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DEVELOPMENT OF A SQUAT FORMULA BASED ON NUMERICAL CALCULATIONS

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SUMMARY

Many different formulae for the estimation of the squat exist, but they do not cover a real wide range of variables describing the hydrodynamic details of the flow situation. Based on an extensive series of numerical calculations using the shallow water code BESHIWA, the squat of an idealized ship including variations of length, breadth, draught, block coefficient, speed, water depth, channel width and the slope of the bank has been calculated.
The new approach is using a base formula over the Froude depth number which is fitted to the numerical results for the idealized standard ship of 100 m length, 10 m breadth and 3 m draught. The value of this base curve is scaled to the project ship size and corrected by considering different influence factors for the variables of the calculations as B/L, T/L, CB, B/W and the slope. The new formula proves to be a universal tool for all applications, e.g. the implementation in simulator software.

NOMENCLATURE

B	Breadth (m)
CB	Block coefficient (-)
Fnh	Froude depth number
h	Water depth (m)
KB	Breadth factor (-)
KC	Block coefficient factor (-)
KL	Length factor (-)
KM	Slope factor (-)
KT	Draught factor (-)
KW	Channel width factor (-)
L	Length (m)
m	Slope of the bank x/y (-)
T	Draught (m)
V	Velocity (m/s)
W	Channel width (m)
W'	Reduced channel width (m)
Wm	Mean channel width (m)
x	x-coordinate of ship hull (m)
y	y-coordinate of ship hull (m)
y	Position in the channel (%)
yPt	Distance from the centerline of the ship to the port shoreline (m)
yStb	Distance from the centerline of the ship to the starboard shoreline (m)
z	Squat (sinkage midships) (m)
λ	Scale between test ship and real ship (-)

1 INTRODUCTION

A simulator software for the calculation of the own ship's behavior should ensure that every possible situation is handled with satisfactory results. The squat behavior can be either stored in a data base or it can be computed by a formula, taking into account or considering all or most imaginable. The installation of the new inland waterway simulator SANDRA at the DST as well as the availability of an appropriate software entailed to this project. A formula to replace the rather simple approach, based on a quadratic speed dependency of a maximum squat should be developed for the simulator.

As an institute with special dedication to shallow water hydrodynamics, the main question was: How does the squat change with speed and water depth? Additional variables are the ships parameters as length *L*, breadth *B*, draught *T*, block coefficient *CB* and the parameters of the waterway as width *W*, the slope *m* of the bank and the Position *y* of the ship in the channel.

2 THE SOFTWARE "BESHIWA"

The numerical code BEShiWa (Boussinesq Equations for Ship Waves), which has been developed in the DST, uses a Boussinesq-approach [1, 2] to calculate the generation and propagation of waves in shallow water. The dynamic sinkage and trim of the ship is fully regarded. Thereby it is suitable for the planned squat calculations.
In Figure 1 the wave patterns generated by a ship running through channels of different width are shown.

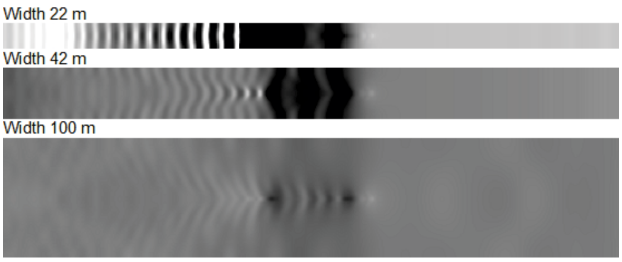

Figure 1. Density plots of wave patterns at constant speed in canals of different width

A full calculation of all elements of the multidimensional matrix consisting of the variables *V, h, L, B, T, CB, W, m* and *y* with say 7 steps per variable would need nearly 5 million cases. To make the project manageable, a simplification strategy was followed:

- Deeply investigate the speed and the water depth
- Use the length for scaling the results
- Check the dependencies of the other variables and develop functions to handle the alterations

In the end, about 300 cases have been calculated for the final development of the formula.

3 THE IDEALIZED SHIP

Disregarding changes due to differences of *L, B, T* and *CB,* a basic ship with standard main dimensions was defined:

L	100 m
B	10 m
T	3 m
CB	0.75

For the primary calculations standard conditions for the other variables have also been specified:

h	6 m
W	240 m
V	4.6 m/s = 16.6 km/h (Fnh=0.6)
m	0 (vertical wall)
y	50% (Centerline of the channel)

As the main focus for the calculations in BeShiWa is given to the displacement distribution, but the section data have to be given as input, automatisms have been developed to generate ships with different *CB*.

They are identical in bow and stern and have a varying parallel midship length. The displacement distribution is shown in Figure 2.

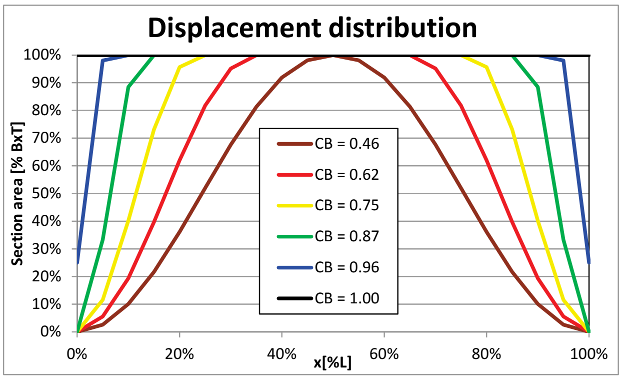

Figure 2. Displacement distribution of test ship

The sections in Figure 3 have a flat bottom, a bilge radius dependent on the block coefficient and a vertical side following a waterline similar to the displacement distribution. Besides the complicated variation in *CB*, the ship modifications due to *B* and *T* have been done by simple scaling of *x* and *y*.

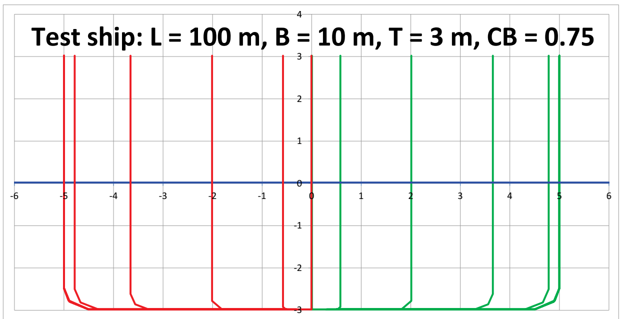

Figure 3. View of sections

4 THE BASIC FORMULA

The most important parameter for the squat is the speed. It would be appropriate for deep water calculations to use this for the generation of a formula but the second important influence is the water depth and it has also a major impact.

The Froude-depth number *Fnh* covers both influences in a single value. After several unsuccessful attempts with both *V* and *h* this dependency was chosen for the regression. This implies a failure in deep water which can be treated by a lower limitation of *Fnh* to 0.2.

In Figure 4 the basic formula (1) for the test ship in default conditions (see chapter 3) is compared to the calculations with BeShiWa.

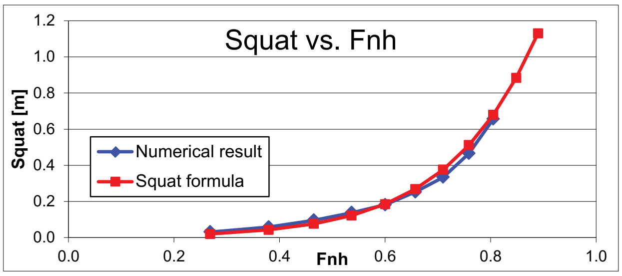

Figure 4. Basic formula for the default case

$$z = 0.0065 \cdot e^{5.2 \cdot Fnh} + 0.95 \cdot Fnh^6 - 0.065 \qquad (1)$$

As the squat for the test ship with L = 100 m is calculated for the same speed and water depth conditions as the target length, the squat can be scaled up or down using a length factor *KL* (2).

$$KL = \lambda = \frac{L}{100} \qquad (2)$$

5 FURTHER DEPENDENCIES

All other dependencies are used as changes to the default case and not as absolute values. A green line which intersects with the curves always at the ordinate 1 marks the basic condition in the figures. For stability reasons polynomials will be avoided. To prevent unsafe extrapolation limits for the correction factors are given in the following.

5.1 BREADTH

With the dimensions L and B of the test ship the default value for the breadth factor *KB*=1 (3), Figure 5 is at *B*/*L*=0.1.

$$KB = 16 \cdot \left(\frac{B}{L}\right)^{1.17} \;,\; 0.25 < KB < 4 \qquad (3)$$

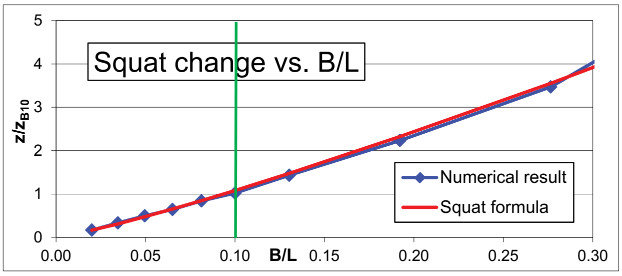

Figure 5. Breadth factor *KB*

5.2 DRAUGHT

The draught variation was calculated with constant speed *V* and water depth *h*, consequently constant *Fnh*. For different water depth the squat change was always the same for varying *T/L*. Compared to the handling of the breadth, the draught is also related to the length to achieve a result of 1 for the default ship. The outcome for the *KT* is shown in Figure 6 and the equation (4) below.

$$KT = 38.3 \cdot \frac{T}{L} - 0.15\,, 0.25 < KT < 4 \qquad (4)$$

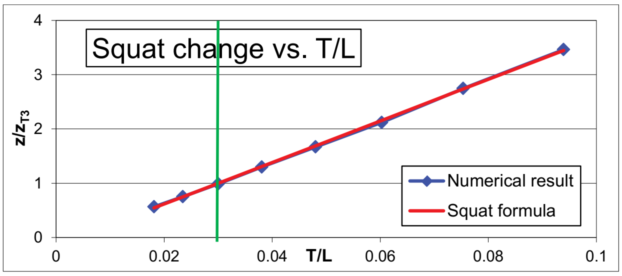

Figure 6. Draught factor *KT*

5.3 BLOCK COEFFICIENT

For unknown reasons the numerical results for the CB-variation were not as good as the others. But a clear tendency can be seen. Equation (5) and Figure 7 give the results.

$$KC = 0.07 \cdot \left(\frac{CB}{0.75}\right)^6 + 0.93\,, 0.5 < CB < 0.9 \qquad (5)$$

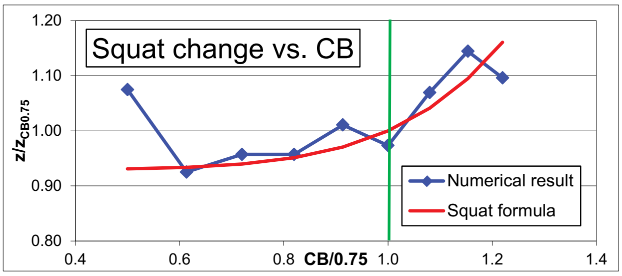

Figure 7. Block coefficient factor *KC*

5.4 CHANNEL WIDTH

On the basis of the default channel width of 240 m, which is close to infinite width, the calculations have been carried out with decreasing width. The comparison with the formula is given in Figure 8 and equation (6).

$$KW = 42 \cdot \left(\frac{B}{W}\right)^2 + 0.93\,, 1 < KW < 6 \qquad (6)$$

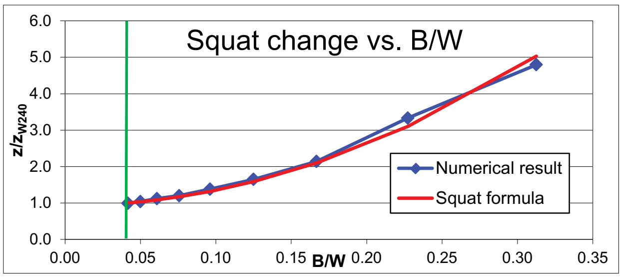

Figure 8. Channel width factor *KW*

5.5 CHANNEL SLOPE

For evaluation purposes the slope should be independent from the channel width. Therefore, a mean channel width *Wm* is defined, which is measured at half depth. This means, that the channel cross section area *Wm·h* is always constant for all slopes *m*.

Several calculations have been carried out varying *m*, *Wm* and *Fnh* to detect the dependencies regarding the squat. As regards the results of the increase of squat due to the bank slope a reasonable formula (7) has been developed which takes into account all influences as shown in Figure 9.

$$KM = 1 + 1.2 \cdot m^2 \cdot Fnh^{11} / \left(\frac{Wm}{L}\right)^{2 \cdot Fnh}\,, 1 < KM < 4 \quad (7)$$

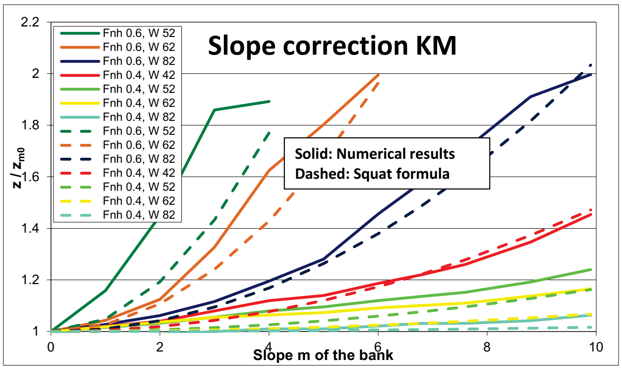

Figure 9. Slope factor *KM*

5.6 ECCENTRICITY OF THE SHIP

For this parameter no calculations have been carried out, however a procedure is proposed to handle this influence. A half circle over the width of the channel may be used to estimate a reduced channel width *W'* which increases the squat due to the eccentricity of the ship. The estimated approach is shown in Figure 11 and equation (8)

$$W' = W \cdot \sqrt{1 - \left(1 - 2 \cdot \frac{yPt}{yStb}\right)^2} \qquad (8)$$

To take this effect into account *W'* should be used in section 5.4 instead of *W*.

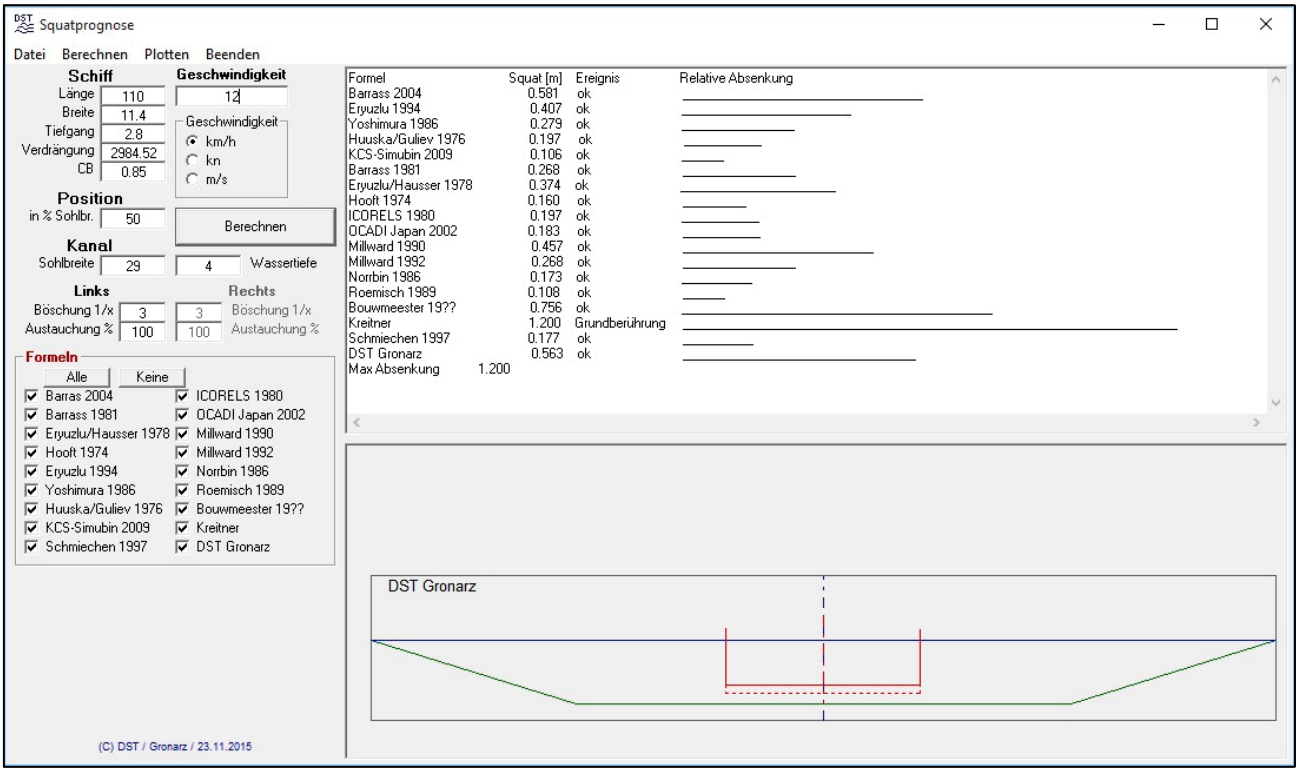

Figure 10. Squat prediction program

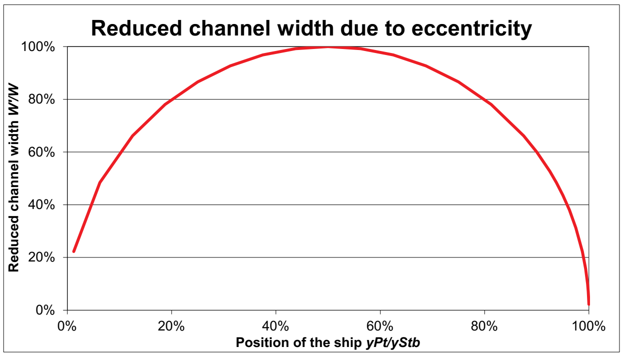

Figure 11. Reduction of W due to eccentricity

5.7 FINAL FORMULA

Based on the estimated squat z for the basic ship in default conditions the squat including all influences can be calculated by multiplying all correction factors to z as shown in equation (9).

$$z_{Final} = z \cdot KL \cdot KB \cdot KT \cdot KC \cdot KW \cdot KM \qquad (9)$$

It is recommended to limit the squat to a value of e.g. $T/2$ to avoid extrapolation errors and to indicate grounding if z increases h-T.

6 COMPARISON WITH OTHER FORMULAE

The evaluation of a squat formula can be either made by full scale results or by comparison with other existing formulae. The full scale comparison would be the best but the main problem is the availability of results for inland vessels considering a broad variety of influencing parameters.

As there are many formulae existing [3, 4] it is interesting to check both the new approach and the other published estimations regarding their behavior with varying input parameters. A software has been programmed which includes most of the recent published squat formulae and which is able to compute their results both for a single case and for a systematic variation of one parameter only. Figure 10 shows an example for a special scenario which is used as default case (boundary conditions see in the screenshot) for all following calculations. The selected speed of 12 km/h is higher than allowed for loaded vessels in German channels but gives a better impression of the capabilities of the different formulae than the lower one of 8 km/h.

The results of these systematic calculations are presented below. Comments to the results are placed above the figure. The results of the approach presented in this paper are always marked with a fat red line.

The variation of the **water depth *h*** in Figure 12 shows an increasing squat for all formulae. Barras 2004 predicts a significant squat for deep water but has a simply linear dependency with h. Kreitner and Bouwmeester calculate the most steep shallow water influence. All results are limited by the grounding condition.

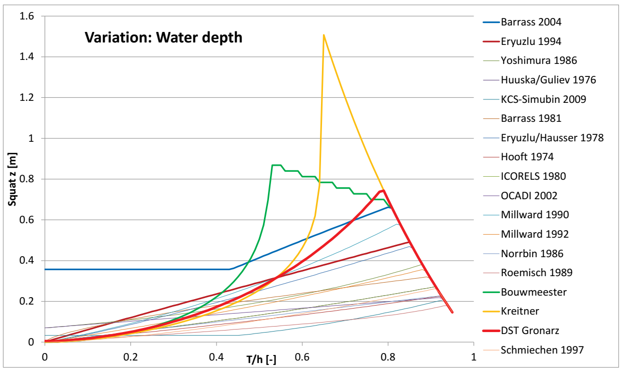

Figure 12. Variation: Water depth

The variation of the **speed *V*** in Figure 13 (here given in km/h as standard in inland navigation) is present in all examples, but with a different development. They are all limited by z=h-T, here 1.2 m, except of Bouwmeester, which has an internal limit below.

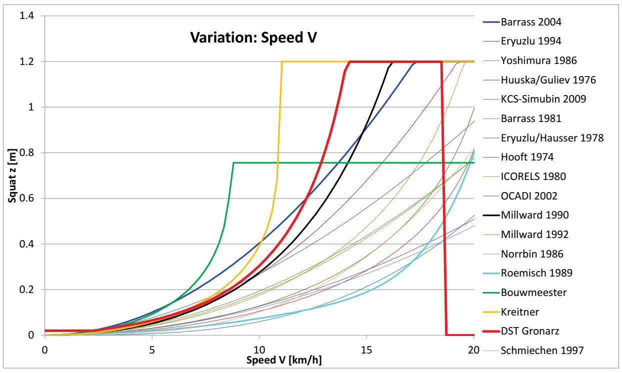

Figure 13. Variation: Speed

The variation of the **length *L*** in Figure 14 is not an input variable in several attempts. This should be linear at minimum as Millward 1990, but realistic is a nonlinear behavior as estimated by most formulae.

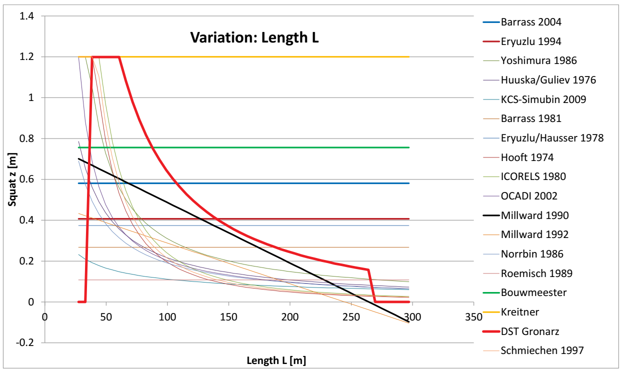

Figure 14. Variation: Length

The variation of the **breadth *B*** in Figure 15 is not an input variable in several attempts. This should be linear at minimum as Millward 1990, but realistic is a nonlinear behavior as estimated by most formulae. Barras 1981 fails completely because he estimates a decreasing squat with increasing beam.

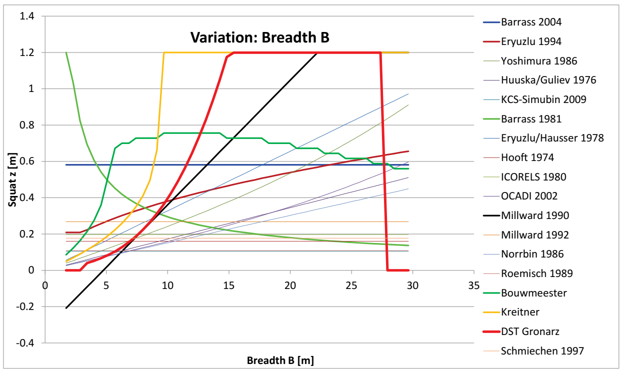

Figure 15. Variation: Breadth

The variation of the **draught *T*** in Figure 16 is obviously overestimated by Kreitner and disregarded by many other formulae. The rest of the graphs show a more or less linear dependency, all limited by the grounding condition.

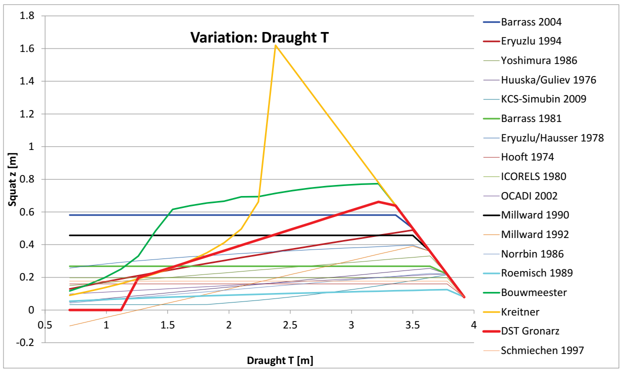

Figure 16. Variation: Draught

The variation of the **block coefficient *CB*** in Figure 17 is missing in some formulae or linear in the other ones. Kreitner is out of discussion because he predicts grounding at this speed, compare Figure 13. Only the new approach forecasts a nonlinear behavior which seems to be obvious.

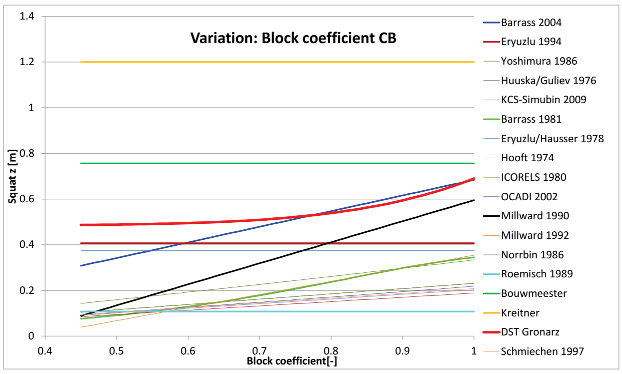

Figure 17. Variation: Block coefficient

The variation of the **channel width *Wm*** in Figure 18 is handled only by some authors. There are great differences about the magnitude of the squat and the behaviour with changing *W*. A reason for that may be that some formulae are designed only for unrestricted water.

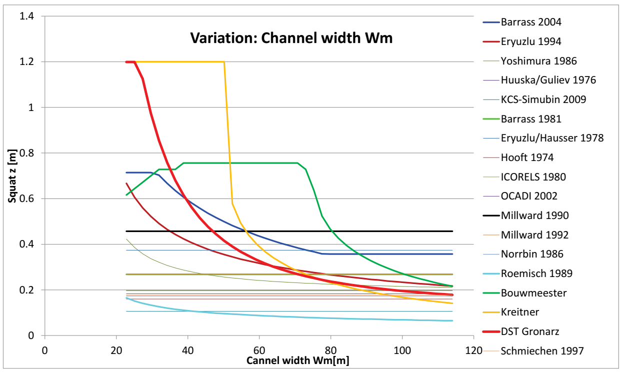

Figure 18. Variation: Channel width

The variation of the **bank slope *m*** in Figure 19 is disregarded by most formulae. There should be a decrease with steeper walls because the proximity of the bank to the bilge decreases. In this respect Bouwmeester fails and only Eryuzlu 1994 and DST Gronarz calculate a dependency however with different shape.

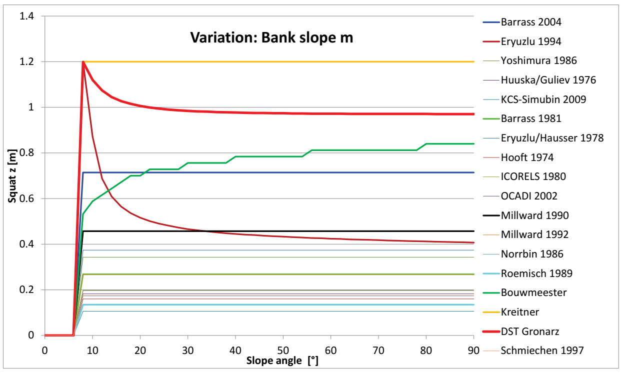

Figure 19. Variation: Bank slope

The variation of the **lateral position *y*** in Figure 20 is only calculated by the new approach presented in this paper. Even if the data are not based on calculations but on realistic assumptions the results seem to be acceptable because observations have shown that the proximity of a wall at one side increases the squat. Model tests or numerical calculations might substantiate this proposal.

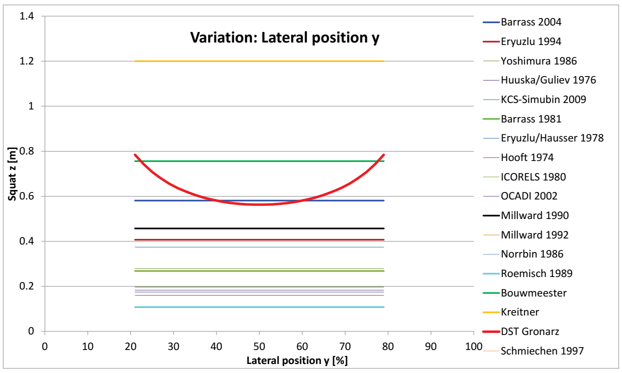

Figure 20. Variation: Lateral position

7 TRIM

Although the numerical results deliver also a trim of the ship, no estimation formula will be generated, because the calculations have been carried out for the resistance case. As most applications need the trim for the self-propelled ship, the trim based on the resistance is not only imprecise to use but sometimes completely wrong.
For seagoing ships on deep water it is known that with increasing block coefficient ($CB > 0.6 - 0.7$) the trim changes from stern down to bow down. On open water the difference between trim in resistance and propulsion is rather small.
Otherwise inland waterway vessels, which sail on restricted and shallow water, behave in a different way as it is known very well from model tests in the DST. Because of the normally large block coefficients they trim always bow down in resistance tests. In propulsion condition the stern mostly trims down due to the suction of the propeller at the bottom which creates a low pressure field at the stern.
To avoid misunderstandings and misinterpretations a trim estimation is omitted in this paper. In addition, the influence of the longitudinal centre of buoyancy is disregarded because it affects mainly the trim.

8 CONCLUSIONS

- A new formula (additional to the big number of formulae by different authors) has been developed based on systematic calculations with a software specially dedicated to the flow around ships in shallow and restricted waters.
- The new approach is based on the dependency on the Froude depth number Fnh, calculated for a default ship.
- Other dependencies like L, B, T, CB, W, slope and eccentricity are treated as correction factors for the basic formula.
- The new approach is compared with several existing ones and fits well into their results.
- The formula presented in this paper is the unique one which covers all important influences.
- This makes it recommendable as a module to be used in simulators.

Constraints:

- Only the sinkage z is considered – the trim is not investigated.
- The formula predicts the squat for the resistance case. In self-propulsion the result might be slightly higher due to the propeller suction at the bottom.
- The results for infinite water depth might not be correct because Fnh is zero in that case. It is recommended to limit the water depth to $5 \cdot T$ to overcome this problem.

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10 AUTHOR'S BIOGRAPHY

Andreas Gronarz holds the position of a research engineer at the DST. Since his employment 30 years ago he is working in the field of manoeuvrability of ships, especially in shallow and restricted waters. With the installation of the inland waterway simulator SANDRA he is responsible for the mathematic modeling and the operation of the simulator. The successful execution of several nautical studies on inland waterway increased his experience in the assessment of inland navigation.