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RESULTS OF EXPERIMENTAL INVESTIGATION FOR CAPSIZING IN BREAKING WAVES

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The problem of ship motion in breaking waves becomes particularly essential for medium and small ships. Many ship losses can be explained only as a result of capsizing in breaking waves, Reference [1]. In the past, the theoretical solution to the problem did not go beyond stating of the problem. Thus, we conclude that for the most part an experiment is the only source for practical recommendations.

Shallow water model tests carried out in the tank of Leningrad Shipbuilding Institute initiated by S. N. Blagoveschensky and combined with theoretical analysis may be considered a first attempt in obtaining a general solution of this problem. This paper gives some results of the above mentioned tests and the highlights of the theoretical approach to the problem.

Description of experiment

The general scheme of the experiment is given in Figure 1. The wave breakage has been achieved by means of a raised bottom which consisted of an upper part (wooden with steel framing) with the dimensions 5400 x 5400 mm. and a hinged sloping panel (size 5400 x 2800 mm.) to prevent any flow under the raised bottom. The raised bottom allowed a change of depth and inclination of the upper part so that ℓ_1 and ℓ_2 (Fig. 1) were varied independently

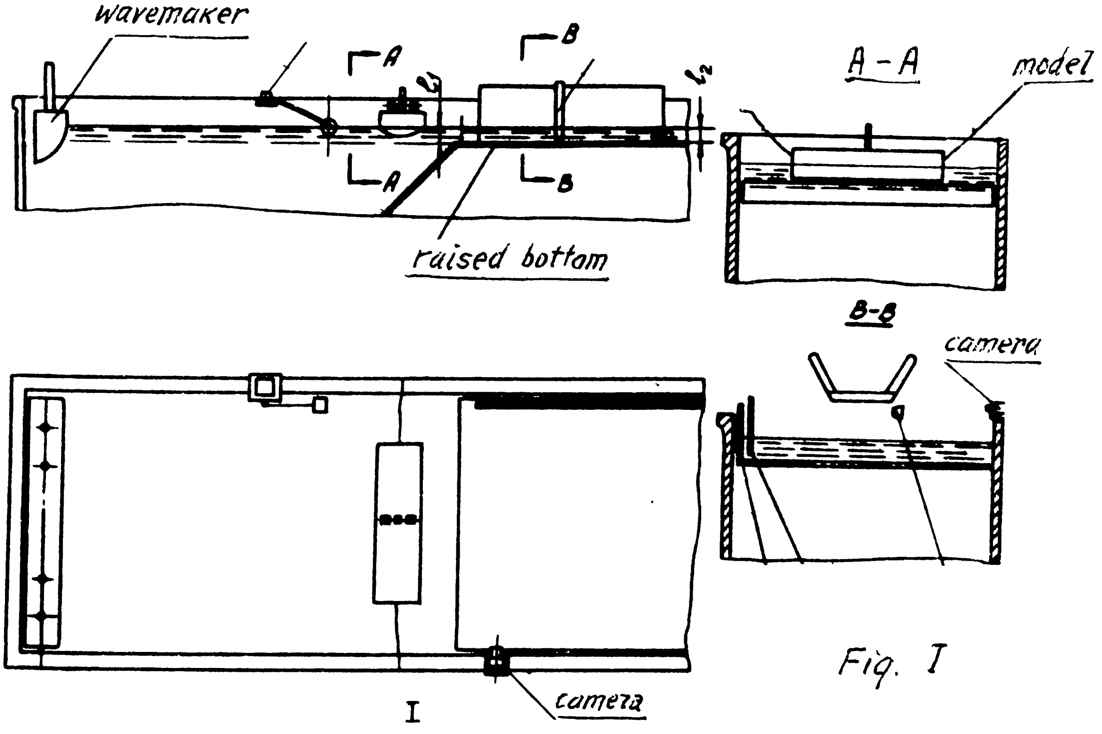


Fig. I

Two models tested in last series (N 40597 and 40598) had the following particulars:

Model # 40597

L = 2500 mm
B = 200 mm
T = 66 mm
H = 123 mm, 198 mm

D = 26.2 kg

Model # 40598

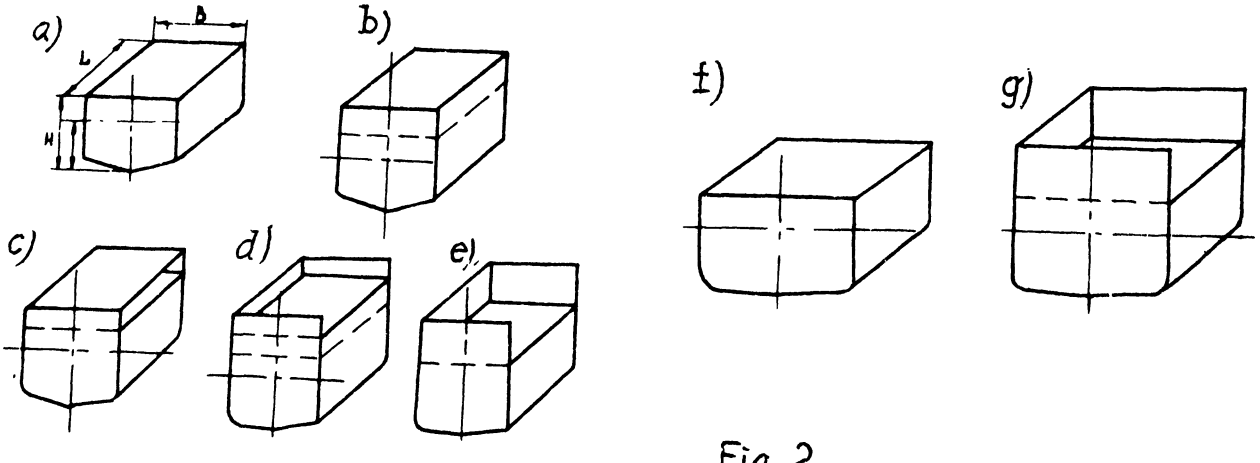
L = 2500 mm
B = 360 mm
T = 119 mm
H = 221 mm

D = 85.1 kg

Model # 40587 was tested as follows (Fig. 2)

a) low freeboard (123 mm) without superstructure
b) high freeboard (199 mm) without superstructure
c) low freeboard with open low (70 mm) superstructure
d) high freeboard with open (70 mm) superstructure
e) low freeboard with open high (145 mm) superstructure

The length of the deckhouses were equal to the length of models. The side



Fiq. 2

of deckhouse opposite to side subjected to wave impact and the superstructure deck were left open.

Model # 40598 was tested

f) without superstructure

g) with a open high (185 mm) superstructure

All models were equipped with pressure gauges located in the middle of the side facing the waves. A block of gauges consisted of 3 or 5 devices forming a vertical line (Figs. 3 and 4).

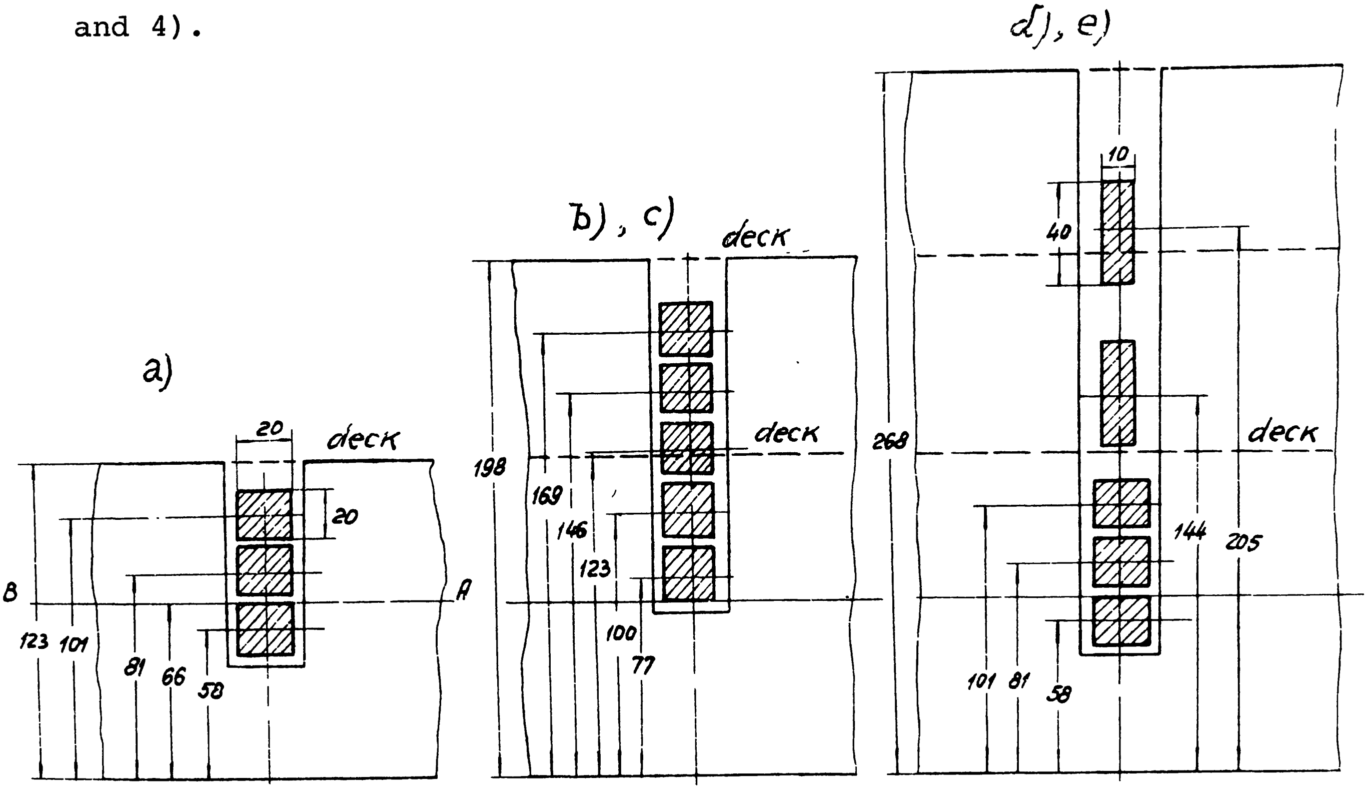


Fig 3

Both models were tested with constant displacement and different magnitude of initial meticentric height. In the initial stage of the experiment the model was placed transversely, 0.5 - 1.5 m. from the rising bottom. Under the action of waves the model started to drift, depending upon height and length of the waves; the number of waves in any particular test ranged from seven to ten. The last wave reached the model 1.5 to 2.5 m. behind the step of the bottom, so that the entire tidal drift was 3-4 m.

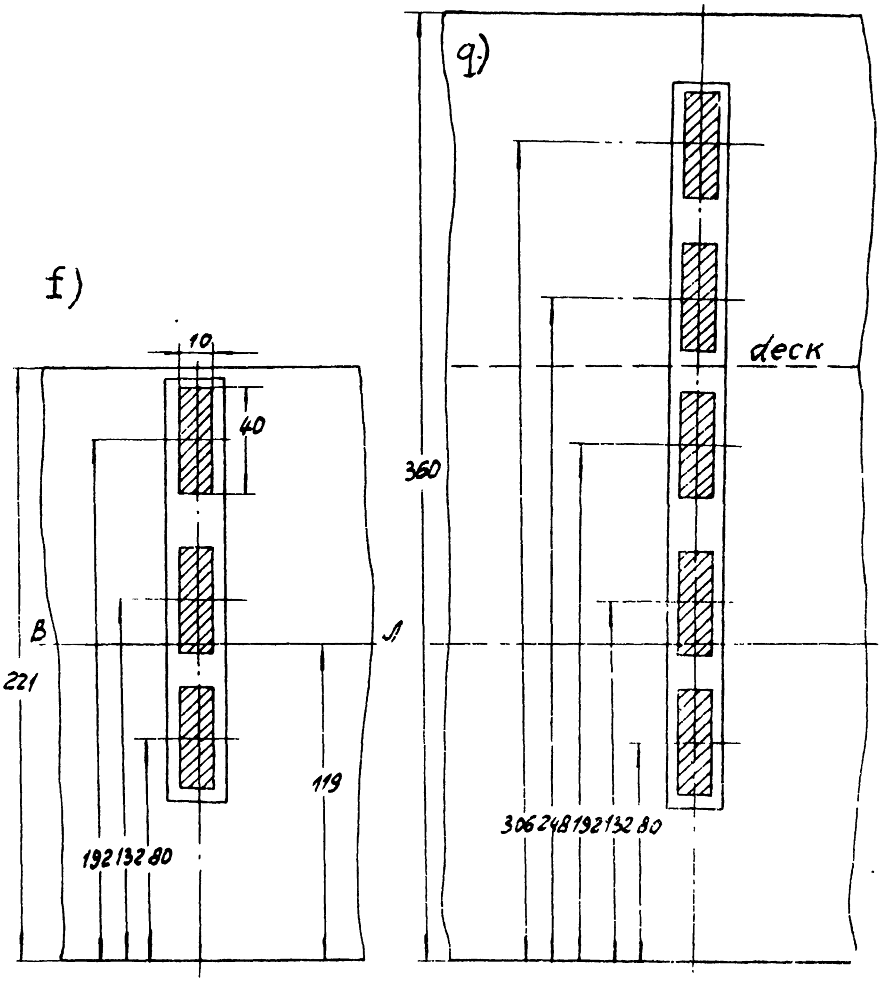


Fig 4

Just after the model passed the step of the bottom, the oscillograph started to record the impulses of the gauges and the wave parameters. At the same time the movie camera started operating. Wave parameters were measured at two points: in deep water, before the slope of the rising bottom, and in shallow water, above the rising bottom. For each model the position of the center of gravity was determined from the period of roll in calm water. To determine the damping coefficient, a film was taken of free rolling with decaying amplitude.

WAVES

It is known, Reference [4], that with a wave moving from deep water to shallow water the wave parameters are changing. The height of the wave is increasing while its speed and length are decreasing. The wave period, however, remains practically constant. The deformation of the wave form depends upon the slope of the bottom. When the slope is small, a wave with a long fetch transforms to a shallow water type with a steep crest and a flat trough. In this case the wave crest just dissipates. With a steep slope, the wave transformation occurs over a relatively short distance and the wave crest actually breaks.

The wave parameters in the described experiment were selected to cover a range from sub-critical to super-critical wave types, on a scale of their ability to capsize ships. Wave parameters are given in Table 2, where: J and h = period and height of deep water wave; λ = length of wave, $\lambda = 1.56\ T^2$.

$\frac{\lambda}{h}$ = relative length

H = depth of shallow water

$\frac{H}{h}$ = relative depth of shallow water

Table I

Type	Z_g sm	$\rho - a$ sm	T sec.	Wave № (Table 2)	
				Capsized	
		Model № 40597			
a	I0,3	0			4,8
	9,84	0,46	I,90	II$^{x)}$	4
	8,60	I,70	I,50	II$^{x)}$	4,8
	8,29	2,0I	I,39	II$^{x)}$	-
	7,85	2,45	I,I3	II$^{x)}$,I2	-
	7,50	2,80	I,00	-	4,8
b	I0,3	0		II,I5	I,4,I2,I3,I4
	I0,0	0,30	2,80	I5	4,II,I2,I3
	8,60	I,70	I,52	I5	I,4,II,I2,I4
c	I0,3	0		8,II	I,4
	9,84	0,46	I,38	8,II	4
	9,48	0,82	I,65	-	8
	8,60	I,70	I,4I	II	I,4,8
d	I0,3	0		II,I5	-
	I0,0	0,30	3,80	II,I2,I5	I4
	9,84	0,46	3,I2	I2	-
	9,50	I,08	I,79	II,I2,I5	I3,I4
e	I0,3	0		3,6,8,I0	I,2,4
	9,84	0,46	3,24	8,9,I2	2,3
	9,48	0,82	2,42	6,7,8,9	I,3,4,5
	8,60	I,70	I,49	2,4,6,8,9, I0,I2	3
	8,00	2,30	I,I2	2,6,7,9,I0, I2	3,4
		Model № 40598			
f	I8,50	0	-	8	-
	I7,67	0,83	2,50	-	2,6,8
	I7,03	I,47	2,05	-	8
	I5,44	3,06	I,30	-	2,8,6
	I5,I5	3,35	I,23	-	7
q	I7,67	0,83	2;75	3,5,6,8	I,2,4
	I7,03	I,47	2,I0	2,3,8	I
	I5,44	3,06	I,39	2,4,5,6	I,3

Table 2

Wave №	τ sec	h sm	λ m	λ/h	H sm	$\frac{H}{h}$	$\bar{h}$
			model 40597				
I	0,85	II,I	I,I2	I0,I	I5	I,35	$0,40 \cdot I0^{2}$
2	0,97	II,8	I,46	I2,5	I5	I,3	$0,53 \cdot I0^{2}$
3	0,90	I2,4	I,26	I0,I	I5	I,2	$0,58 \cdot I0^{2}$
4	0,8I	I3,5	I,03	7,6	I5	I,I	$0,68 \cdot I0^{2}$
5	"	"	"	"	25	I,85	$0,57 \cdot I0^{2}$
6	0,98	I4,2	I,50	I0,6	I5	I,05	$0,92 \cdot I0^{2}$
7	"	"	"	"	25	I,75	$0,78 \cdot I0^{2}$
8	0,95	I5,8	I,40	8,8	I5	0,95	$I,22 \cdot I0^{2}$
9	"	"	"	"	25	I,6	$I,0I \cdot I0^{2}$
I0	I,00	I8,6	I,56	8,4	I5	0,8	$2,I9 \cdot I0^{2}$
II	I,00	I9,9	I,56	7,8	I5	0,75	$2,47 \cdot I0^{2}$
I2	"	"	"	"	25	I,25	$2,08 \cdot I0^{2}$
I3	0,85	I6,6	I,I2	6,8	I5	0,9	$I,25 \cdot I0^{2}$
I4	"	"	"	"	25	I,5	$I,05 \cdot I0^{2}$
I5	I,03	22,2	I,65	7,5	25	I,I	$2,92 \cdot I0^{2}$
			model 40598				
I	0,95	I5,8	I,40	8,9	25	I,6	$0,20 \cdot I0^{2}$
2	I,I3	I6,8	2,00	8,4	25	I,5	$0,35 \cdot I0^{2}$
3	I,00	I9,9	I,56	7,8	25	I,25	$0,43 \cdot I0^{2}$
4	I,I4	I7,6	2,03	II,5	25	I,4	$0,35 \cdot I0^{2}$
5	I,05	2I,2	I,72	8,I	25	I,2	$0,54 \cdot I0^{2}$
6	I,03	22,2	I,65	7,5	25	I,I	$0,6I \cdot I0^{2}$
7	I,28	I8,4	2,56	I3,9	25	I,35	$0,44 \cdot I0^{2}$
8	I,II	22,6	I,9I	8,4	25	I,I	$0,68 \cdot I0^{2}$

Capsizing as a rule occurred in the direction of wave motion. The cases where capsizing occurred in the opposite direction are marked by "X". For each test the angle of heel was plotted against time (Fig. 5, Model #40598). In the same figure is a plot of drift against time. Using this graph we can determine the position as well as the linear and angular velocities of the model at the time of impact.

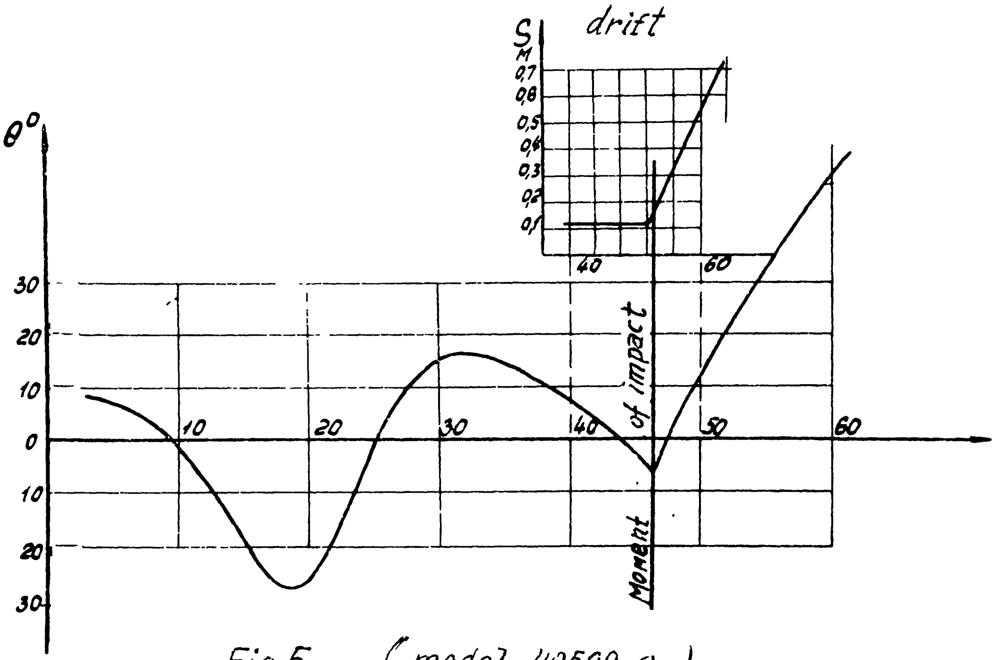


Fig 5. (model 40598 c.)

The depth of shallow water for model #40597 was equal to, $H_1 = 150$ mm. For model #40598 the depth was $H_2 = 250$ mm., which provided a ratio $H_2/H_1 = 1.7$, which was very near to the scale ratio (1.8).

RESULTS OF THE EXPERIMENT

All results of the experiment are given in Table I. For each wave parameter and loading condition, 5 to 6 tests were performed to account for different relative positions of the model and wave at the time of impact. The wave was considered critical if the model capsized in one or two of these tests.

VERTICAL DISTRIBUTION OF PRESSURE ON A SHIP SIDE

Earlier experiments, Reference [2], [3], showed that the action of breaking waves is that of an impact nature. The recordings of pressure distribution reaffirmed this fact (Fig. 5). The placement of 3 or 5 strain gauges on a ship's side allowed us to plot the vertical pressure distribution at the time of impact. As an example, we may consider figure 6 (model no. 40597). These gauges recorded the pressure at intervals of 0.0222 seconds so that for an impact which lasted about 0.1 seconds, the pressure was measured 4-5 times. Tests tests indicated that the total pressure and its distribution varied, even for the same model and wave parameters. The explanation can be found by considering that there are different phase angles between the wave and ship motion.

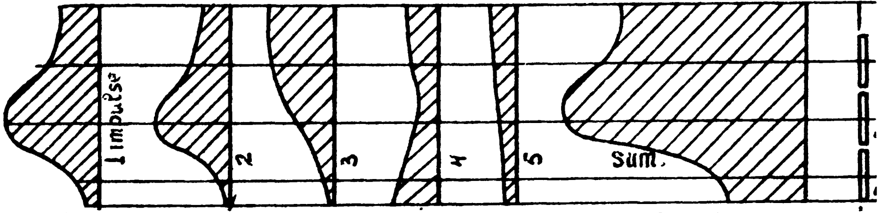


Fig.6

INFLUENCE OF ROLLING AND STABILITY

The theoretical investigations indicated that the intensity of wave impact is proportional to the relative wave energy, jh^2, steepness of the wave, h/λ, and degree of shallowness, h/H. These qualitative relations were taken as the basis for evaluation of the experimental results, in the form of these criterion:

$$\bar{h} = \frac{h^2 \lambda L}{V^{4/3}} \sqrt{\frac{h}{\lambda}} \sqrt[3]{\frac{h}{H}} \cdot$$

It was discovered that resistance to capsizing is characterized mainly by rolling parameters and closeness of the resonance zone, as well as by initial metacentric height.

We also found that $\bar{p}=\frac{p-a}{B}\left(1-\frac{\tau_k}{T_c}\right)^2$ can be used as a measure of this resistance. As an example of this we can refer to Fig. 7, where $\bar{p}$ is plotted against (p-a). The final experimental results were plotted as a series of graphs. An example is given in fig. 8 for model no. 40597 in test "a",

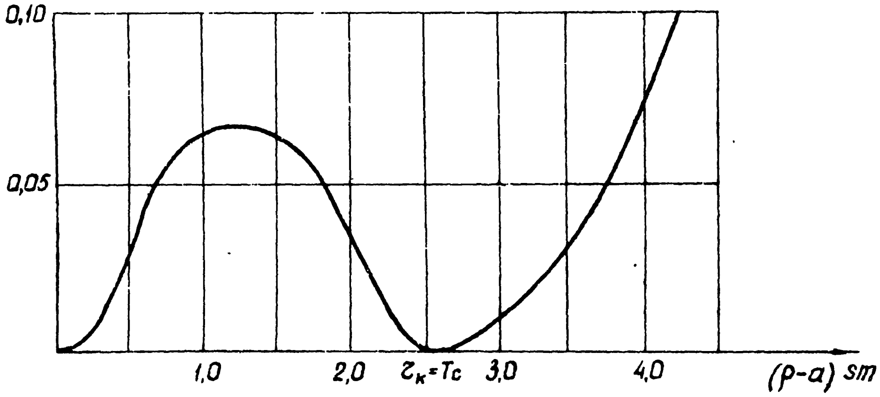


Fig.7

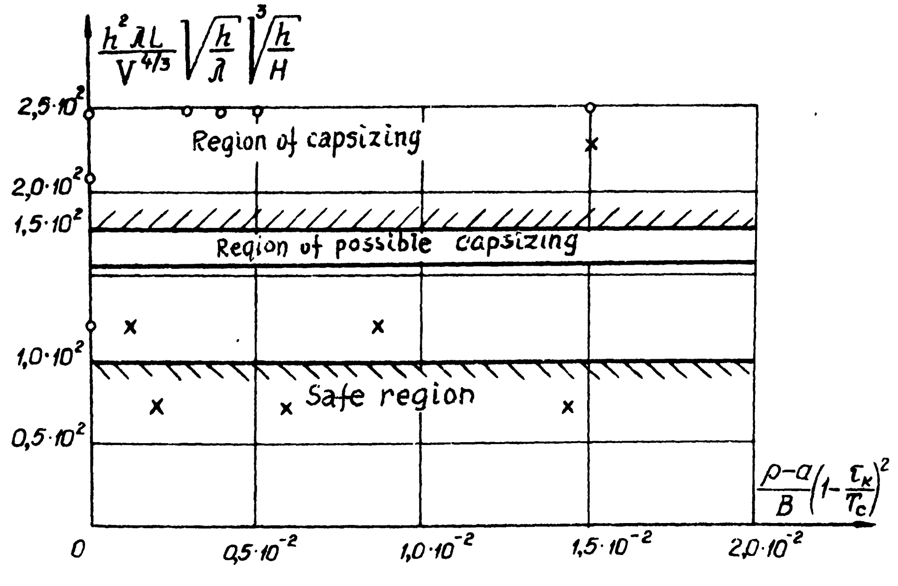


Fig. 8

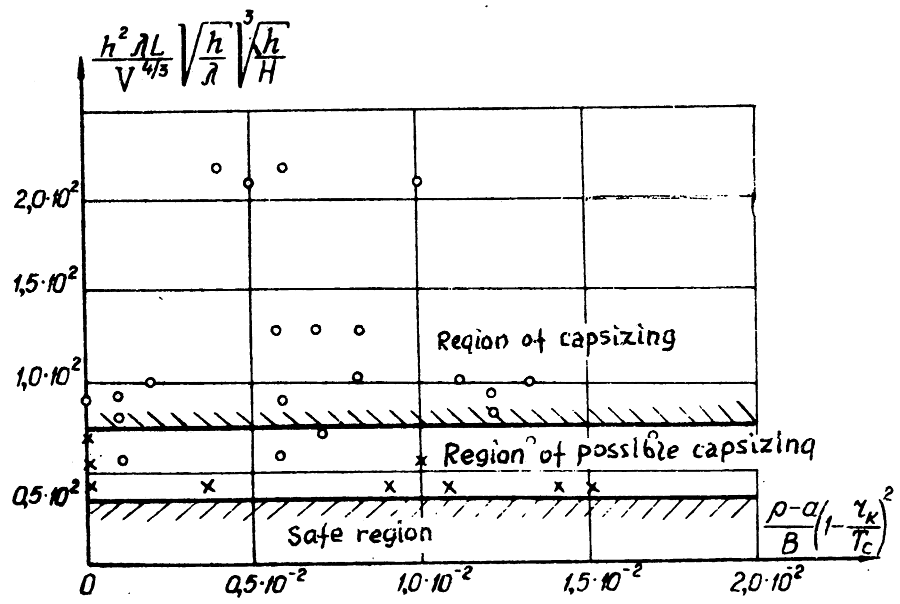


Fig. 9

and in figure 9 for the same model in test "d". On these graphs we can see three distinct zones:

1) A safe region containing the parameter $\bar{h}$ when the model did not capsize.
2) Region of Capsizing.
3) Region of Possible Capsizing, a transiational zone where both phenomena can take place.

In spite of their limited significance to other areas the above parameters can help to make positive distinctions between the three regions of wave parameters:

1) Waves which cannot capsize models.
2) Waves which can capsize models for all types of loading conditions and any value of metacentric height.
3) Waves which can capsize models only under unfavorable loading conditions.

We can assume that the same conditions exist in real situations where we can determine the critical wave parameters, relative to the ships safety.

INFLUENCE OF FREEBOARD AND SUPERSTRUCTURES

To determine the influence of superstructures and freeboard we can use the data given in tables 1 and 2. For example, in table 3 the results of tests with different superstructure heights are given. As we can see the increase of depth due to the addition of a superstructure increases the chances of capsizing. We can get some better insight into the influence of a superstructure by studying the impulse distribution. The magnitude of the impulses and their moments are given in table 4. In all examples the order of impulses acting on a superstructure was approximately the same as those acting on a hull, but the moments were considerably greater. This fact explains the influence of superstructure on capsizing. Evidently increasing the height of the superstructure will influence the capsizing, until the freeboard

Table.3

	p-a sm.	T sec.	τ sec	$\frac{\tau}{T}$	Result
model 40597, wave N4, τ_K = 0,81sec					
no superstruct.	I,70	I,50	0,90	0,60	
Superstract. 76mm	I,70	I,4I	0,90	0,64	
— " — 145mm	I,70	I,49	0,90	0,60	Capsized
model 40598, wave N8, τ_K = 1,11sec					
No superstruct.	I,47	2,05	I,24	0,6I	
Superstruct. 135mm	I,47	2,I0	I,24	0,59	Capsized

Table 4.

Test №	Model		Wave			θ_o	θ_o'	Impulse			Moment of impulse			z sm	θ_1 (angle velos.)		$V_{dr.}$ sm/sec	Result
	p-a sm	T_c cek	h cm	λ cm	τ sec			total	super-stuct	hull	total	superstr.	hull		experim	calcul.		
I	2	3	4	5	6	7	8	9	I0	II	I2	I3	I4	I5	I6	I7	I8	I9
Model № 40597 D = 26,3 кg																		
I09	0,46	I,88	I9,9	I56	I,00	5,5	-0,86	2I00	800	I300	-4660	-5200	+ 540	-2,2	6,3	6,49	52,0	Capsized
236	2,45	I,I5	I9,9	I56	I,00	-8,0	2,00	I770	-	I770	-I950	-	-I950	-I,I	3,5	4,I0	40,0	″
426	I,70	I,49	I5,8	I4I	0,95	-I2,5	-0,30	I990	I460	530	-I2900	-I3300	+ 400	-6,5	4,5	6,20	5I,0	″
432	0,46	3,24	I5,8	I4I	0,95	-I,5	0,44	3380	2350	I030	-I2350	-I4I00	+I750	-3,7	5,7	5,9I	80,0	″
Model № 40598 D = 85,I кg																		
609	0,83	2,75	22,6	I93	I,II	-6,5	-0,75	I0000	5940	4060	-4I900	-58500	-I6600	-4,2	4,4	4,55	76,0	″
6I7	3,06	I,39	I6,8	I99	I,I3	-32,5	0,47	6290	3050	3240	-30000	-34300	+ 4300	-4,8	3,2	4,37	49,0	″
639	3,06	I,39	I7,6	20I	I,I4	0	I,04	4I00	I380	2720	-7900	-I3400	+5500	-I,9	2,4	2,56	28,0	—

becomes greater than the height of the wave.

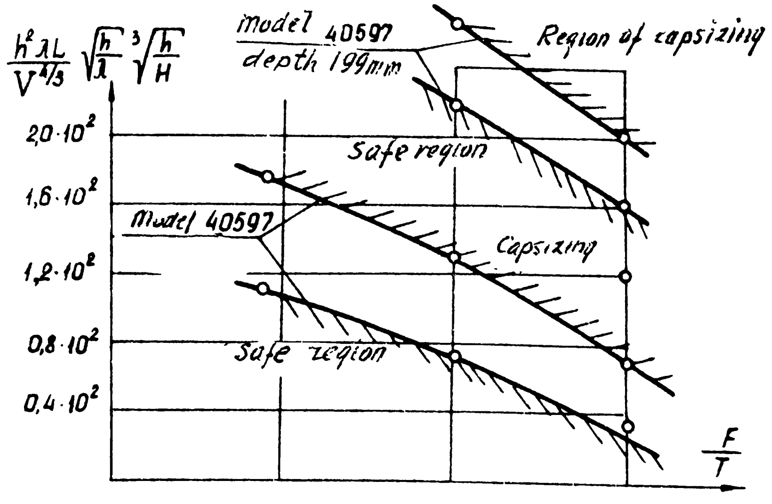
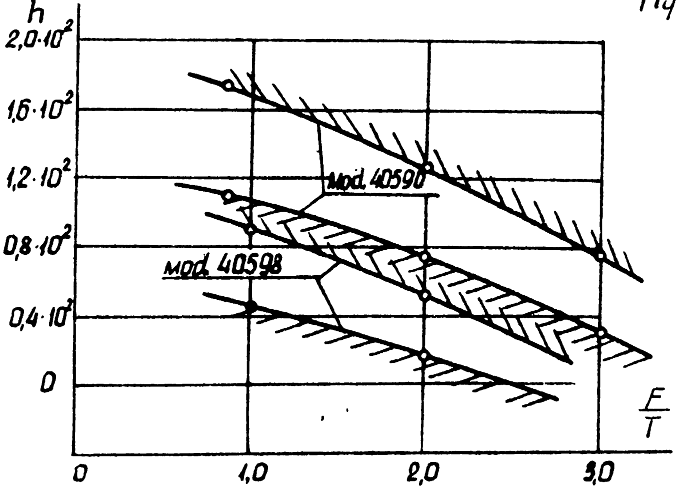


Fig. 10

Figures 10 and 11 give the dependence of $\bar{h}$ upon the ratio F/T where: T-draft and F is freeboard including superstructure. The ratios F/T for models are as follows:

Model 40597		Model 40598	
type	F/T	type	F/T
a	0,86	f	0,86
b	2,0	g	2,0
c	2,0		
d	3,I		
e	3,06		

Fig 11



SCALE EFFECTS

To consider the influence of scale,we can use the tests where the scale factor of wave parameters and model dimensions are nearest. The best examples of this were when the small model was with wave no. 4 and the big model was tested with wave no. 6. The comparison of results is given in figure 11, where corresponding zones for model #40598 are located in areas of smaller values of $\bar{h}$, than those for the small model.

CONCLUSIONS

1. Ships operating in shallow water might be subjected to the action of breaking waves causing capsizing. The forces which are a result of these waves depend on wave parameters, degree of shallowness, area of impact and relative position of the ship and wave at the time of impact.

2. The criterion: $\bar{h} = \frac{h^2 \lambda L}{V^{4/5}} \sqrt{\frac{h}{\lambda}} \sqrt[3]{\frac{h}{H}}$ were adopted to determine the critical range of wave parameters. The magnitude of this region depends on the size of the ship and its superstructure.

3. An increase in stability might lead to either positive or negative results.

4. The presence of a superstructure increases the possibility of capsizing.

5. The modeling process is difficult due to the scale factors which account for existance of forces other from those of a gravitational nature.

6. Subsequent work in this area should be aimed towards theoretical investigation of impact phenomenon, scale effects and testing of real ships in breaking waves.

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