FLOMEKO 2003
11th IMEKO TC9 Conference on Flow Measurement
Groningen, NETHERLANDS, 12 - 14 May 2003

CALIBRATION OF THE SLUICE GATES IN THE AFSLUITDIJK

Ivo Pothof, Christof Lubbers, WL | Delft Hydraulics, The Netherlands

Introduction

The Afsluitdijk (literally Closing Dike) has been constructed in 1932. The objectives of the dike were flood protection, an area increase for agriculture and a fresh water reservoir (IJssel Lake). The Afsluitdijk comprises two sluice gate structures: the Stevin sluice gates (15 gates) at the West end of the dike and the Lorentz sluice gates (10 gates) at the East end of the dike. Every low tide with Wadden Sea levels sufficiently below the IJssel Lake level, the gates open and fresh water flows into the Wadden Sea. Rising sea levels, bottom depletion and climate change result in decreased discharge capacity. Therefore an additional sluice structure is planned. The discharge coefficients of each of the 12 m wide gates are still based on physical models from 1922 (Karlsruhe), 1927 and 1933 (Delft) with an estimated uncertainty of 20%. A more accurate determination of the discharge capacity of the sluice gate structures is required to establish the design capacity and associated cost of the new structure. Therefore the Ministry of Transport, Public Works and Water Management, Water Management Direction (RWS) has decided to calibrate the sluice gate structures in the Afsluitdijk, aiming for an uncertainty of 5%.

The calibration project is carried out by RWS with support from WL | Delft Hydraulics. RWS carries out the water level and velocity measurements and develops software for primary evaluation and time synchronisation of the data. WL | Delft Hydraulics has developed the calibration method and the uncertainty evaluation for this particular construction, in close co-operation with RWS. Furthermore, WL has performed statistical analyses.

First the global geometry, the typical operation and the possible flow regimes are outlined. Then the instrumentation and approach of the calibration are discussed. The approach requires calibration of the layers near the bottom, the walls and, especially, the water surface. These calibrations are discussed in more detail. Finally an estimate of the total uncertainty of the calibrated discharge through a sluice gate in the Afsluitdijk is given.

Sluice gate structures

The Stevin structure consists of 3 groups of 5 gates, each 12 m wide; see Figure 1. The Lorentz structure consists of 2 groups of 5 gates; see Figure 2. The geometry of each gate is identical. The bottom gradually rises from the IJssel Lake bottom to -4.70 m NAP; the length of this section is approximately 20 m. At this point the basalt walls start, that separate the individual sluice gates. The length of the basalt walls is 50 m. The bottom profile elevates 20 respectively 30 centimetre at the location of the two subsequent stop gates. Downstream of the structure the bottom profile suddenly drops to -6.0 m NAP. The length of this section is approximately 17 m. Downstream of the structure, the Wadden Sea bottom profile drops to *-30 m NAP*, due to the eroding force of the flow velocities through the sluice gates. Maximum velocities are about 5 m/s in the Stevin structure and 6 m/s in the Lorentz structure, because the Wadden Sea tides are lower at the Lorentz structure. The roughness of the basalt walls is about 3 cm, based on visual inspection. The bottom is made of evenly laid brick with an estimated roughness of a few millimetres.

Operational modes during a discharge period

The operational modes of the sluice gates are based on the target water level in the IJssel Lake, the actual level in the IJssel Lake and the expected Wadden Sea tide. The target level in summer is -0.2 m NAP and in winter -0.4 m NAP. The gates open if the Wadden Sea level becomes 0.10 m lower than the IJssel Lake level. The gates close again, if the level difference again reduces below 0.10 m. Each gate may be fully open, partially open (for fish migration) or closed. The gates within a group of 5 gates are arranged in certain configurations, that are always symmetrical. Only gates 1 and 5 may be partially open for fish migration.

The approach for the calibration should take the modes of operation and the dynamics during the discharge period into account.

Flow regime and discharge equation
In order to determine the type of overflow, it is necessary to summarise a few water level and tide statistics:

Table 1: Water level statistics [m NAP]

Percentile [%]	IJssel Lake levels		Wadden Sea low tide	
	winter	summer	winter	summer
5	-0.43	-0.27	-1.25	-1.19
95	+0.10	-0.10	-0.09	-0.49

The Wadden Sea low tides are values in Den Oever, close to the Stevin structure. In summer, the variation in both the IJssel Lake water level and Wadden Sea low tides are significantly smaller, because there are fewer storms and smaller river inflows during summer. The crest in the bottom profile of the sluice gates is -4.4 m NAP, resulting in the water heights of table 2.

Table 2: Water heights [m relative to gate crest]

Percentile [%]	IJssel Lake heights		Wadden Sea heights	
	winter	summer	winter	summer
5	3.97	4.13	3.15	3.21
95	4.50	4.30	4.31	3.91

The flow regime in broad or short crested weirs is determined by the submergence S, which is the ratio of downstream and upstream water height [1, 2 and list of symbols].

$$S = \frac{h_3}{h_1} \qquad (1)$$

If the submergence is less than 2/3, the flow regime is critical on the weir, otherwise the flow regime is sub-critical and the structure is submerged. The flow over a critical weir is not affected by the downstream water level, while the flow over a submerged weir is affected by the downstream water level. The submergence of the sluice gates is always greater than 0.7 (= 3.15 / 4.50). Hence the sluice gates are affected by the downstream water level and the discharge changes continuously with the Wadden Sea tide. The rise of the tide may occur very quickly; 0.5 m in 10 minutes.

A general equation for the flow per unit width over a submerged weir is the following:

$$Q_p = C_{d3} \cdot h_3 \sqrt{2 \cdot g \cdot (h_1 - h_3)} \qquad (2)$$

The symbols are explained in figure 3 and in the List of symbols.

$$Q_p = C_d \cdot h_2 \sqrt{2 \cdot g \cdot (h_1 - h_2)} \qquad (3)$$

If the water height on the crest is essentially level with the tailwater, the discharge coefficients are equivalent; there is no pressure recovery. Equation (3) is preferred, because it is anticipated that the most accurate discharge coefficients are obtained. This discharge coefficient accounts for upstream losses only and downstream losses must be accounted for by correlating the downstream water level with the water level in the sluice gate.

The fact that the gates have a non-standard geometry necessitates the calibration, because the discharge coefficient is strongly affected by the local up- and downstream conditions of geometry and approach flow.

<u>Instrumentation</u>

Essential instrumentation
The calibration requires, at least, the determination of the water levels in the IJssel Lake (section 1 in figure 3), in the sluice gate (section 2) and in the Wadden Sea (section 3) and the flow velocities in the sluice gate. The water level meters in section 1 and 3 are standard devices, based on the pressure difference with atmospheric pressure; see the red and green triangles in figures 1 and 2. These gauges are installed at locations where the velocity is negligible during sluice gate flow.

The water level meter in section 2 is mounted on a measurement bridge on a known elevation. This device measures the distance to the water level using ultrasonic waves.

The flow velocities in section 2 are measured with Acoustic Doppler Current Profilers (ADCPs, 1200 kHz ‘Workhorse’ from RD Instruments). The ADCP is also mounted on the measurement bridge and driven by a step-motor. The ADCP is positioned just below the water surface, facing downward. The position is adjusted during the discharge period as the water level changes. The ADCP comprises 2 perpendicular pairs of acoustic beams, looking in an angle of 20° with the vertical. The reflected acoustic signal results in a profile of bin velocities. The Ministry has selected the ADCP devices for various reasons:
- availability within the organisation;
- experience with the operation;
- the sluice gate structures belong to the national heritage, implying that the basalt walls and brick bottom may not be damaged by mounting velocity meters, reducing the choice of the velocity meters to acoustic profilers;
- a significant portion of the velocity profile is measured instantaneously;
- the method is non-intrusive for the measured profile.

The bin size has been set to 0.25 m and the measurement time has been set to 1 minute to obtain sufficient accuracy. The vertical profiles are measured at 5 positions in the gate: 1 m, 3 m, 6 m, 9 m and 11 m from the wall. Since we are interested in the net discharge parallel to the gate walls, only two perpendicular beams are evaluated. The advantage is that velocities can be measured relatively close to the wall.

Three measurement bridges have been constructed such that three gates can be measured simultaneously. The bridges are installed in three gates within one group, or in gate number 3 of each group, in order to compare and inter-relate the discharge coefficients. The bridges are put on top of the basalt walls approximately 3 m above the water surface. The drag force on an ADCP is sufficient to overturn the complete measurement bridge at high flow rates, even if the ADCP is put just below the surface. Therefore the ADCPs have been streamlined.

The main disadvantage of the ADCPs is the fact that velocities cannot be measured very close to the water surface or close to the bottom. The ADCP must be sufficiently submerged to prevent air entrainment and disturbance of the measurement. The height of the streamlined ADCP is 30 cm. One binsize of 25 cm can not be measured. Finally a margin is required to prevent air entrainment in the wavy flowfield. Consequently, the velocity in 80 cm to 1 m below the surface cannot be measured. The binsize is 25 cm, the pulse angle is 20°, resulting in an unmeasured layer of 6% of the distance to the bottom plus half a bin size. Close to the bottom, this vertical distance of 6% plus half a bin size cannot be measured. If the ADCP is located 4 meter above the bottom, this unmeasured bottom layer is about 37 cm. Test measurements indicated that reliable measurement of both the water level and velocity profiles are possible from 1 m from the walls. Consequently the velocity profiles near the bottom, the walls and the free surface have to be calibrated separately.

Additional instrumentation

The water level gauges in the inside harbour (Binnenhaven) and outside harbour (Voorhaven) are currently being used for determination of the total sluice gate discharge. These gauges belong to a national system of water level gauges (MSW) and for this reason the Ministry prefers to use only these 'standard' measurements for determination of the sluice gate discharges.

Approach

The bottom line of the calibration is the determination of the discharge coefficient per sluice gate, its uncertainty and the possible variation with:

- upstream water level in section 1;
- downstream water level in section 3;
- gate configuration;
- wind, which is expected to affect the uncertainty mainly.

Furthermore it is verified whether fixed ratios between the discharge coefficients of the sluice gates exist.

The overall discharge coefficient of a gate is derived from the discharge coefficients in the vertical profiles and the calibrated wall profile. The discharge coefficient of a vertical profile is computed from the ADCP measurements, the water level measurements in section 1 and 2 and the calibrated bottom and surface profiles. The advantage of working with discharge coefficients per vertical is that all these values are measured simultaneously. Therefore these measurements can be inter-related and compared, irrespective of the water levels. These vertical profile discharge coefficients may vary with:

- water levels, but only slightly;
- gate configuration;
- horizontal position of the profile;
- gate (number within the group of 5 gates);
- time after opening or before stopping (inertia effects), and
- wind.

$$C_d\left(n, x_i, t_j, b_k, w\right) = \frac{Q_p\left(n, x_i, t_j, b_k, w\right)}{h_2\sqrt{2g\left(h_1 - h_2\right)}} \tag{4}$$

The importance of accurate velocity profiles near the walls, bottom and surface becomes obvious, if we calculate the cross-sectional area of these layers. Assuming a water height in section 2 of the gate of 4 m, the total discharge area is 48 m^2. The area of the wall layers is 8 m^2, the area of the bottom layer is at most 4.0 m^2 (without double counting the corners) and the area of the surface layer is at most 10 m^2. Hence at most 46% of the total discharge area must be calibrated differently.

The remainder of this paper is dedicated to the establishment of the profiles in the wall layers, bottom layer and surface layer.

Calibration data

The calibration measurement of the velocity profile near the walls and below the surface has been carried out with a small ADCP instrument, the Aquadopp from Nortek. The binsize is 10 cm, the pulse angle is 25°, resulting in an unmeasured layer of 9.6% of the distance to the wall plus half a bin size. The wall profile has been measured by positioning the instrument 2 m from the wall, facing towards the wall at various water depths. The surface profile has been measured by positioning the instrument as close as possible to the surface. The small size of the instrument results in an unmeasured surface layer of 0.5 m. Test measurements indicated that the instrument could not look upward, because of surface waves and influence from the measurement frame. The ADCP has been used with a bin size of 10 cm for calibration of the bottom profile, while the position is as deep as possible without overturning the measurement bridge, which was about 2.5 m above the bottom.

All calibration data for the velocity profiles in the wall layers, the bottom layer and the surface layer has been obtained with the Aquadopp and ADCP with 10 cm bins. The 5 Aquadopp positions for calibrating the surface layer velocities are located at 1.4 m, 3.4 m, 6.4 m, 9.4 m en 11.4 m from the East side of the gate. The 5 ADCP positions for calibrating the bottom layer are located at 0.5 m, 2.5 m, 5.5 m, 8.5 m en 10.5 m from the East wall. The reason for these non-standard horizontal positions is the fact that the Aquadopp was mounted to the frame as well. Unfortunately the data in the first position (0.5 m) proved to be useless, because of the short distance to the wall.

The following velocity measurements have been recorded for the profiles in the layers:

- Over 3000 wall layer velocity profiles (10 s average values) in gate 15 facing West wall and East wall with velocities ranging from 0.1 m/s to 4.4 m/s.
- 761 bottom layer velocity profiles (10 s average values) in gates 13 and 14 with velocities ranging from 0.7 to 3.9 m/s.
- 645 surface layer velocity profiles (3 minute average values) in 3, 8, 13 and 15 with velocities ranging from 0.1 m/s to 5.2 m/s.

Wall layer profile

We need to establish an expression for the average velocity in the wall layer, using the measured velocity during the regular calibration measurements at 1 m from the wall. The following expression is a logical starting point:

$$\bar{v}_w = c_w \cdot v_{ADCP} \tag{5}$$

Visual inspection of the data shows that the last reliable bin is at 20 cm from the wall, which is consistent with the observation that 9.6% plus half a bin is not measured.

De calibration factor, c_w, could depend on:

- distance from bottom;
- measured velocity at 1 m from the wall;
- West wall or East wall, since the approach flow enters the sluice gates with angle.

The measurements have been carried out in gate 5 of group 3, because the difference between the walls is most pronounced in this gate, because of the large angle between approach flow and gate. If a difference between the East wall and West wall profiles cannot be identified in this gate, then the velocity profiles in the other gates must be similar.

The analysis confirms that the depth does not affect the profile at all. Figure 4 and Figure 5 show that the profiles are similar for velocities above 1 m/s. Velocity profiles below 1 m/s are flatter than the other profiles. These low velocities occur only in the initial stage of the discharge period. In this stage the flow is accelerating, probably causing the flatter profile. Since velocities below 1 m/s hardly occur (6% of the time during these calibration measurements), these measurements are not used in establishing the calibration factor. The velocity decrease at 1.5 m resp. 1.6 m from the wall is probably caused by the presence of the Aquadopp instrument, because these bins are in the wake of the instrument. The profiles near both walls are very similar (Figure 6), despite the direction of the approach flow. For this reason an average wall profile is proposed for all wall layers.

Table 3: calibrated wall profile (distance [m] and dimensionless velocity)

0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
0	0.5	0.721	0.806	0.870	0.911	0.944	0.966	0.986	0.996	1.0

The following average velocity in the wall layers is derived:

$$\bar{v}_w = 0.820 \cdot v_{ADCP} \tag{6}$$

The standard deviation in the bins drops from 5% at 0.2 m from the wall to 1.1% at 1 m. The relative standard deviation in the average wall layer velocity is 2.8% and remains the same if we would adopt separate profiles for both walls. The tabulated profile does not fit very well with a power law, probably due to a not fully developed boundary layer.

Bottom layer profile

The approach for the analysis is similar with the approach for the wall layers. The highest bins are measured at –2.8 m NAP for these measurements. Visual inspection shows that the lowest bin is 20 cm from the bottom, which is consistent with 6% plus half a bin of 10 cm. The velocity profile is estimated based on measured values between 0.20 m and 1.00 m from the bottom. The calibration factor, c_b, might depend on:

- horizontal position (wall influence);
- measured ADCP velocity.

The analysis confirms that the horizontal position does not affect the profile at all. Since the number of profiles is relatively small (126 profiles), the dependency on the ADCP velocity is not evaluated. The profiles are depicted in Figure 7, where the velocities at 1.0 m from the bottom varied between 0.7 m/s and 3.9 m/s.

It is concluded that the bottom velocity profile closely matches a power law profile (n = 9.60).

$$v(z) = v(z_g) \cdot \left(\frac{z}{z_g} \right)^{1/9.60} \tag{7}$$

The relative standard deviation of the power law approximation is only 1.7%. It may be concluded that the bottom velocity profile is fully developed, due to the smooth bottom transition from the IJssel Lake bathymetry to the sluice gates.

Surface layer profile

The surface layer profile must be based on regular ADCP calibration measurements at least 1 m below the water surface. The analysis starts with the two measurements approximately between 1.0 m and 1.5 m below the water surface. The exact elevation of these ADCP bins should not deviate significantly from these values; say 10 cm. The following expression is a logical starting point:

$$\bar{v}_s = c_s \cdot \frac{v_{ADCP}(z_M) + v_{ADCP}(z_{M-1})}{2} = c_s \cdot \bar{v}_{ADCP} \qquad (8)$$

The calibration factor, c_s, might depend on:

- horizontal position (wall influence);
- measured ADCP velocity.

Again, the analysis confirms that the horizontal position does not affect the profile at all. Visual inspection of the Aquadopp measurements shows that the velocity reduces towards the surface at velocities below 4 m/s. The velocity increases towards the surface at velocities above 4 m/s. Furthermore the profile in the 6 bins closest to the surface (0.5 m tot 1.1 m below the surface) is close to linear. Since the velocity at the surface is not measured directly, the calibration of the surface profile consists of two steps:

1. the velocity at the surface is estimated based on linear extrapolation from the first 6 bins;
2. the average velocity in the surface layer (appr. 1 m) is estimated from the average velocity between 1.0 and 1.5 m below the surface (see equation (8)).

The relative standard deviation of the extrapolated surface velocity is calculated from linear regression theory. The standard deviation increases as the distance between the measured Aquadopp bins and the surface increases; this standard deviation is 4.0%.

It has been checked whether the wind affects the velocity profile near the water surface, because wind may change the surface velocity compared to the core velocity at 1.0 m below the surface. However, the correlation between the hourly averaged wind velocity and the ratio of surface velocity and core velocity is only 0.06, which is negligible.

The extrapolated surface velocity is depicted as a function of the average core velocity between 1.0 and 1.5 m below the surface in Figure 8. The figure shows a strong linear relation below 4.1 m/s and a sudden change at 4.1 m/s. The explanation of the sudden change at 4.1 m/s is a shift towards the critical flow regime. The flow is still accelerated in the measurement plane. The calibration equation of the surface velocity as a function of the core velocity is:

$$\begin{aligned} \bar{v}_{ADCP} < 4.08\,m/s: &\quad v(h_2) = 0.028 + 0.934 \cdot \bar{v}_{ADCP} \\ \bar{v}_{ADCP} > 4.08\,m/s: &\quad v(h_2) = -4.561 + 2.062 \cdot \bar{v}_{ADCP} \end{aligned} \qquad (9)$$

The relative standard deviation of the calibration equation is 6.5%. The total relative standard deviation at the surface then becomes 7.6%. Assuming a linear increase in the standard deviation from 1.5% in the measured ADCP bins to 7.6% at the water surface, the standard deviation in the average surface layer velocity is 4.6%. Table 4 below shows that the residuals cannot be correlated to other variables.

Table 4: correlation between the surface velocity residuals and other variables

Other variable	Correlation coefficient
Average ADCP velocity	-0.03
Distance between ADCP bin and water surface	0.04
Average ADCP velocity in horizontal position 1	-0.24
Average ADCP velocity in horizontal position 3	0.02
Average ADCP velocity in horizontal position 5	0.44

The correlation with the profiles that are close to the walls (position 1 and 5) indicate that the velocity at the surface close to the walls behaves slightly different. Plotting the residuals against the measured ADCP velocity in horizontal positions 1 and 5 and trying tot remove the trend, using a linear or non-linear curve, results in coefficient of determination (explained variation) of 6% only; 94% of the variation is not explained. Consequently, refining the equation for the surface velocity in positions 1 and 5 does not give a significant improvement.

Total uncertainty in the instantaneous discharge per sluice gate

A rough estimate of the total uncertainty, which is twice the standard deviation, can be made based on the standard deviations of the calibrated profiles. Assume:

- Water height is 4.5 m;
- Bottom layer is 0.5 m, wall layers are 1 m, surface layer is 1 m;
- Average core velocity is 3 m/s with a standard deviation of 1.5% (instrument and turbulence);

The different layers make up 9 zones in the cross section, leading to an estimated relative standard deviation in the total discharge of 1.3% only (see Table 5). This relative standard deviation is smaller than all contributing relative standard deviations, because the absolute variance contributions must be added (see Table 5) and divided by the square of the total discharge; the square of the total discharge is significantly larger than the sum of squares of zone discharges. The total uncertainty is estimated 2.5% of the total discharge.

Table 5: determination of standard deviation of total discharge (zones are indicated in figure 9)

zone	Average velocity [m/s]	Cross section [m^2]	Q [m^3/s]	Relative Standard deviation [%]	Variance [m^6/s^2]
1	2.4	1.0	2.4	5.4	0.016
2	2.9	10.0	28.9	4.6	1.772
3	2.4	1.0	2.4	5.4	0.016
4	2.5	3.0	7.4	2.8	0.043
5	3.0	30.0	90.0	1.5	1.823
6	2.5	3.0	7.4	2.8	0.043
7	2.1	0.5	1.1	3.3	0.001
8	2.6	5.0	13.0	2.8	0.049
9	2.1	0.5	1.1	3.3	0.001
	Total	54	153.6	Absolute total variance	3.76
				Relative standard deviation in total discharge [%]	1.26

The last column shows that the total variance is mainly determined by the surface layer (zone 2) and the core zone (zone 5).

Project status

At this moment (February 2003), most of the calibration measurements have been carried out and the discharge coefficients per sluice gate can be determined and analysed as outlined in section Approach.

The uncertainty in the discharge coefficients will be somewhat greater than the uncertainty in the total discharge, depending on the goodness-of-fit of the discharge coefficient relation (eq. (4)).

Finally the uncertainty in the discharge, based on the standard up- and downstream water level measurements (MSW values), will be greater than the uncertainty in the discharge coefficients. The increase will depend on the goodness-of-fit of the relation between the standard water level measurements and the measured water levels in the sluice gates.

Conclusions

The calibration methodology of the sluice gates in the Afsluitdijk has been discussed, including global geometry, possible flow regimes and used instrumentation. Part of the calibration is the establishment of velocity profiles near the walls, the bottom and the water surface. The determination of these profiles has been discussed in detail, resulting in an estimate of the uncertainty in the total calibrated discharge of 2.5%.

The uncertainty will increase if the total discharge is based on standard water level measurements only; this work is yet to be done.

Acknowledgements

The authors wish to thank following people from RWS for their contributions and discussions: Arjen Ponger, Carlijn Bak, Dirk Vlag, Hans van Vugt, Cees Berkeveld, Thijs Broersma, Rinus Schroevers and Peter Verburgh.

List of Symbols

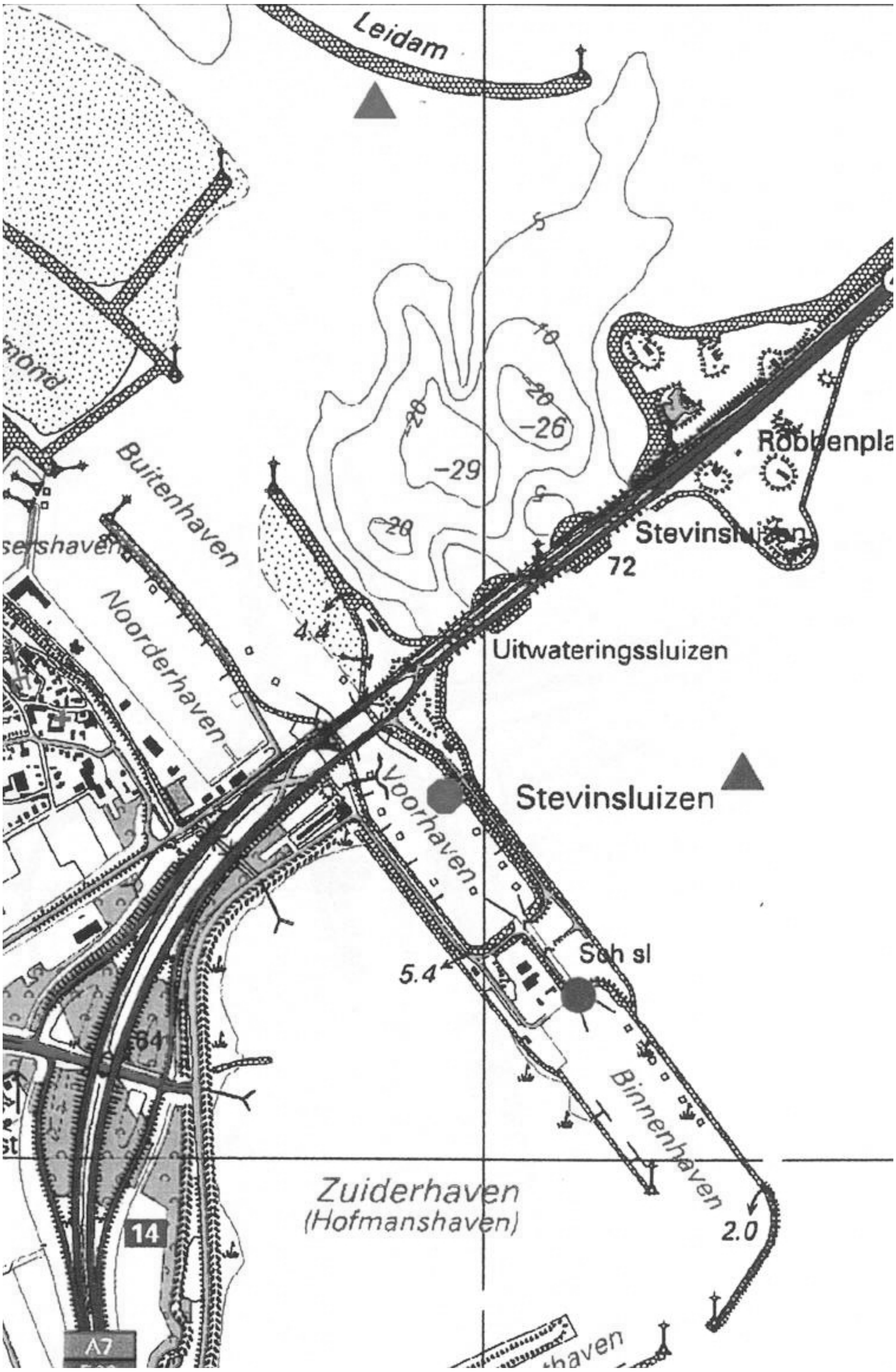
y_1	waterlevel in IJssel Lake, where velocity head is negligible [m NAP]
$y_{1,b}$	waterlevel in inside harbour (Binnenhaven) [m NAP]
y_2	waterlevel in gate in the velocity measurement plane [m NAP]
y_e	bottom of gate [m NAP]
y_3	waterlevel in Wadden Sea, where velocity head is negligible [m NAP]
$y_{3,v}$	waterlevel in outside harbour (Voorhaven) [m NAP]
h_1	water height in IJssel Lake [m], $h_1 = y_1 - y_e$
$h_{1,b}$	water height in inside harbour (Binnenhaven) [m], $h_{1,b} = y_{1,b} - y_e$
h_2	water height in gate [m], $h_2 = y_2 - y_e$
h_3	water height in Wadden Sea [m], $h_3 = y_3 - y_e$
$h_{3,v}$	water height in outside harbour (Voorhaven) [m], $h_{3,v} = y_{3,v} - y_e$
S	submergence as the ratio of downstream and upstream water heights [-], $S = h_3 / h_1$
Q_p	Discharge per unit width through gate [m^3/s/m]
$Q_p(n, x_i, t_j, b_k, w)$	Discharge per unit width through gate n in vertical profile x_i, at time t_j after opening, subject to gate configuration b_k and wind w [m^3/s/m]
$C_d(n, x_i, t_j, b_k, w)$	Discharge coefficient of gate n in vertical profile x_i, at time t_j after opening, subject to gate configuration b_k and wind w [-]
n_b	Bottom layer velocity profile power [-]
c_b	Bottom layer velocity calibration factor [-]
c_w	Wall layer velocity calibration factor [-]
c_s	Surface layer velocity calibration factor [-]

Literature

[1] V.T. Chow, Open-channel hydraulics, McGraw-Hill Int. Editions, Auckland, 1973.
[2] D.S. Miller (ed.), Discharge characteristics, Balkema, 1994.

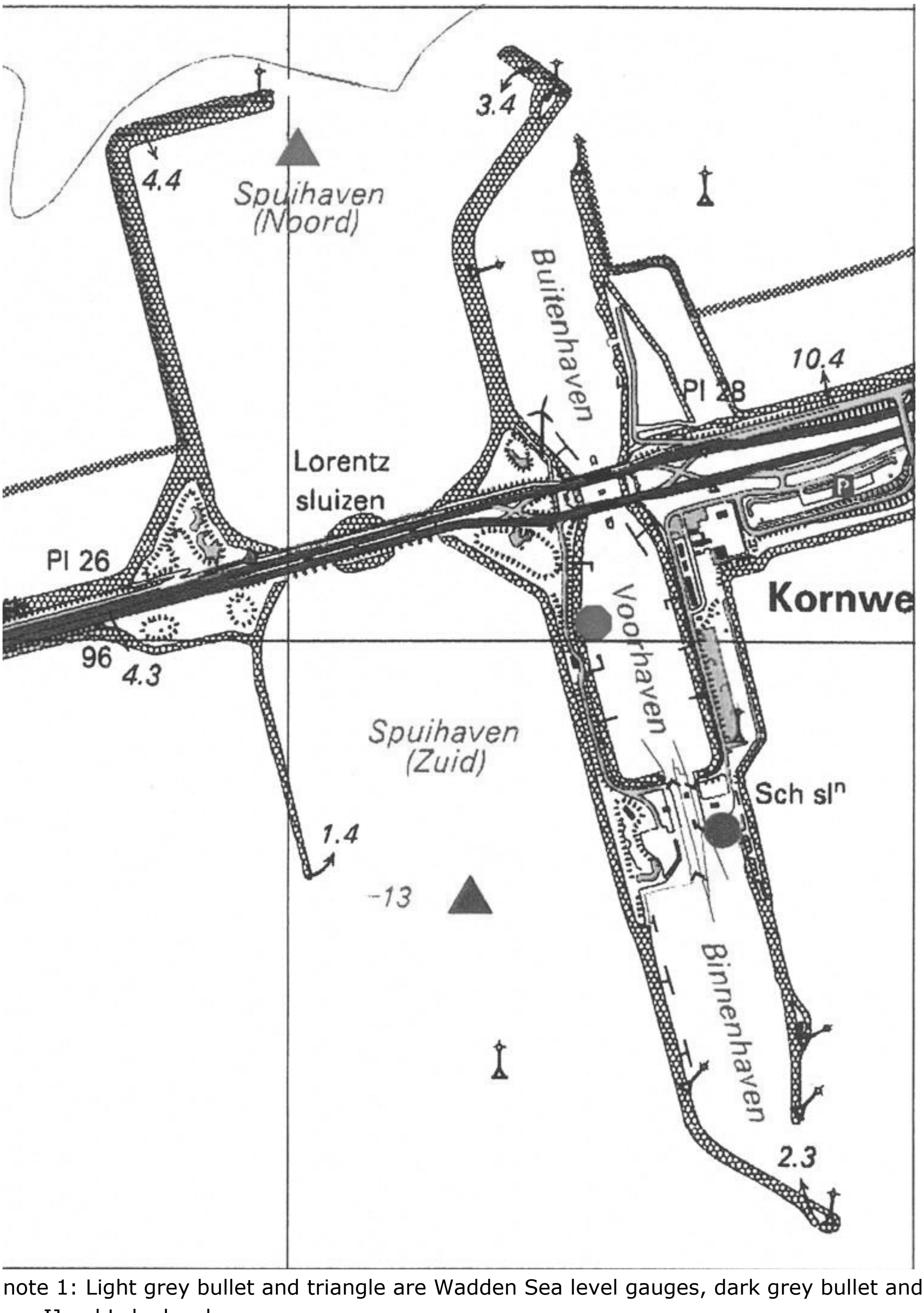
Figures

Figure 1: Overview of Stevin sluice gates



note 1: Light grey bullet and triangle are Wadden Sea level gauges, dark grey bullet and triangle are IJssel Lake level gauges
note 2: used by permission from Min. V&W, RD IJsselmeergebied, ANM

Figure 2: Overview of Lorentz sluice gates



note 1: Light grey bullet and triangle are Wadden Sea level gauges, dark grey bullet and triangle are IJssel Lake level gauges
note 2: used by permission from Min. V&W, RD IJsselmeergebied, ANM

Figure 3: Side view schematic of sluice gate (see also List of Symbols)

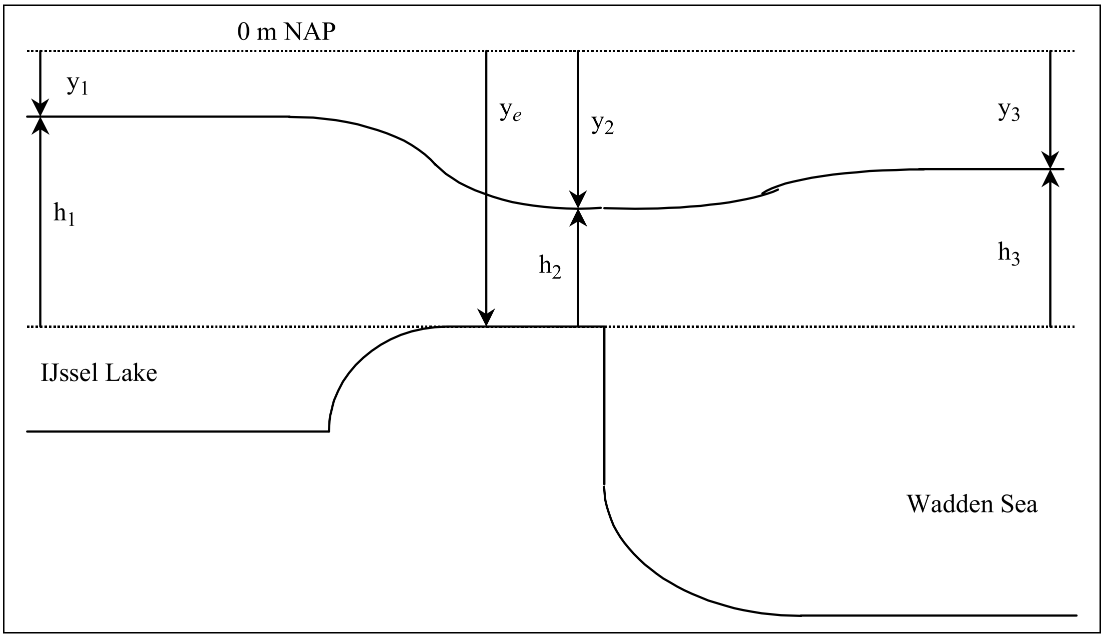


Figure 4: Scaled profiles at different velocity ranges near the East wall

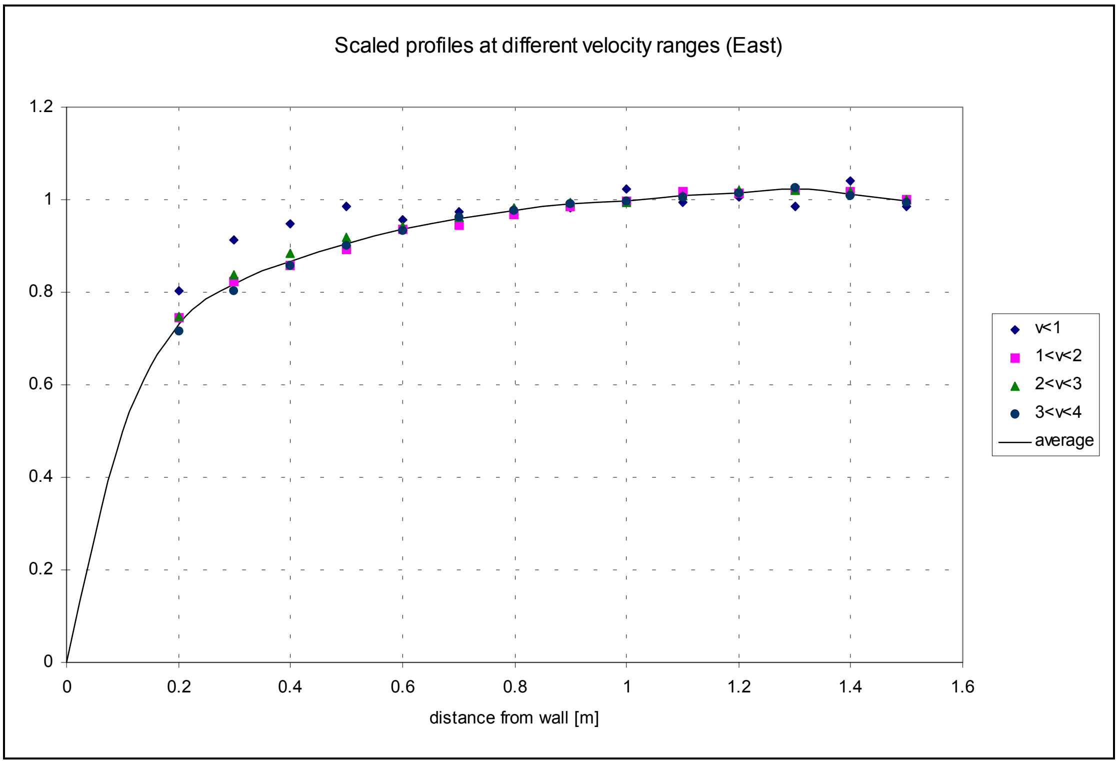


Figure 5: Scaled profiles at different velocity ranges near the West wall

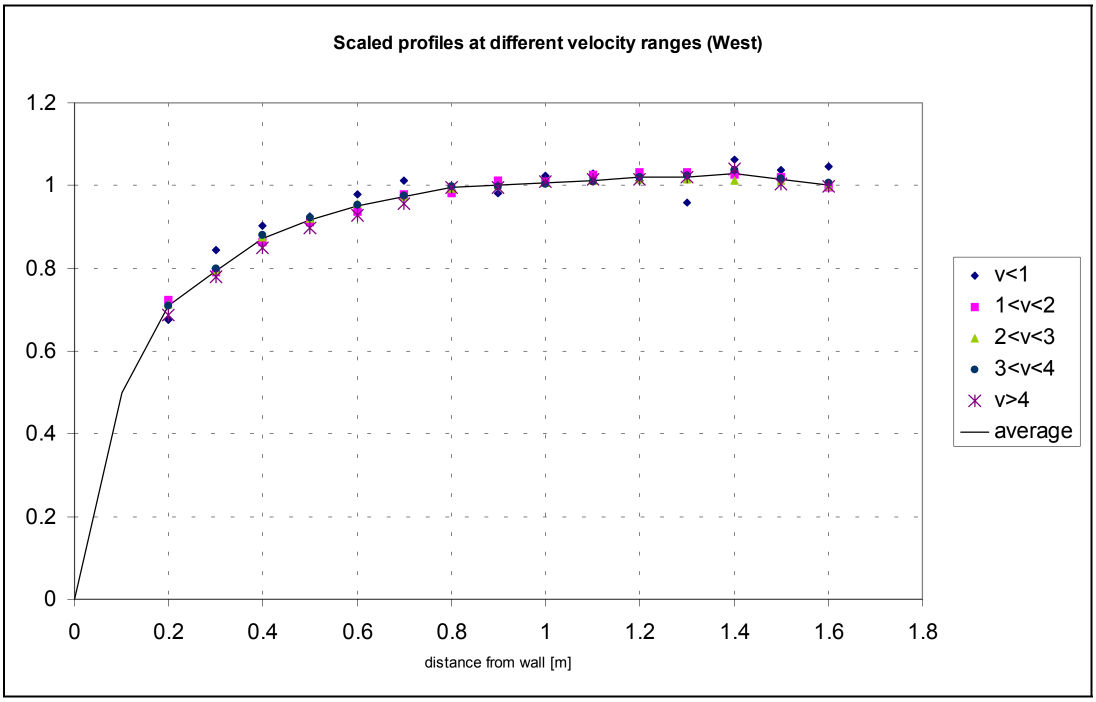


Figure 6: Comparison of East wall and West wall profiles

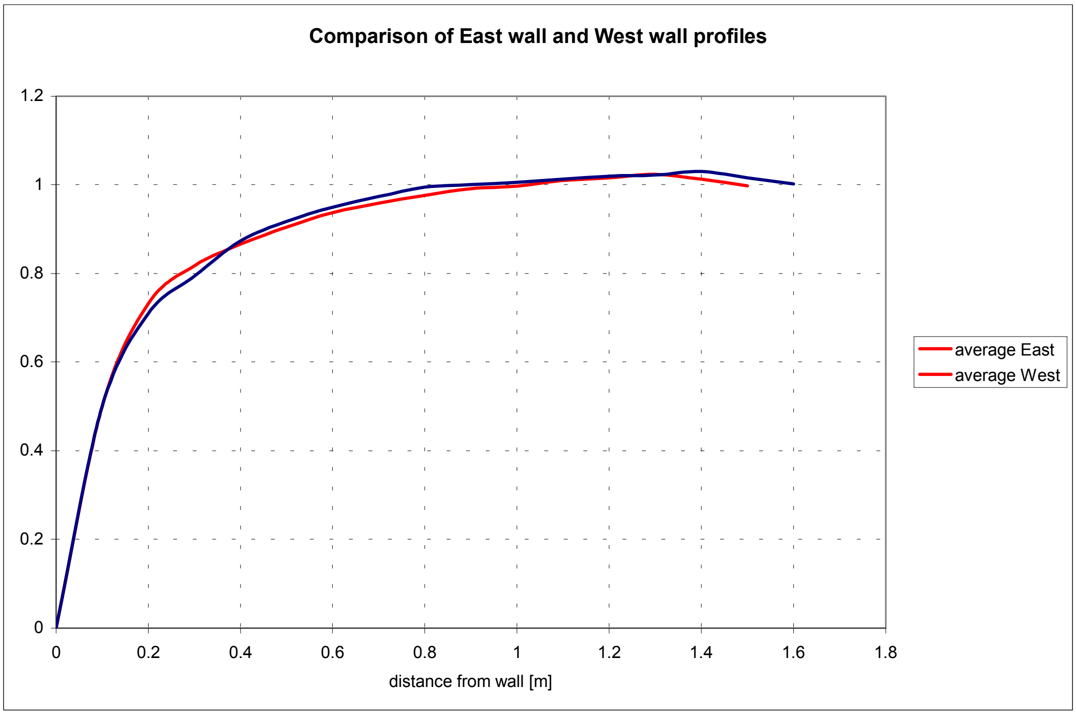


Figure 7: Bottom velocity profile

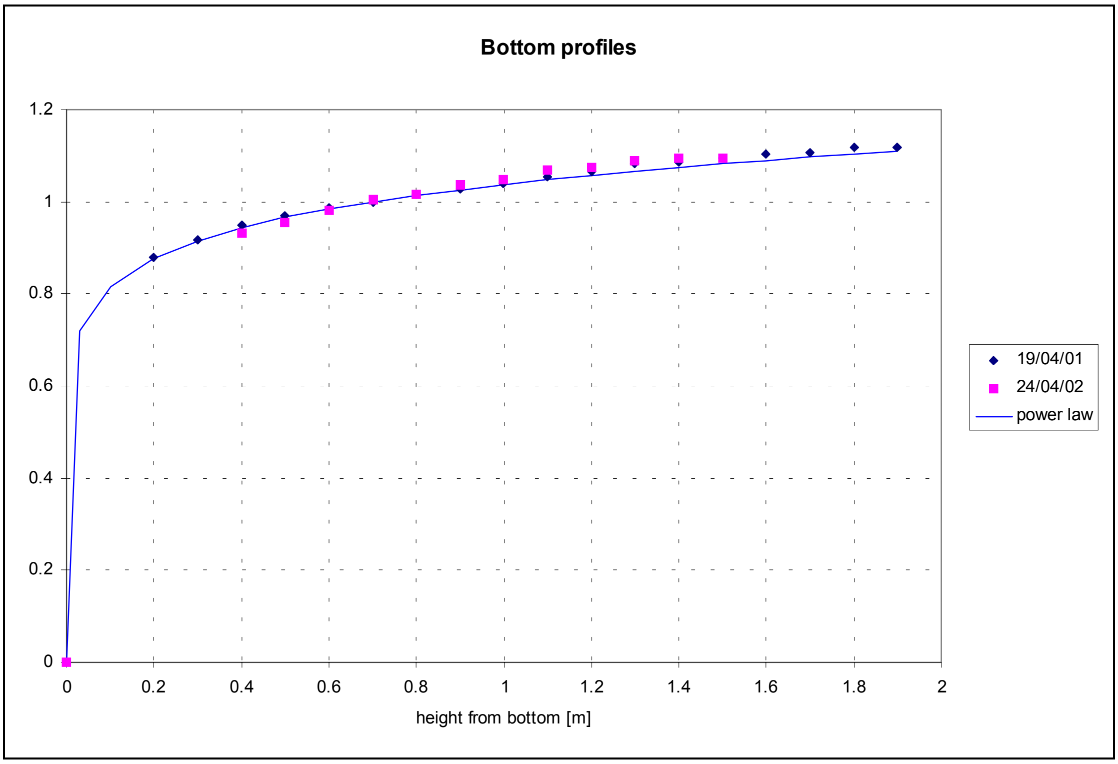


Figure 8: surface velocity against core velocity on 6 days

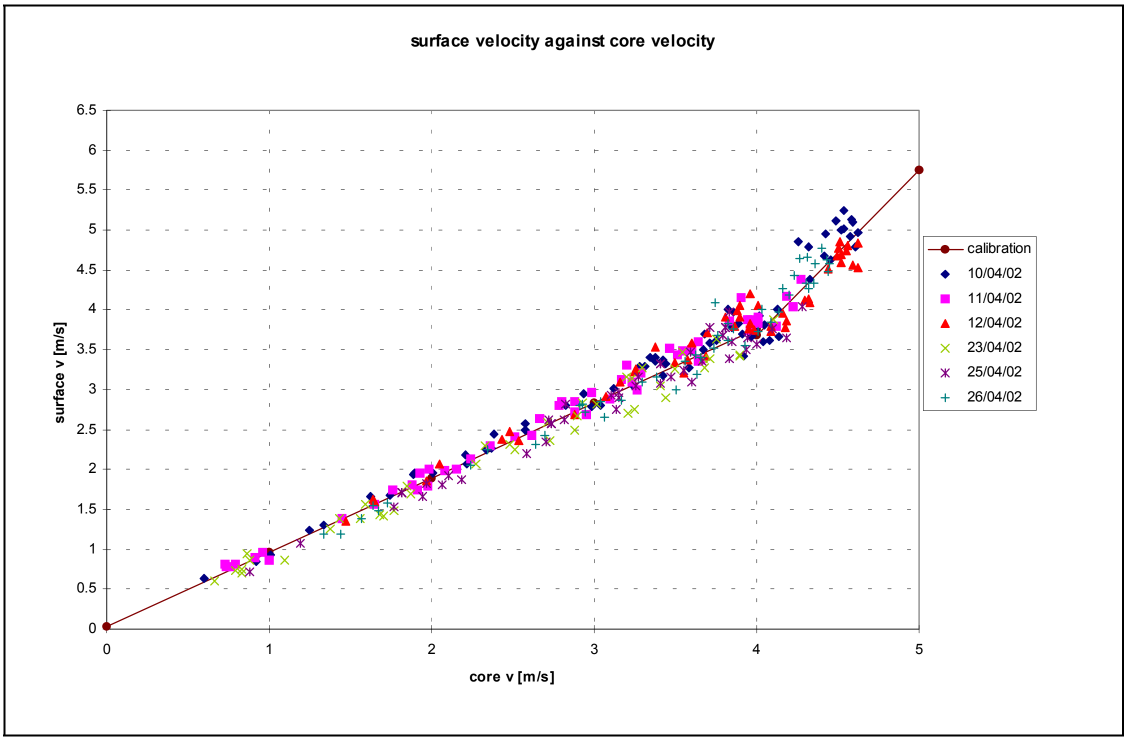


Figure 9: definition of cross section zones