	147	80.9	1.817	53.76
	115	62.8	1.831	54.17
	58	32.1	1.807	53.47
60.5	149	113.8	1.309	39.06
	200	152.9	1.308	39.03
	61	45.7	1.335	39.81
	40	29.5	1.356	40.42
	76	57.0	1.333	39.75
	109	82.7	1.318	39.32
	294	221.8	1.326	39.55

TABLE 2

DIMENSIONLESS VARIABLES FOR VERTICAL TRANSIT TESTS

a/h	V_D/V_c	N_*h/V_c	t_*V_c/h	$V_c h\rho/\mu$
0.065	1.000	1.044	256.8	1.6×10^5
		1.044	217.4	
		1.052	174.8	
		1.055	159.2	
		1.041	87.4	
		1.094	73.1	
		1.077	53.0	
		1.038	301.6	
		1.047	221.6	
		1.050	181.1	
		1.044	127.5	
		1.046	93.7	
0.044	1.004	1.485	244.5	2.5×10^5
		1.490	137.0	
		1.503	83.2	
		1.508	55.7	
		1.528	40.6	
		1.504	200.8	
		1.504	247.4	
		1.489	229.0	
		1.517	157.6	
		1.500	98.0	
		1.512	76.1	
0.033	1.003	2.010	74.1	2.4×10^5
		2.008	99.6	
		2.050	29.8	
		2.082	19.2	
		2.047	37.1	
		2.024	53.9	
		2.036	144.4	

TABLE 3

RESULTS OBTAINED WITH VERTICAL TRANSIT METHOD

h cm	V_c cm/s	V_p cm/s	V_p/V_c	a/h
30.7	52.1	52.2	1.002	0.065
45.0	54.7	54.5	0.996	0.044
60.5	39.5	39.3	0.995	0.033

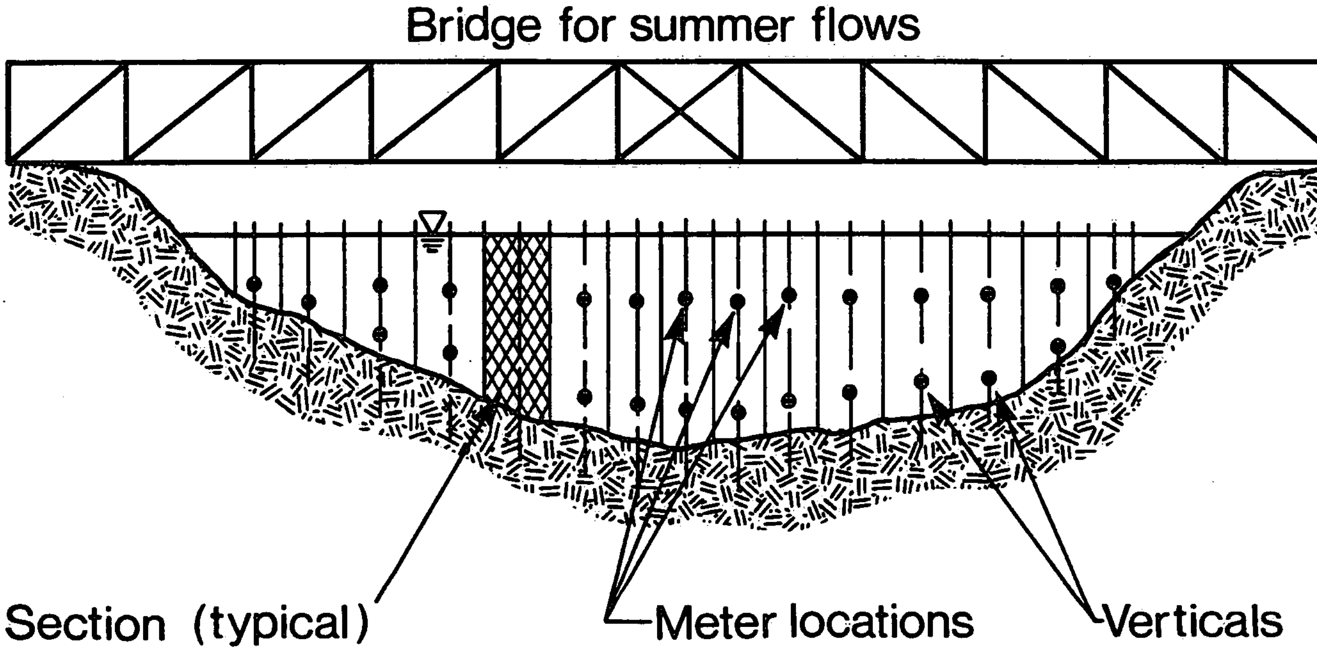
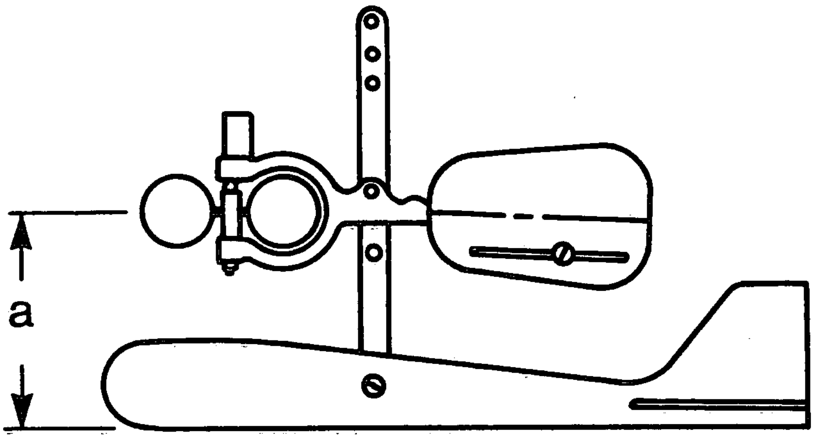


Figure 1 Location of verticals in measurement cross-section. (Lambie, 1978)



Figue 2 Price meter and sounding weight.

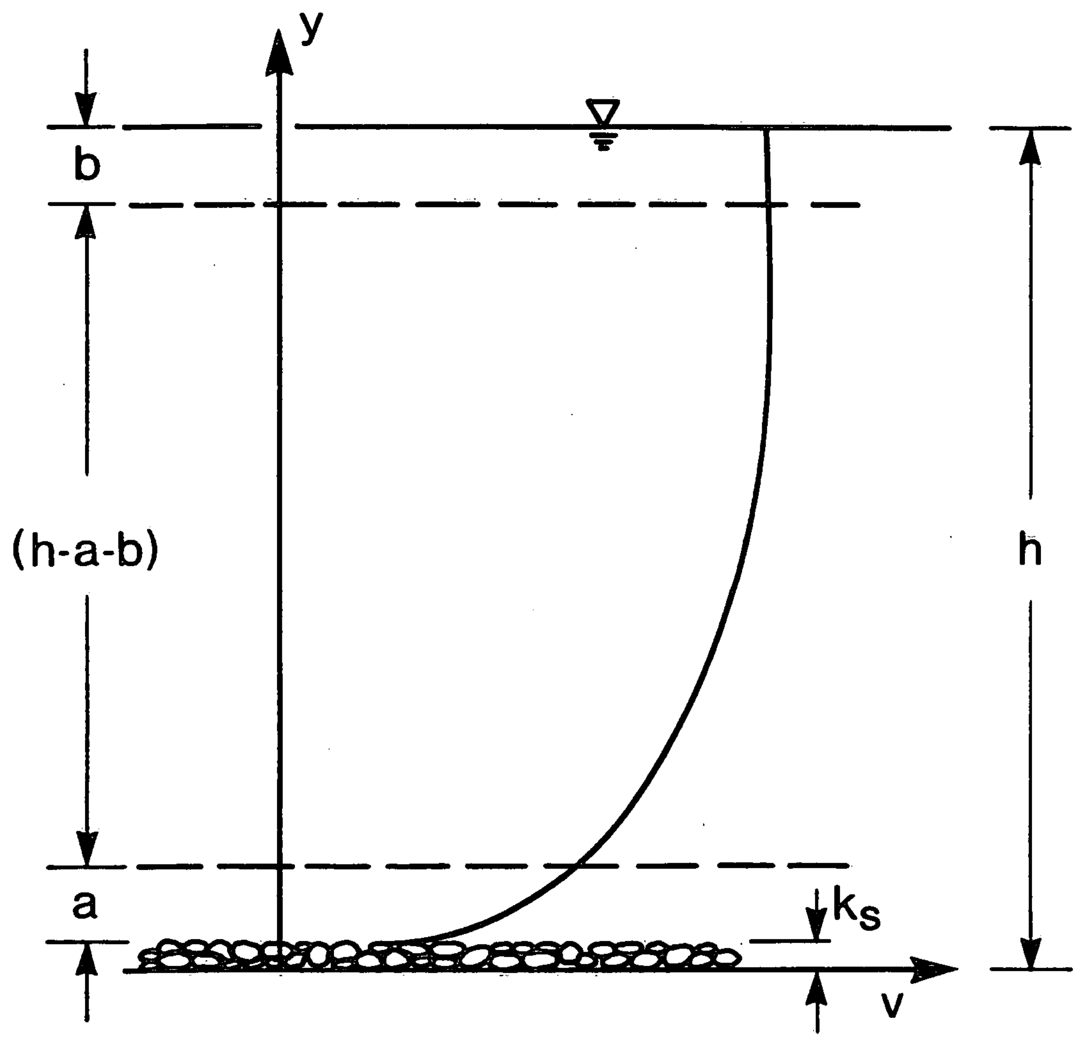


Figure 3 Vertical velocity profile and integration limits.

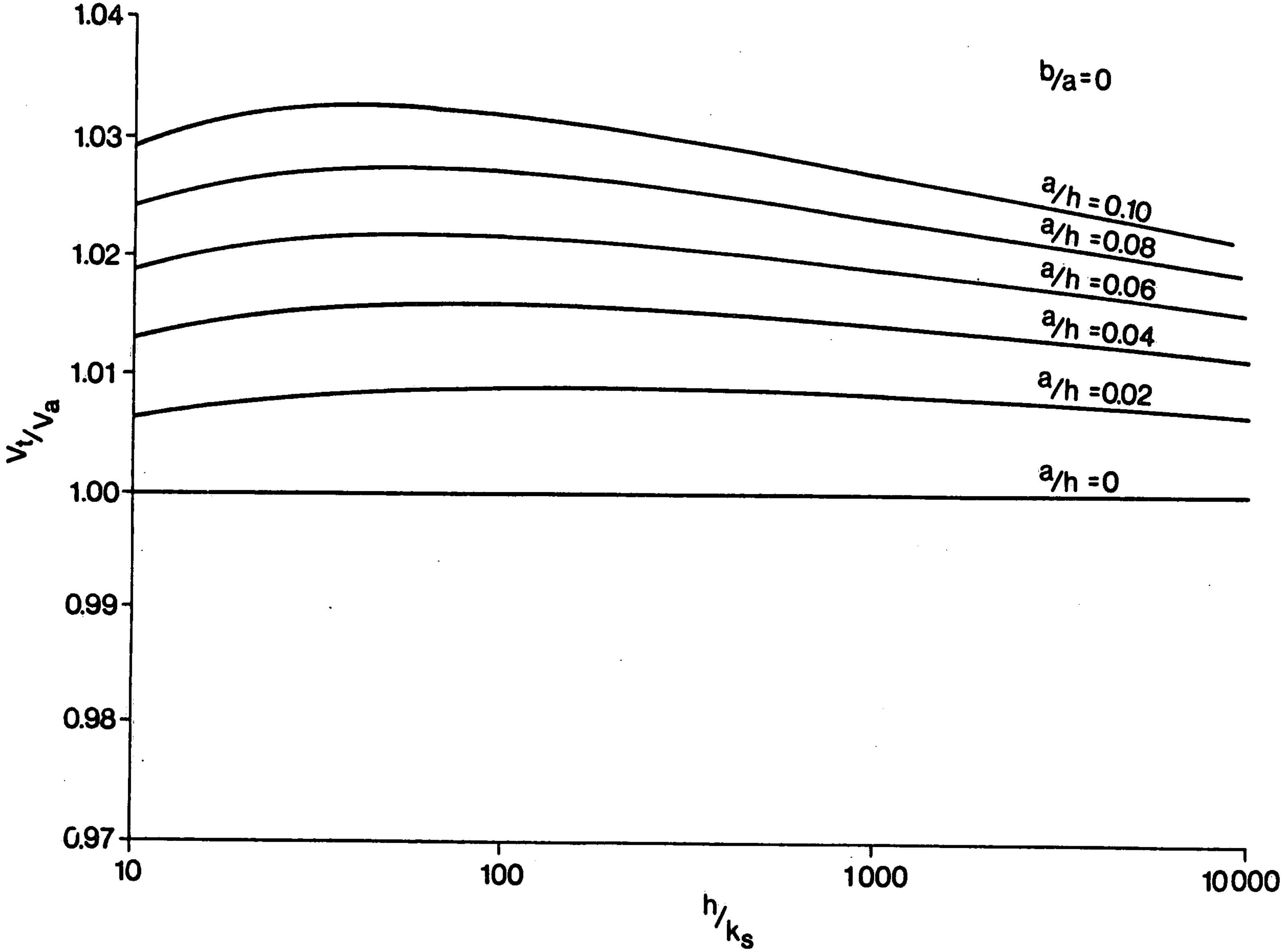


Figure 4 Effect of $^h/_{k_s}$ and $^a/h$ on mean velocity ratio for $^b/a=0$

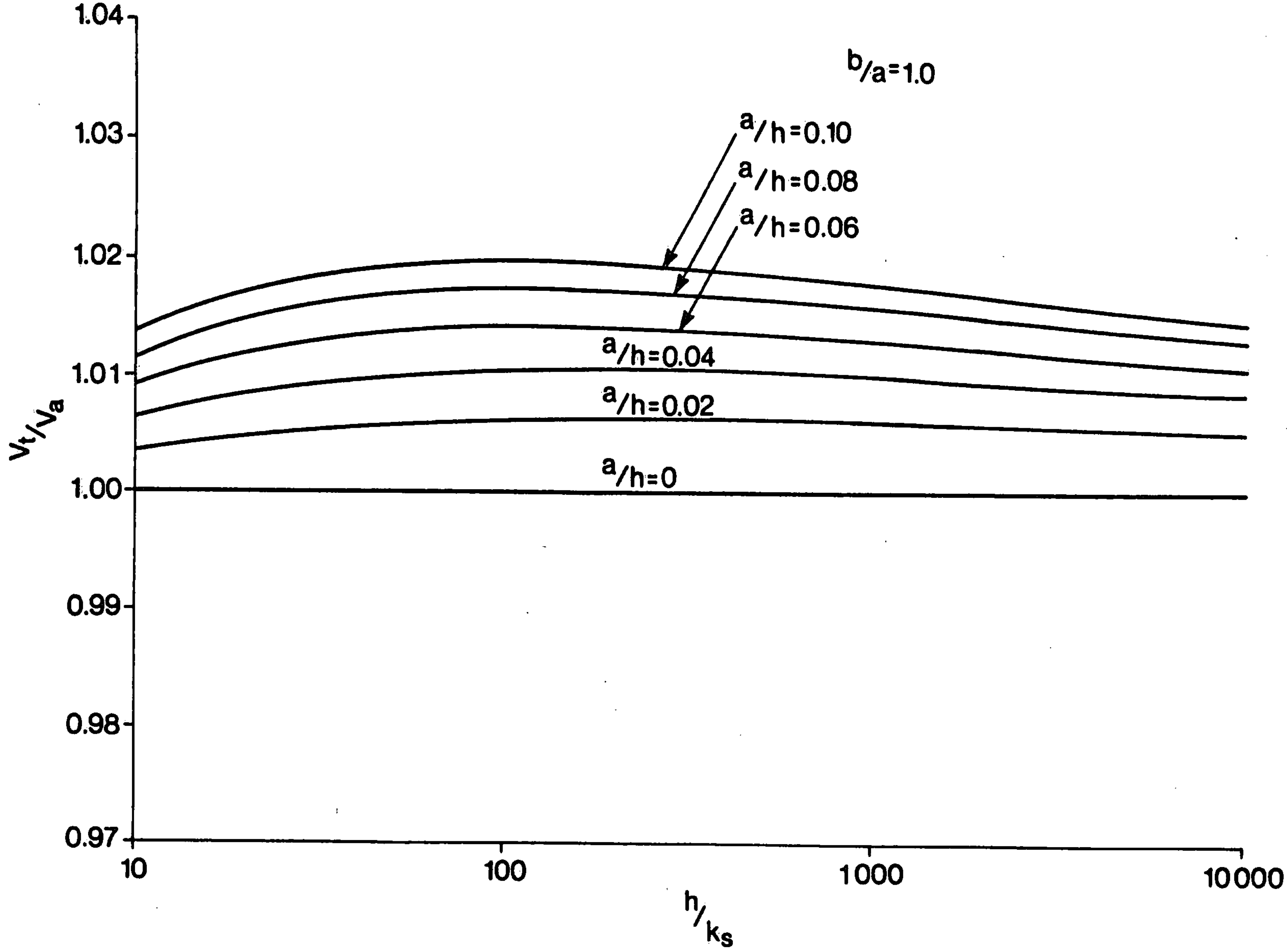


Figure 5 Effect of h/k_s and a/h on mean velocity ratio for b/a=1.0

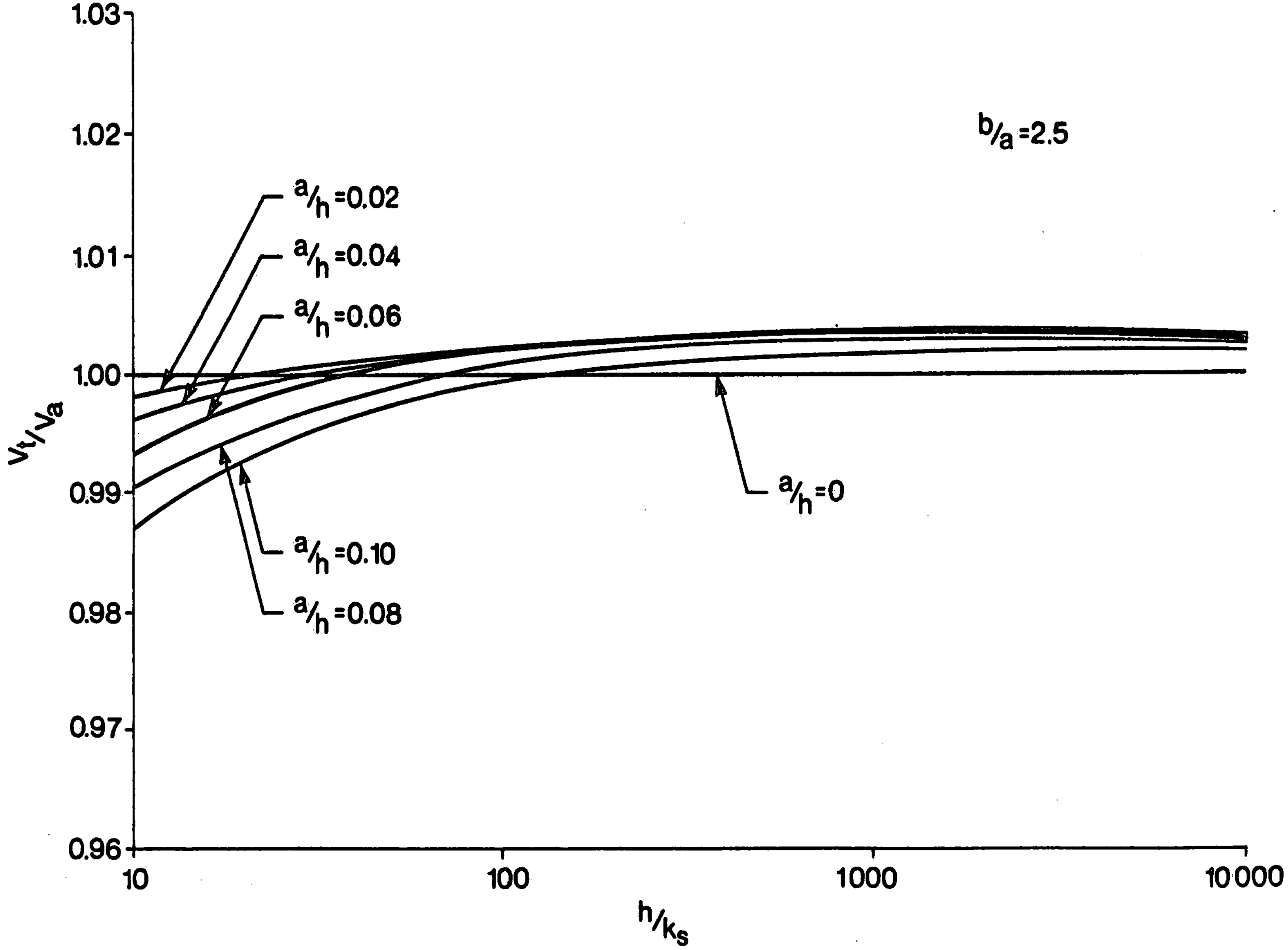


Figure 6 Effect of h/k_s and a/h on mean velocity ratio for b/a=2.5

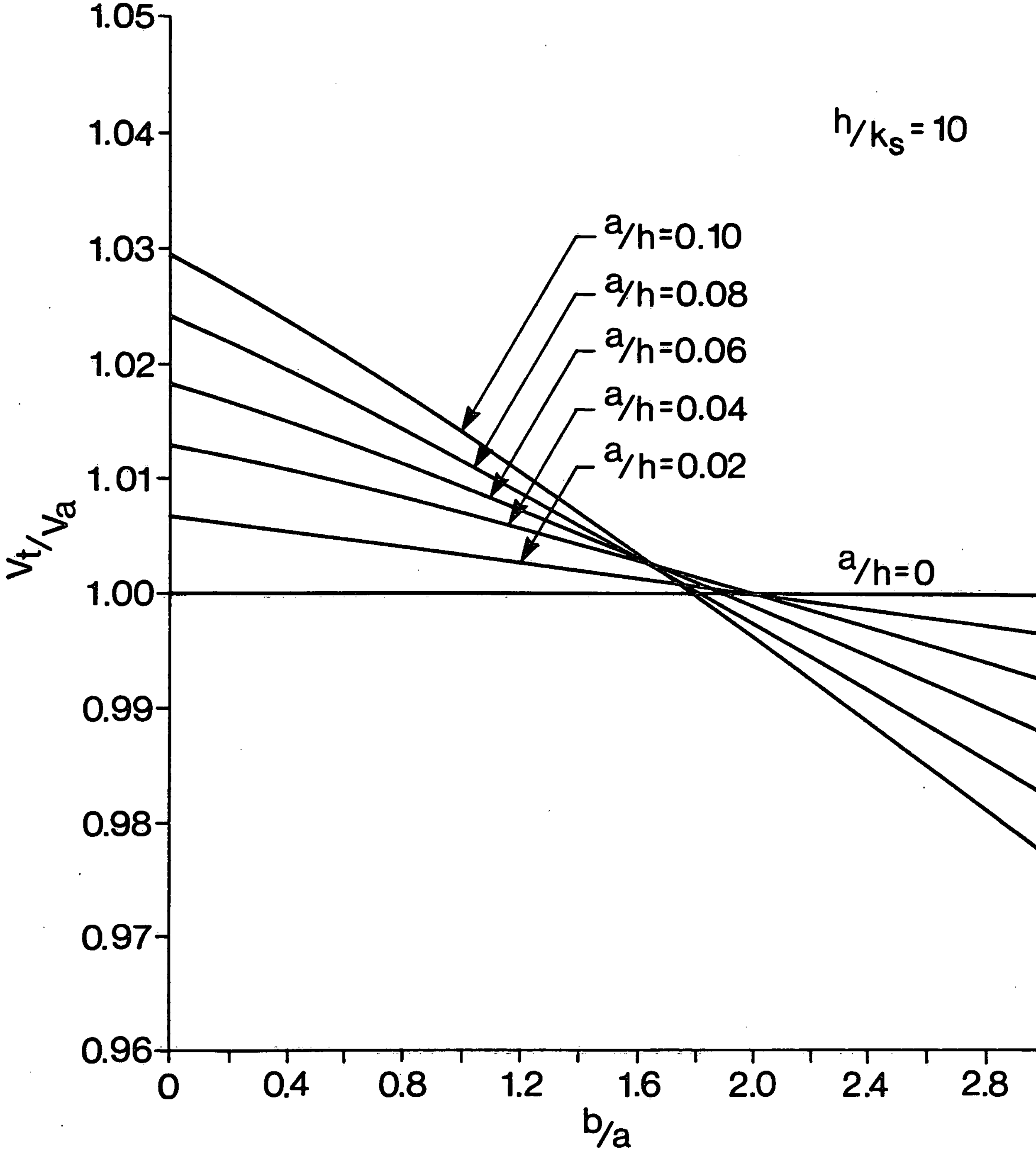


Figure 7 Effect of b/a and a/h on the mean velocity ratio for $h/k_s = 10$

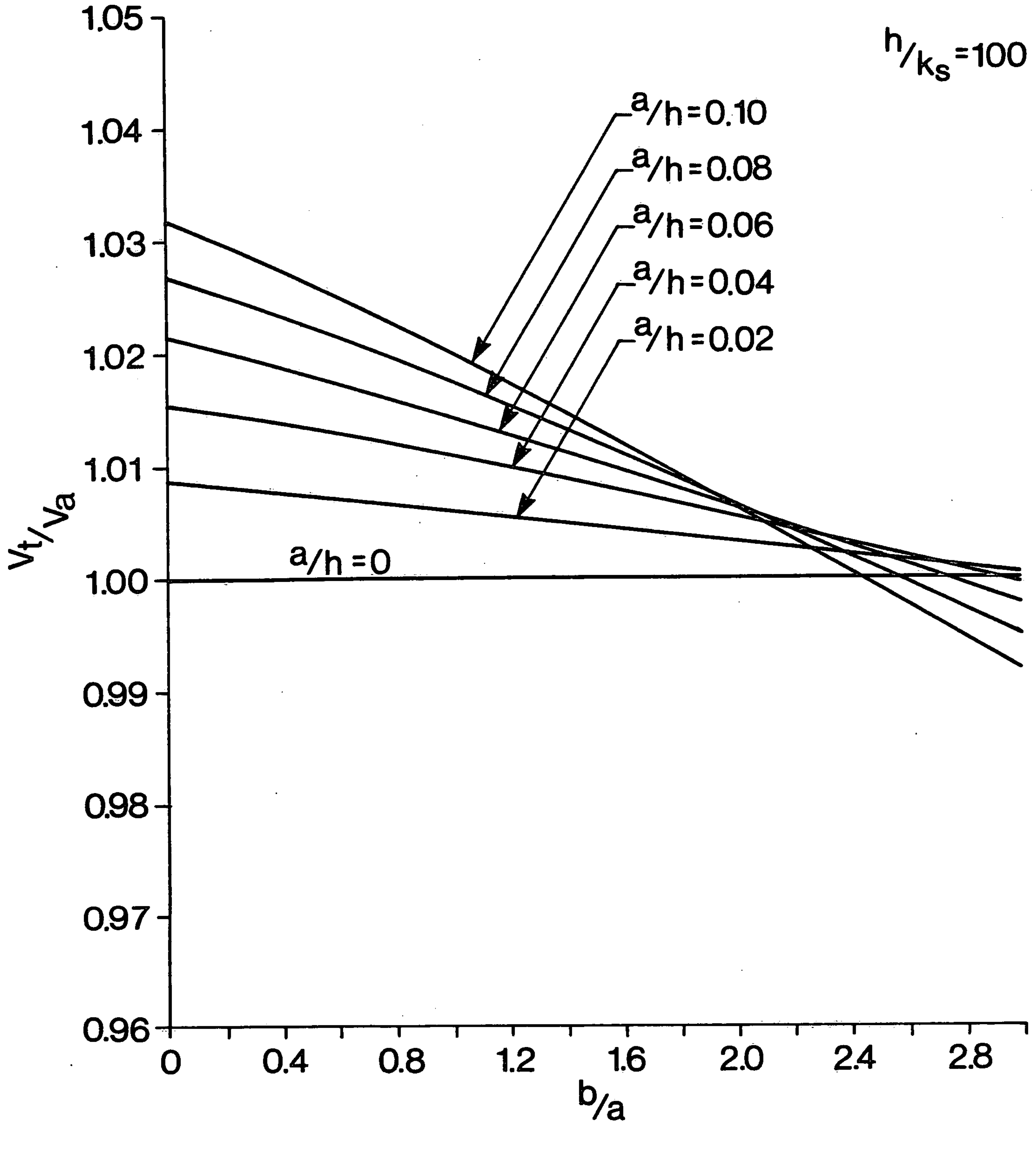


Figure 8 Effect of effect of $^{b}/a$ and $^{a}/h$ on the mean velocity ratio for $^{h}/k_s = 100$

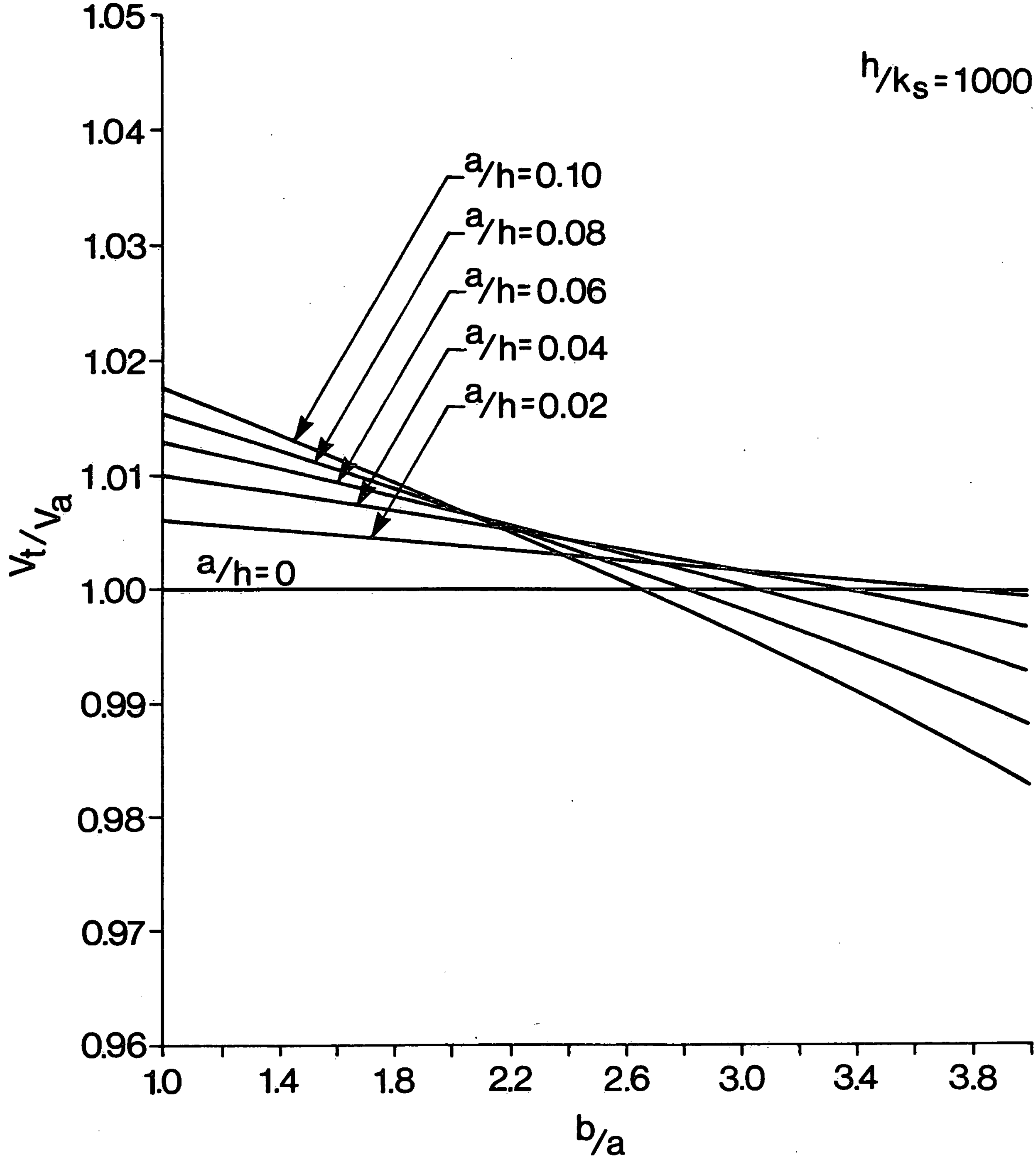


Figure 9 Effect of $^b/a$ and $^a/h$ on the mean velocity ratio for $^h/k_s = 1000$.

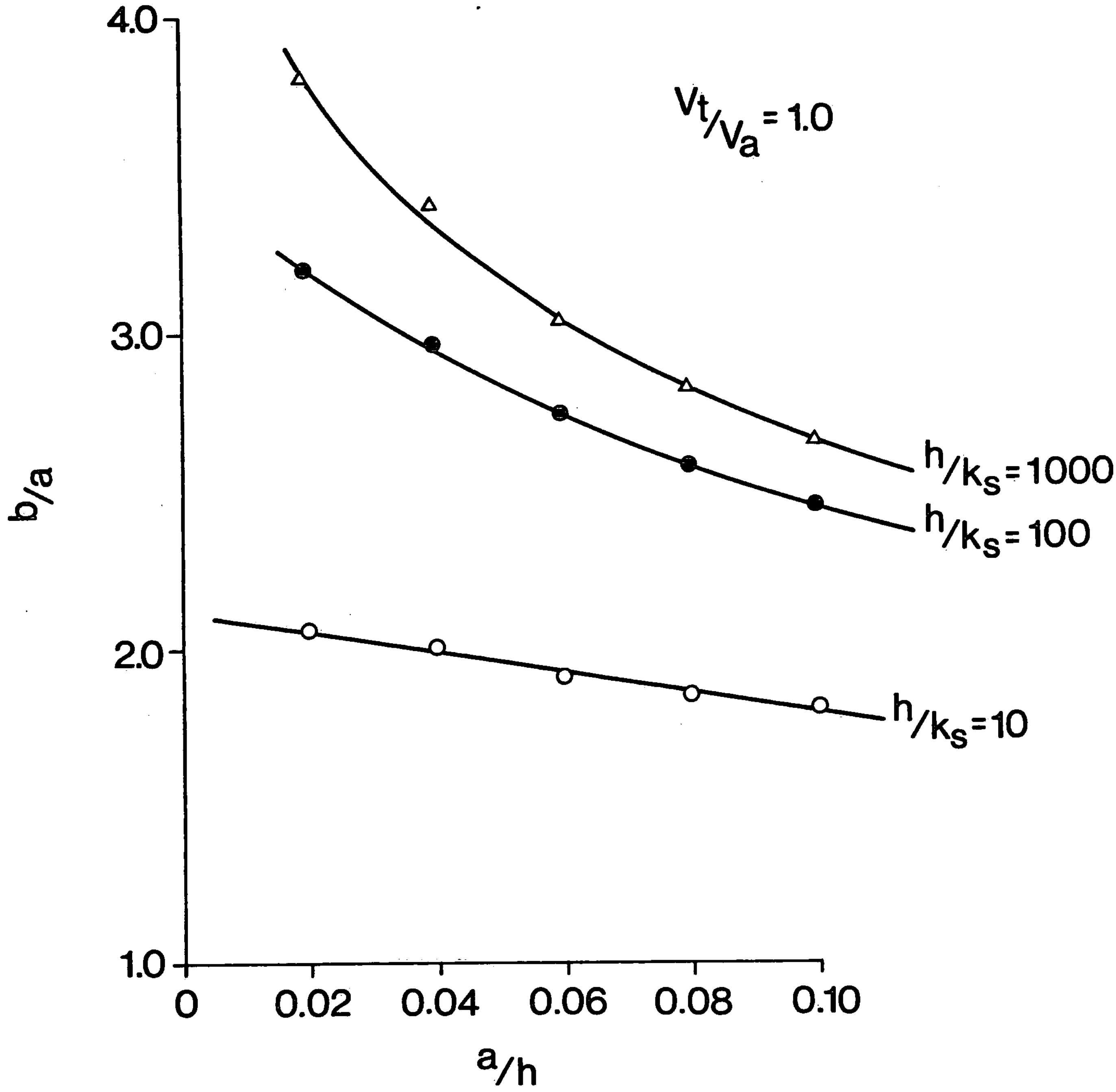


Figure 10 Value of $^{b}/a$ for which $^{V_t}/_{V_a} = 1.0$

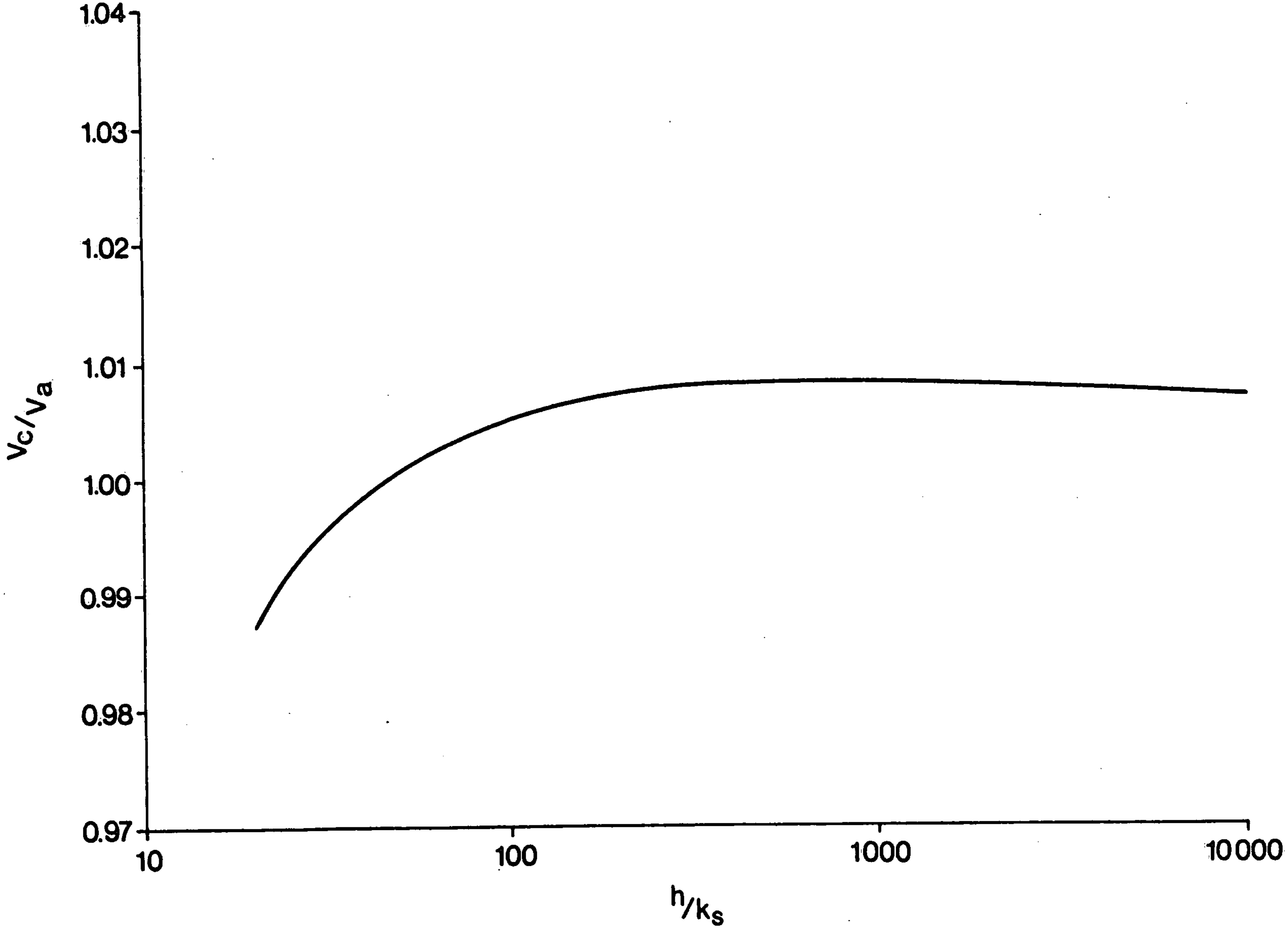


Figure 11 Mean velocity ratio for 0.2-0.8 depth method as a function of $^h/_{k_s}$.

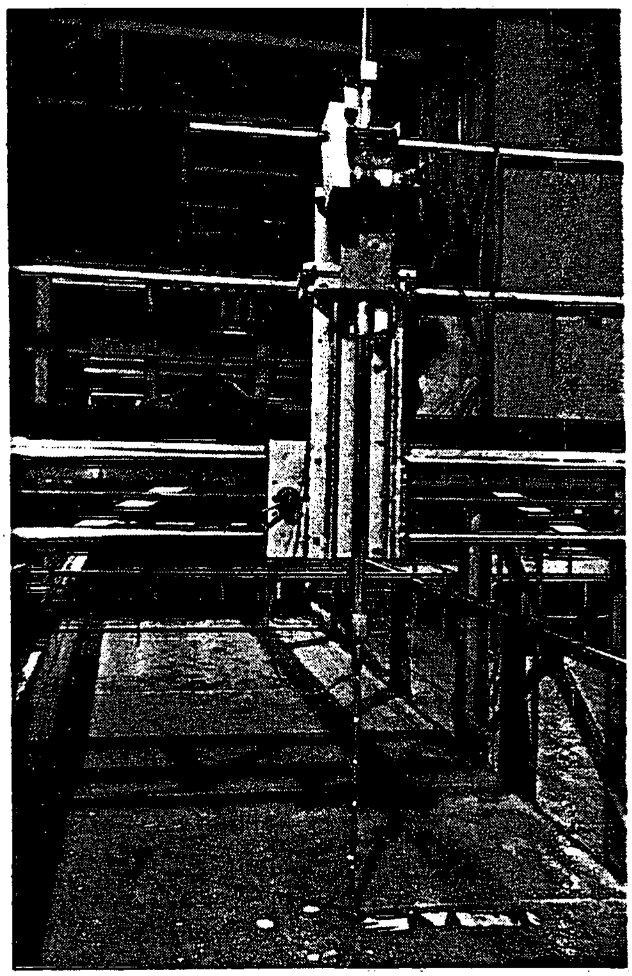


Figure 12 Vertical transit profiling system used in flume tests.

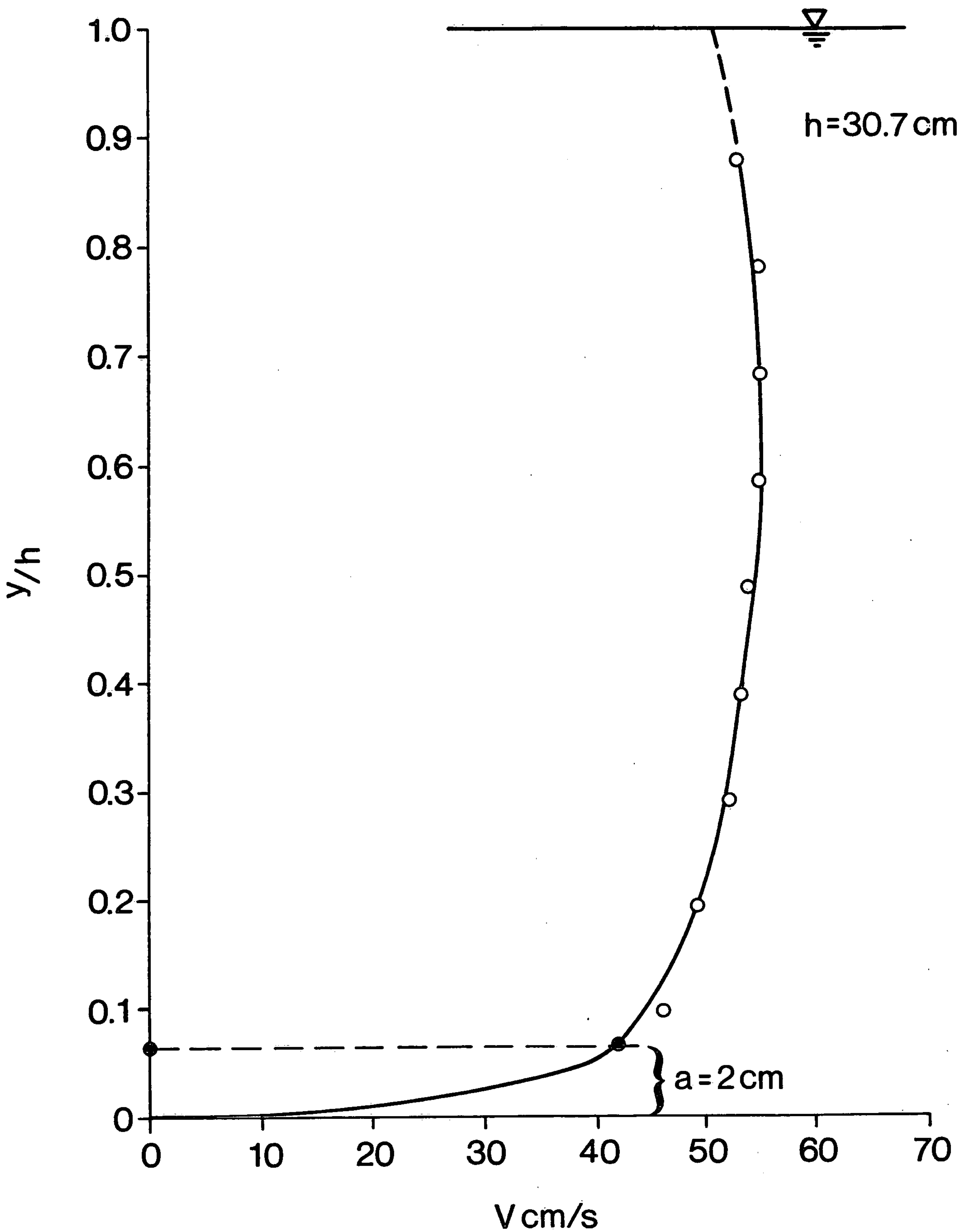


Figure 13 Velocity profile for a depth of 30.7 cm.

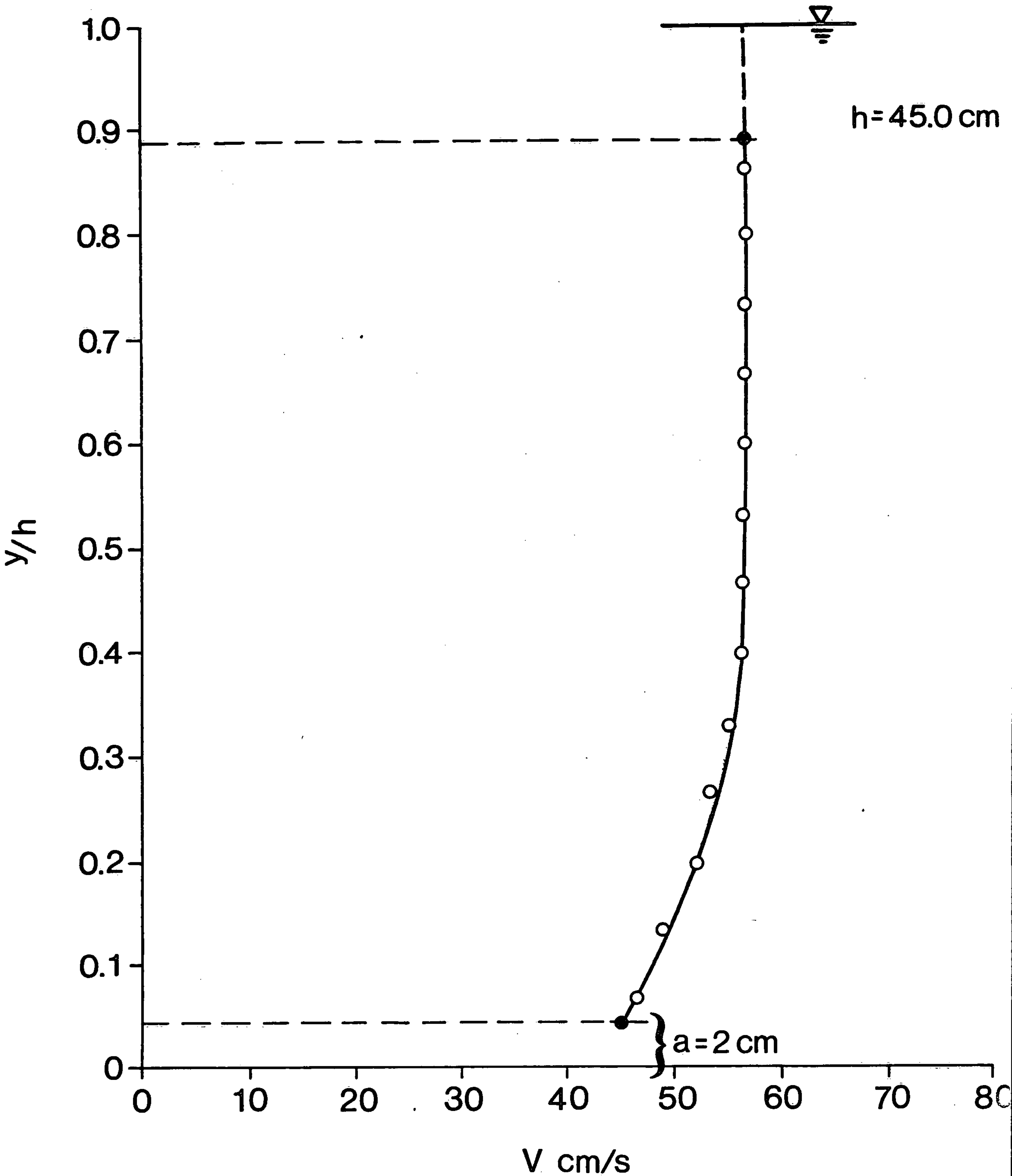


Figure 14 Velocity profile for a depth of 40.0 cm

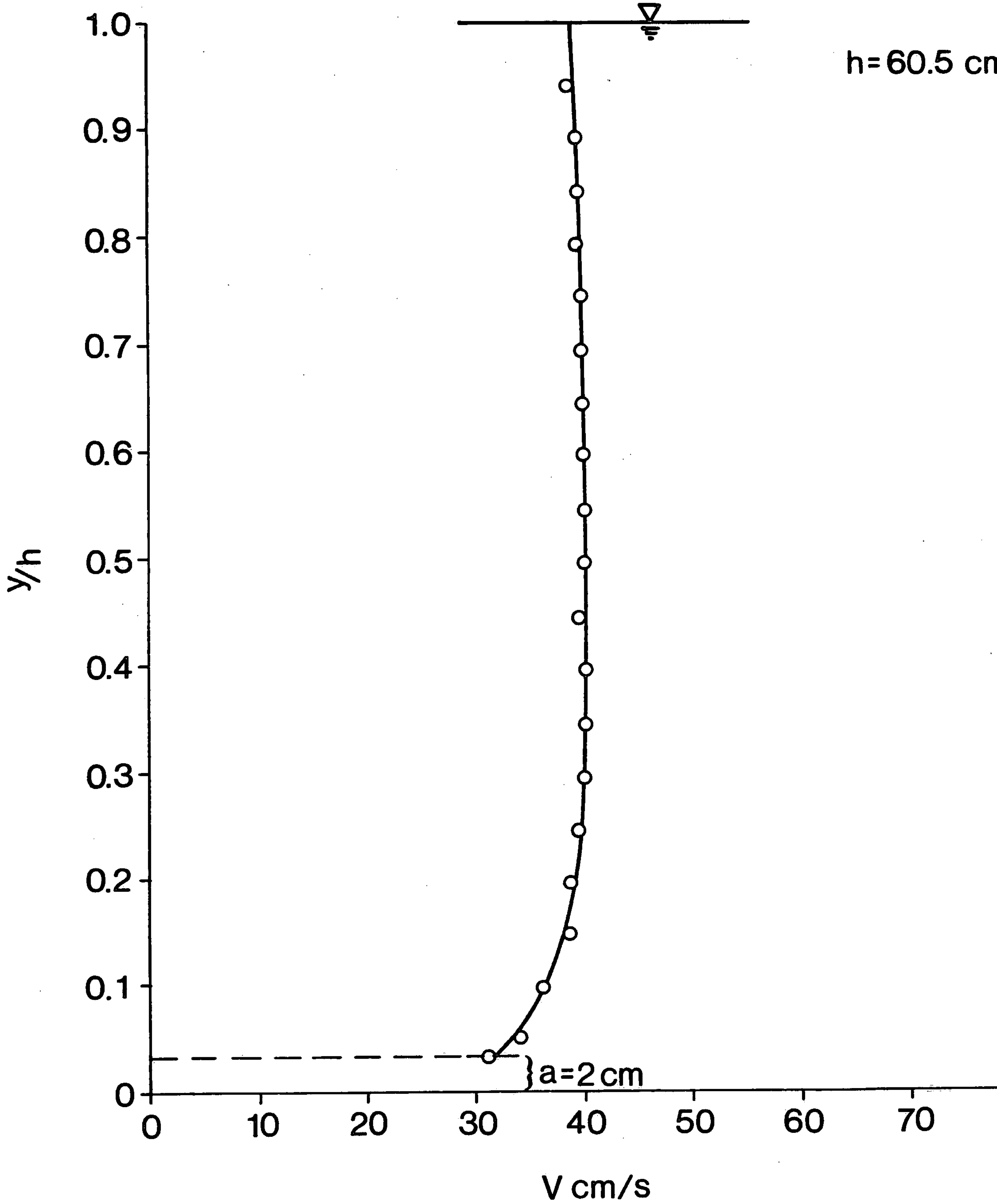


Figure 15 Velocity profile for a depth of 60.5 cm.

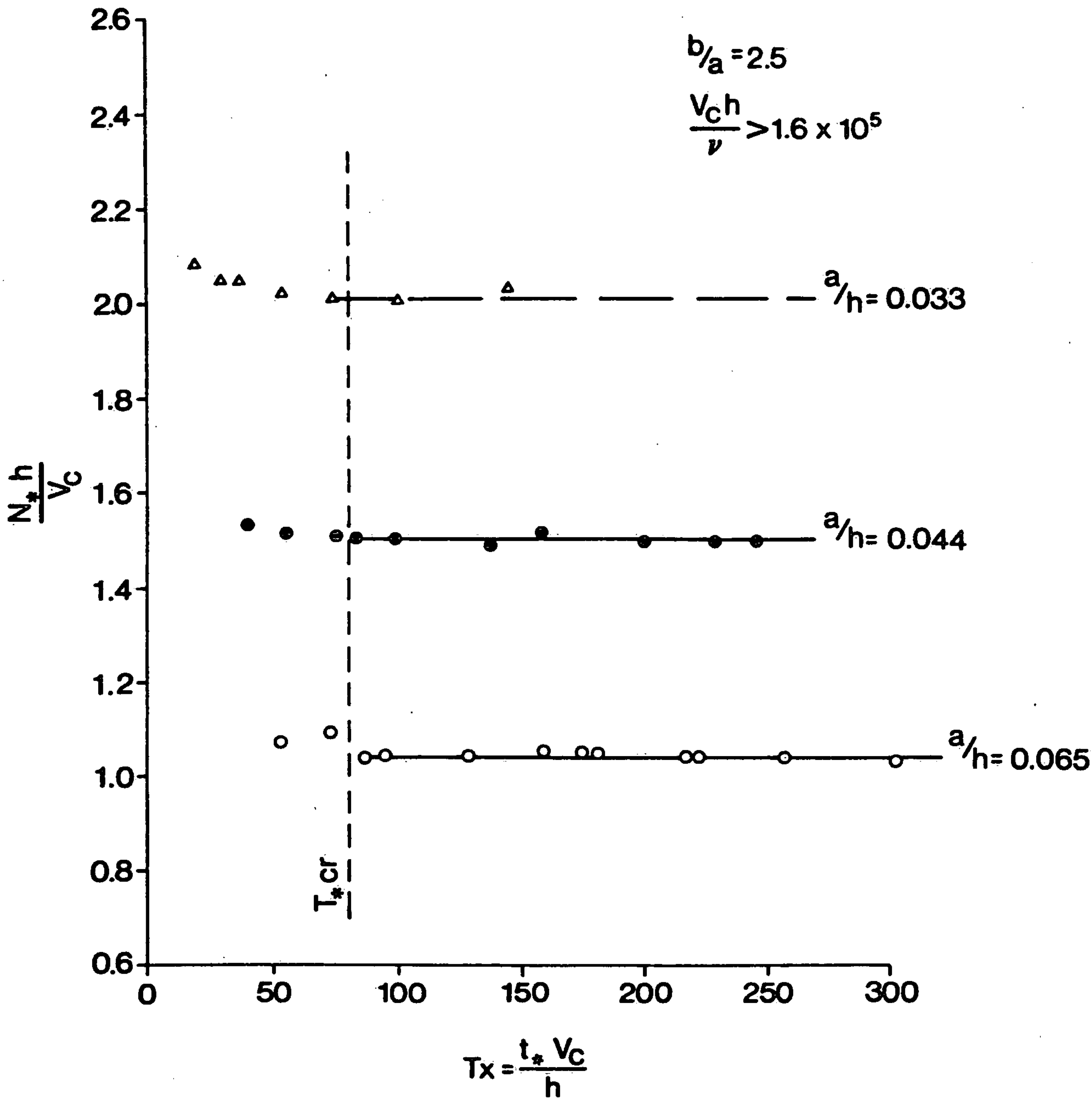


Figure 16 Effect of vertical transit speed on current meter response.

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