

HYDRAULIC AND ENVIRONMENTAL IMPACTS OF HIGH SPEED CARGO SHIPS ON INLAND WATERWAYS

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ABSTRACT

Economy is growing and cargo transport is growing in parallel even faster. Therefore alternatives to truck transport and congested railways are necessary. Cargo transport on inland waterways provides space, capacities, safety, environmental friendliness, less energy consumption and high efficiency. But speed is a major disadvantage of present inland ships for cargo transport.

Accelerating the ships' speed from subcritical to supercritical, i. e. high speed, would increase attractiveness for waterway transport. This increases hydraulic impacts because of the restrictions and shallowness of waterways, resulting in increased ship-generated water level variations and reverse flow velocities. This might affect stability of canal or river banks and bottoms, and also the navigational safety.

To quantify hydraulic impacts of high speed cargo ships on inland waterways, physical model tests were carried out in a model flume with two concepts of high speed cargo ships, a Twin-Hull SES-Catamaran lifted by air-cushion and a Mono-Hull. For different channel cross-sections, ship-generated water level variations and reverse flow velocities close to the bottom were measured. Ship speeds were in the transcritical and supercritical domain.

The results showed that ship-generated reverse flow velocities under the ships are critical for stability of beds. Ship-generated water level variations showed, that the SES-Catamaran is not feasible on artificial canals leading to uncontrollable impacts for banks and beds. In addition operational safety of high speed ships together with conventional ships could be hazardous. For the Mono-Hull reduced water level variations were measured, showing the potential of this concept for future developments.

Keywords: High Speed Cargo Ships, Inland Waterways, Hydraulic Impact, Depth Froude Number

1. INTRODUCTION

Natural and channellized rivers with and without dams as well as artificial canals are restricted waters for ships' navigation depending on the aspect ratio n .

$$n = \frac{A_c}{A_s} \quad (1)$$

where A_C is the channel cross-section and A_S the ship's cross-section. Restricted channel depths h_0 set the limits between subcritical and supercritical speed of a ship v_{ship} which is characterised by the Depth Froude Number F_{nh} .

$$F_{nh} = \frac{v_{ship}}{\sqrt{gh_0}} \quad (2)$$

where g is the acceleration of gravity. The Depth Froude Number gives the relation between ship speed and propagational velocity of waves in shallow waters. Subcritical ship speed therefore is less than the velocity of waves generated by a ship and running along a channel, while at supercritical speeds, the ship is faster than the waves in the channel. Before reaching supercritical speeds in the phase of ship acceleration, there is a transcritical range $0.84 < F_{nh} < 1.15$ [1] due to local superposition of ship and channel waves, Fig. 1.

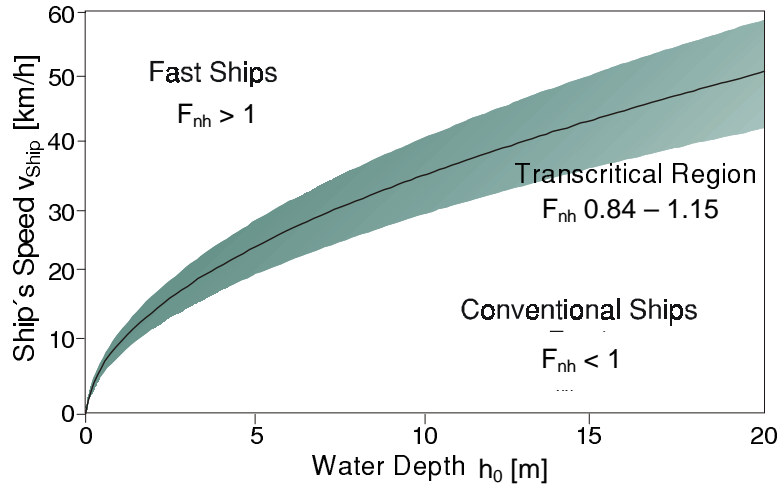


Fig. 1 Subcritical, Transcritical and Supercritical Speed Range [1]

Apart from exponentially increased energy requirements [6] for such ships this energy input results in higher waves and increased velocities and turbulence around the ships' hulls, Fig. 2.

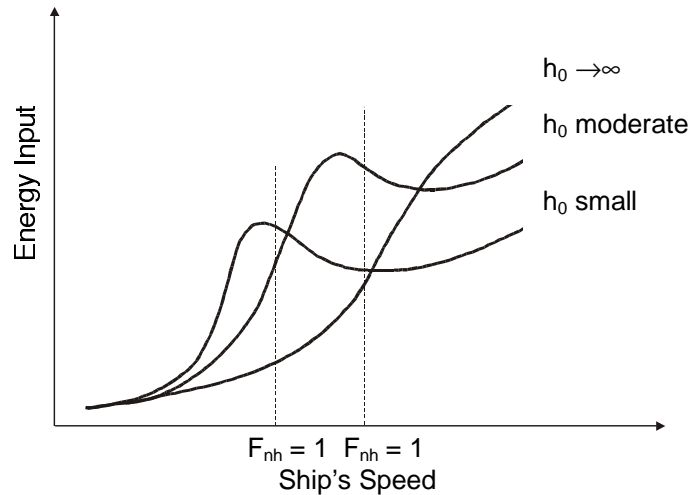


Fig. 2 Relation between Energy Input and Ship's Speed [6]

To quantify such effects for river and canal banks and beds, physical model tests are necessary.

2. PARAMETER ANALYSIS

Moving a ship in restricted, i. e. depth and width limited waters, generates water level variations and velocity fields around the ship's hull, Fig. 3.

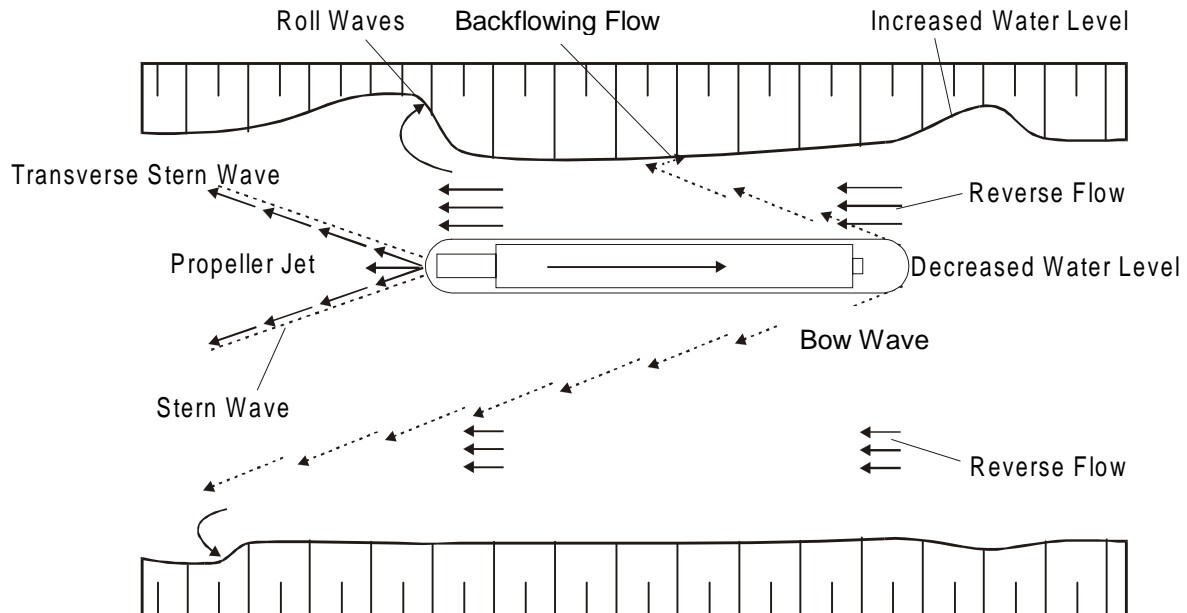


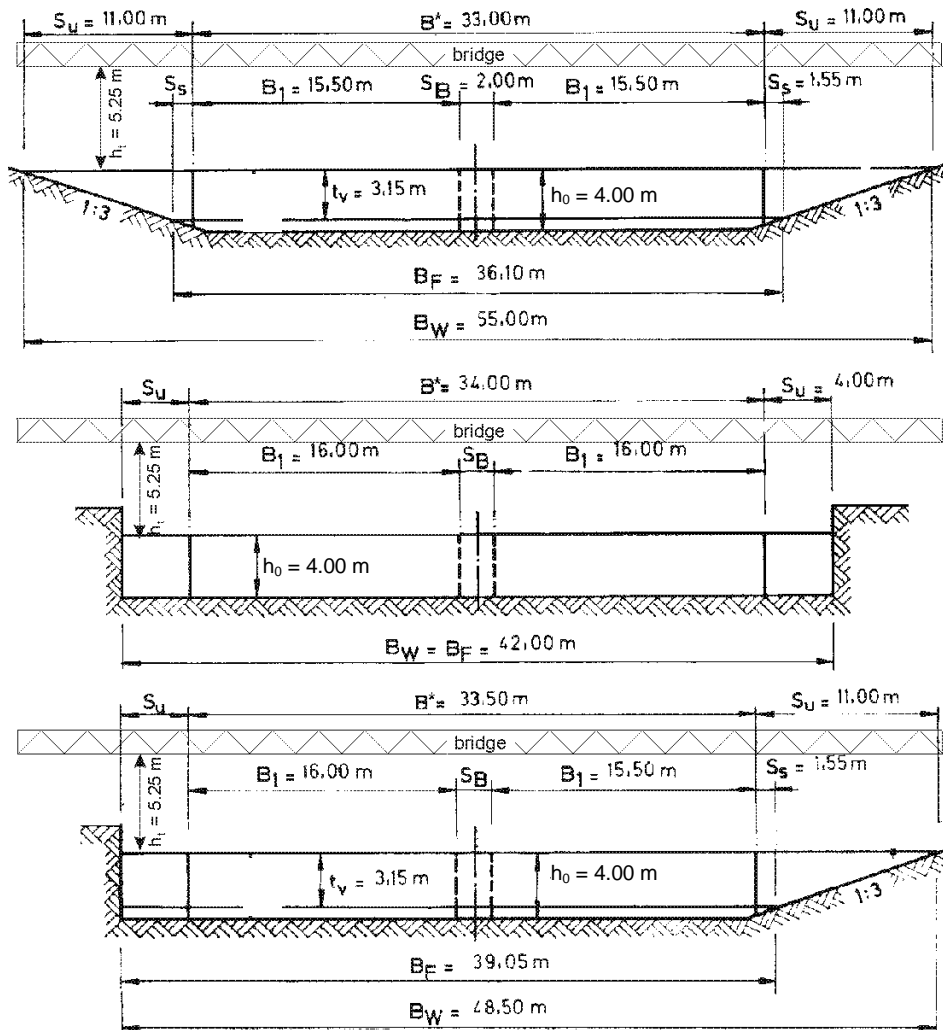
Fig. 3 Water Level Variations and Velocity Fields around Moving Ship in Restricted Waters

Different velocities with changing directions occur between ship bottom and channel bed, which are superimposed by propeller induced velocities near the stern and in the wake of the ship. In a river such velocities are superimposed to river flows, generating new velocity fields, moving with the ship. Looking for bank and bottom stability and river ecology affected from ship motions therefore requires knowledge of locally induced water level variations for analysis of pore pressure variations within bank and bottom materials together with the velocities and their directions.

$$\text{Channel Bank / Bottom Effects} = f \left(\begin{array}{l} \text{Aspect Ratio; Ship's Speed; Draft;} \\ \text{Water Level Variation; Bank / Bottom Density;} \\ \text{Porosity; Channel Shape; Flow Velocity} \end{array} \right)$$

3. EXPERIMENTAL SETUP AND PROCEDURES

Investigations were carried out in a fixed bed model flume without flow with scale 1:14. Different cross-sections are characterising artificial canals in Germany. Three cross-sections were taken for the physical model tests: Rectangular Profile, Rectangular-Trapezoidal Profile and Trapezoidal Profile, Fig. 4.



- | | | |
|-------|---|---|
| B_F | = | Width of Fairway; |
| B_w | = | Width of Water Level; |
| B_1 | = | Width of Traffic Lane; |
| B^* | = | Necessary Distance for a Passage; |
| h_0 | = | Water Depth; |
| h_t | = | Passage Height; |
| S_B | = | Safety Clearance between the Lanes; |
| S_s | = | Safety Clearance to Bank in Depth t_v ; |
| S_u | = | Safety Clearance to Bank; |
| t_v | = | Standard Draught. |

Cross-sections of Artificial Canals in Germany (Trapezoidal Profile (Top), Rectangular Profile (Mid), Rectangular-Trapezoidal Profile (Bottom))

Two types of high speed cargo ship concepts were used, a Twin-Hull SES-Catamaran lifted by air-cushion and a Mono-Hull, Table 1 and Fig. 5. The SES-Catamaran was with jet propulsion at each hull, while the Mono-Hull was without propulsion. To lift the SES-Catamaran above the water surface, air-cushion technology was applied, with an apron at the ship's bow to avoid escape of pressurized air between hull and water surface.

Type of Ship	Length (Prototype)	Width (Prototype)	Length (Model)	Width (Model)
SES-Catamaran	82.88 m	11.40 m	5.92 m	0.814 m
Mono-Hull	79.80 m	9.91 m	5.70 m	0.708 m

Table 1 Dimensions of Tested Ships

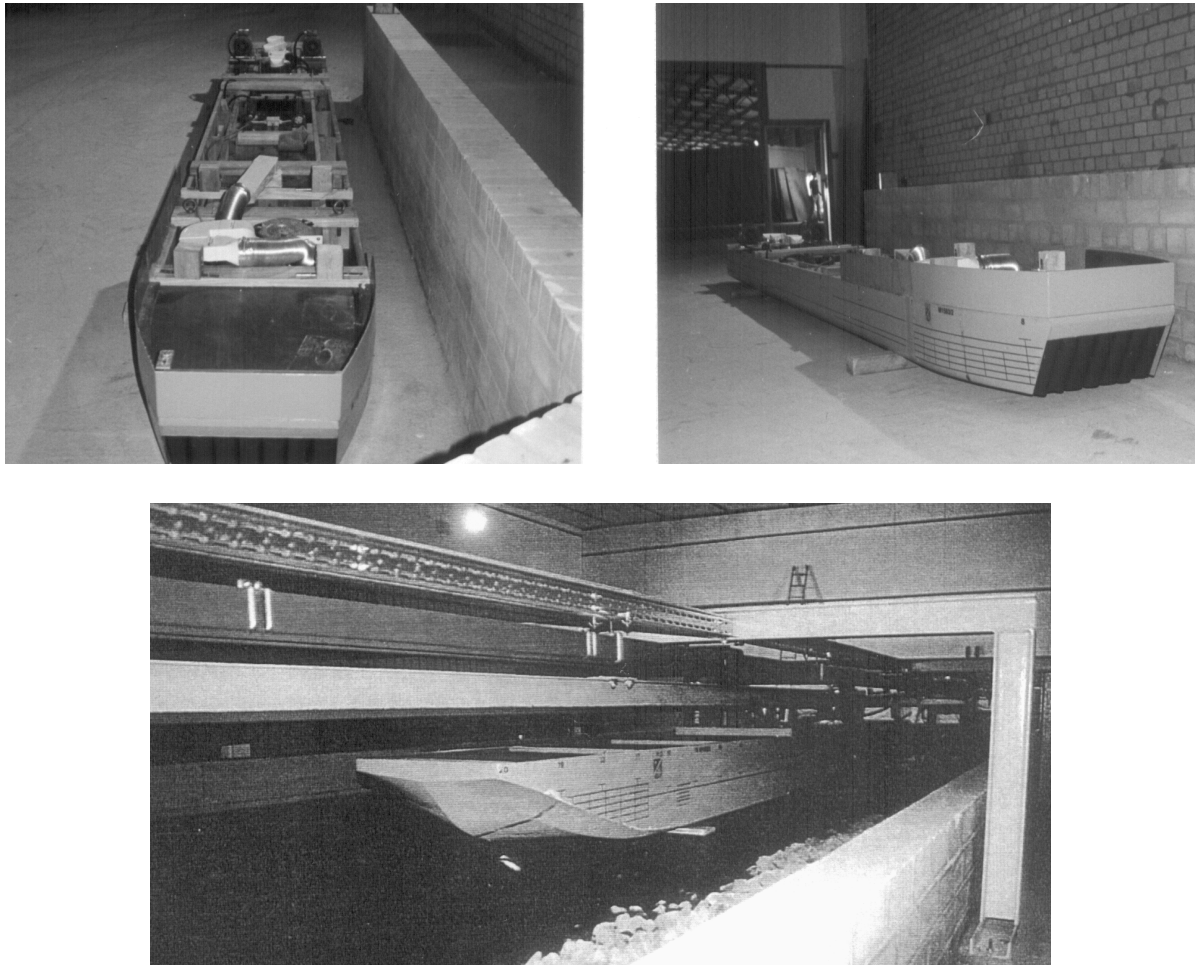


Fig. 5 High Speed Cargo Ship Concepts: SES-Catamaran (Top), Mono-Hull (Bottom)

The ship models were fixed to a rail carriage for quick acceleration to high speed, allowing also for a trim in the longitudinal axis.

Measurements were taken for flow velocities at various locations with Acoustic Doppler Velocitymeters (ADV). Water level variations were recorded with a resistance type of wave gauges.

Test series were carried out with three different speeds: $v_1 = 20$ km/h, $v_2 = 25$ km/h (both transcritical speed range, $F_{nh(1)} = 0.88$ and $F_{nh(2)} = 1.11$) and $v_3 = 35$ km/h (supercritical speed range, $F_{nh(3)} = 1.55$). Ships were operated eccentric on the fairway in order to obtain extrem water level variations on the banks.

4. RESULTS OF PHYSICAL MODEL TESTS

Table 2 contains maximum water level elevations and maximum water level depressions on the banks and maximum flow velocities at the bed of the waterway with the investigated ship speeds and tested canal shapes .

ECCENTRIC				R			RT			T		
Type of Ship	Ship's Speed v_{Ship}		F_{nh}	Water Level Variation		n-Ratio	Water Level Variation		n-Ratio	Water Level Variation		n-Ratio
	[km/h]	[m/s]		max Rise [m]	max Sink [m]		max Rise [m]	max Sink [m]		max Rise [m]	max Sink [m]	
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
SES-Catamaran	20.00	5.56	0.89	6.02	1.20	1.30	6.16	1.20	0.90	6.30	1.10	0.90
	25.00	6.94	1.11	5.40	2.60	1.50	5.53	1.75	1.00	5.66	1.90	0.75
	35.00	9.72	1.55	4.90	2.50	1.25	5.01	1.80	1.20	5.13	1.75	0.80
Mono-Hull	20.00	5.56	0.89	9.15	0.80	1.25	9.37	0.80	1.05	9.59	0.60	0.80
	25.00	6.94	1.11	10.99	1.40	1.00	11.26	1.00	0.80	11.52	0.80	0.60
	35.00	9.72	1.55	25.85	1.20	0.60	26.47	0.50	0.40	27.09	0.50	0.40

ECCENTRIC				R			RT			T					
Type of Ship	Ship's Speed v_{Ship}		F_{nh}	Near Bed Velocities		n-Ratio	Near Bed Velocities		n-Ratio	Near Bed Velocities		n-Ratio			
	[km/h]	[m/s]		u_x [m/s]	u_y [m/s]		u_z [m/s]	u_x [m/s]		u_y [m/s]	u_z [m/s]		u_x [m/s]	u_y [m/s]	u_z [m/s]
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
SES-Catamaran	20.00	5.56	0.89	6.02	-1.95	0.95	-0.55	6.16	-1.80	-1.05	-0.45	6.30	2.20	-0.80	-0.50
	25.00	6.94	1.11	5.40	2.80	-1.50	-0.35	5.53	2.60	1.25	0.40	5.66	2.55	-0.90	0.50
	35.00	9.72	1.55	4.90	2.90	1.00	0.50	5.01	2.15	1.45	-0.35	5.13	2.60	0.85	0.45
Mono-Hull	20.00	5.56	0.89	9.15	1.75	0.50	0.50	9.37	-1.75	0.90	-0.30	9.59	1.50	0.50	0.35
	25.00	6.94	1.11	10.99	1.95	0.50	0.35	11.26	-1.20	-0.65	-0.35	11.52	1.10	0.45	0.30
	35.00	9.72	1.55	25.85	1.70	0.40	0.25	26.47	-0.55	0.40	0.70	27.09	0.55	0.25	0.25

Table 2 Water Level Variations (Top) and Near Bed Velocities (Bottom)

The SES-Catamaran increases draft with increasing ship speed with the apron resulting in a blockage, corresponding to conventional ships, whereas the Mono-Hull decreases draft at higher speed. This leads to a large aspect ratio at higher speeds for the Mono-Hull and a small aspect ratio for the SES-Catamaran.

Comparing the results of tests with the SES-Catamaran with those of the Mono-Hull, the aspect ratio aiming at decrease of water level variations. A comparison between the three canal shapes shows, that water level variations are not corresponding to increasing aspect ratio but to width of water surface in the canal. Moreover, bank roughness in the Trapezoidal Profile has a wave damping effect reducing water level variations, whereas the vertical walls in the Rectangular Profile reflect propagating waves [3]. This results in wave superposition and explains extrem water level variations in the Rectangular Profile, Table 2.

At transcritical speed, i. e. $v_{\text{ship}} = 25$ km/h a single wave (soliton) with water level elevations of more than 2.00 m appear in front of the SES-Catamaran's bow. The soliton runs with wave propagation velocity in front of the ship, whereas solitons generated by the Mono-Hull are less high (1.40 m), Table 2.

Accelerating up to supercritical speed of $v_{\text{ship}} = 35$ km/h, water level variations were reduced slightly for the SES-Catamaran whereas water level elevations generated by the Mono-Hull decreased down to 0.50 m and water level depression to 0.40 m in the Trapezoidal Profile, Fig. 6.

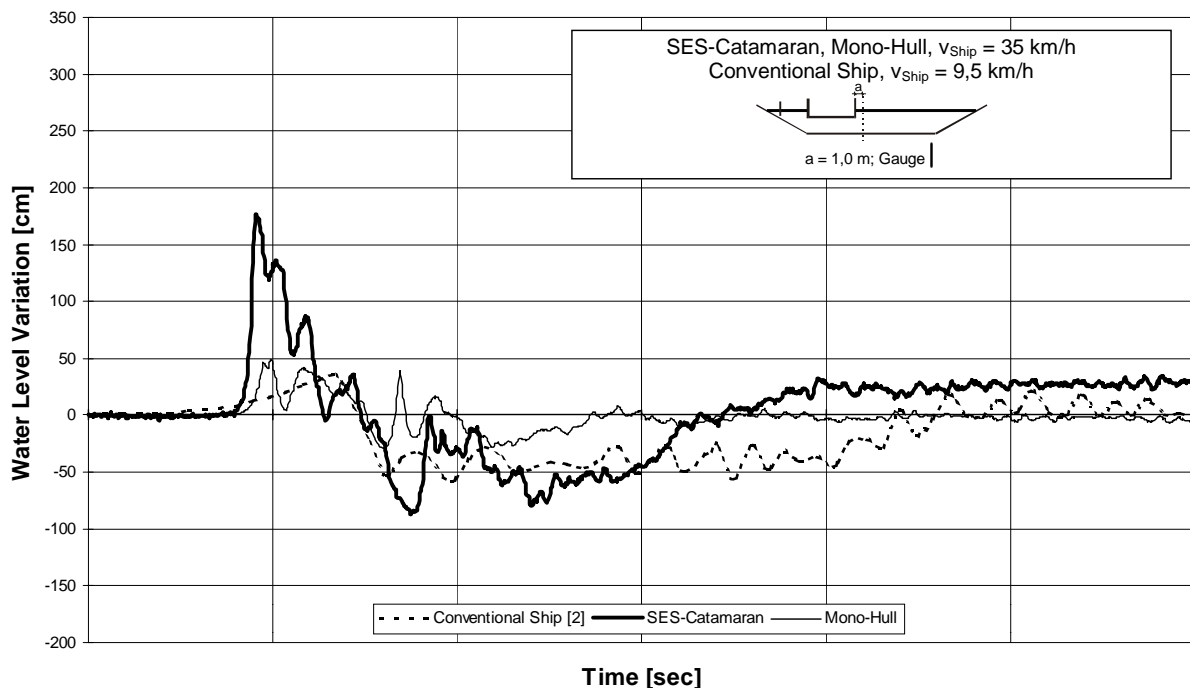


Fig. 6 Water Level Variations Generated by SES-Catamaran and Mono-Hull at a Speed of $v_{\text{ship}} = 35$ km/h and Conventional Ship at $v_{\text{ship}} = 9.5$ km/h, Trapezoidal Profile

Investigations of flow velocities generated by the SES-Catamaran in restricted water show, that flow velocities at the bed increase remarkably in comparison to conventional ships. Acceleration of the Mono-Hull into transcritical speed range also results in high

flow velocities at the bed, whereas at supercritical ship speed flow velocities are reduced distinctly, especially at the Trapezoidal Profile corresponding to the results of water level variation (Table 2). Therefore, both the effects of increasing aspect ratio and wider water surface as detected for water level variations can be transferred to ship-generated flow velocities.

Fig. 7 shows flow velocities for SES-Catamaran and Mono-Hull at $v_{\text{ship}} = 35$ km/h as well as for a conventional ship at $v_{\text{ship}} = 9.5$ km/h.

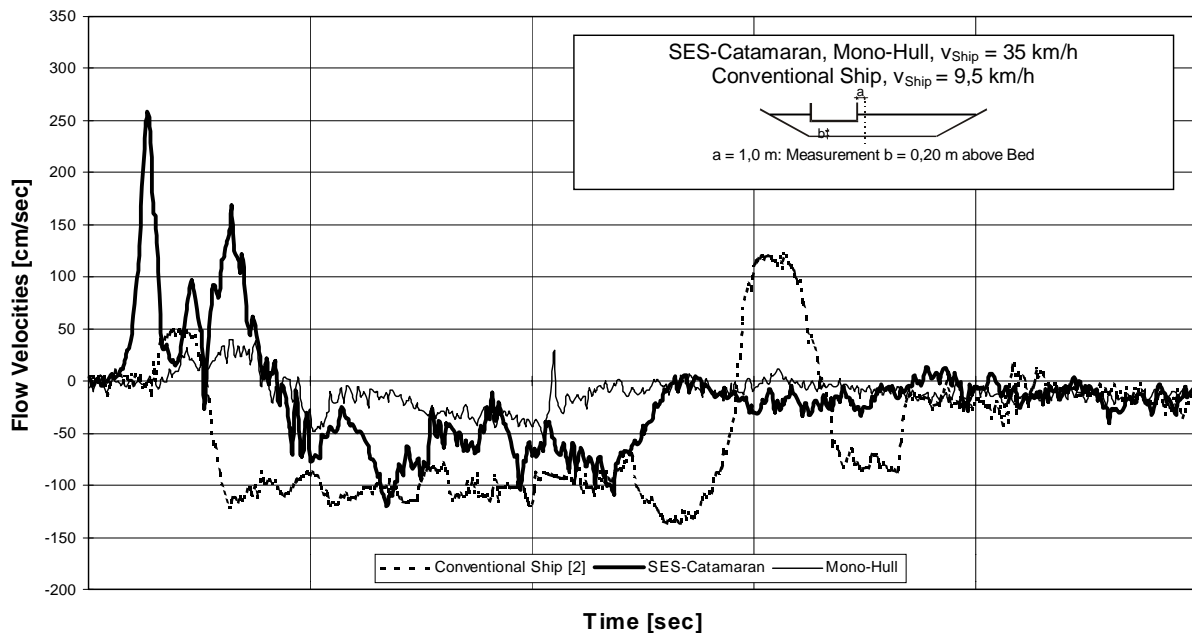


Fig. 7 Flow Velocities around SES-Catamaran and Mono-Hull at a Speed of $v_{\text{ship}} = 35$ km/h and Conventional Ship at $v_{\text{ship}} = 9.5$ km/h, Trapezoidal Profile

The investigations show that flow velocities for both concepts of a high speed cargo ships do not exceed maximum flow velocities determined by Kniess (1983) [5] for dimensioning bottom reinforcements for artificial canals. Though, for unprotected beds, flow velocities generated by high speed cargo ships, especially at transcritical speed, endanger stability of the bottom.

5. CONCLUDING REMARKS

Speed of ships for inland navigation has to be increased in order to improve acceptance in comparison to other transport systems [4]. Due to generation of waves and wake wash on restricted waterways, two concepts of high speed cargo ships, a SES-Catamaran lifted by air-cushion and a Mono-Hull for artificial canals were tested in physical models varying canal designs and ship speeds in order to determine the hydraulic impact for bank and bottom stability and safety of operation.

The results show, that ship-generated flow velocities below the tested fast ships are less critical for the stability of protected beds but would endanger unprotected beds.

Results of ship-generated water level variations reveal, that the concept of the SES-Catamaran is not feasible, especially in the Rectangular Profile. This leads to uncontrollable hydraulic impacts for banks and beds. Moreover, navigational safety of high speed cargo ships and conventional ships cannot be secured.

For the Mono-Hull with reduced beam and lower draft in comparison to the SES-Catamaran, reduced water level variations appear showing the potential of this concept, although effects of the Mono-hull's propulsion flow were not recorded. Therefore, further test series have to investigate the influence of length, width and draft, i. e. the aspect ratio of a Mono-Hull in different canal shapes aiming at reduction of ship-generated water level variations and flow velocities.

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