WAVE-DAMPING EFFECT OF SUBMERGED FORESTS ON THE FLOOD PLAINS

by

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Introduction

The general progress in the management of the water resources requires to study the functional value of the flood-control levees. The best possible knowledge of the technical features of a certain levee section is a necessity both in the period of active protection and during the dry, or low-water period, when strengthening the levee.

This paper reports on the natural and small-scale model tests of the function of the shelter forests in damping waves, one of the decisive factors of the levee's functional value.

General description

To describe the functional value of a levee section, various factors have to be analyzed and the final conclusions will be drawn from these careful investigations. Numerous factors are in general involved to characterize a certain section and most of them are even varying from time to time following the natural changes [1]. Empirical and theoretical formulae were developed to find the most effective measures and profile shapes. For instance, the width of the levee will depend on the permeability of its material, the slopes on its stability and the height of the crest on the highest point of the watercourse hydrograph. Unfortunately, only subjective impressions have been collected on the effects of the wave action, not to be relied upon if single data are not supported by proper observations.

This factor may be of utmost importance, especially at reaches of wide inundation areas where wind gusts are likely to generate considerable waves along the existing long fetches. Such a wave action may become critical within a short time by damaging the line of protection unsheltered from its erosive effect.

To avoid the risk of danger from the attack of waves, some kind of reinforcement ought to protect the slopes, a very expensive procedure indeed in view of the lengths to be protected. These forces are reduced easier by entrusting the damping effect to floating or submerged structures. The latter is often represented by trees grown in areas exposed to inundation (foreshores).

This study has been concerned with the interaction between the trains of waves approaching the embankment and the elements of the tree crown expected to damp the eroding forces.

Composition of the shelter forests

When establishing shelter forests, the engineer is facing a living organic complex created and maintained by agricultural methods. Special sylvicultural techniques have been developed to form compact shelter-belts designed to screen the slopes from the waves. Recently, with the tendency towards an

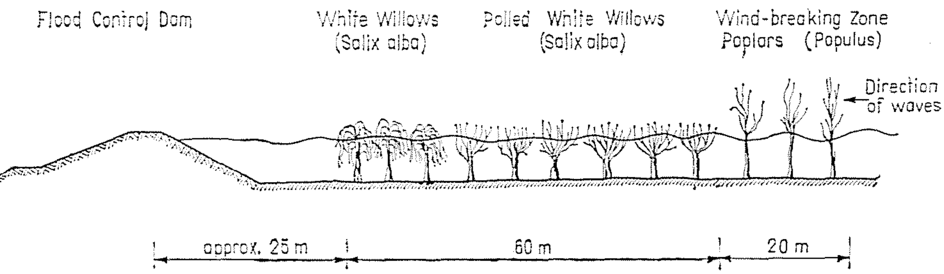

Fig. 1. Typical cross section of a shelter forest

increased demand for protection, the numerical evaluation of the forests is becoming essential where the damping effect is expected to reduce the erosive forces of the waves.

The typical infrastructure of the shelter forests is shown in Fig. 1. Approaching the levee from the riverside, first there is a relatively narrow belt of trees with high fusiform crowns. This is the wind-breaking zone which will keep the winds blowing onshore from regenerating the waves on the free water surface in front of the dam. The next zone is a wide one of trees polled to about cylindrical heads of young branches. This is the active part of the shelter forest, where the damping resistance is due to many partially submerged twigs and branches. The density of these elements is a most significant factor and the investigations were focussed on their effect. This wide intermediate zone of the shelter forests is usually flanked by some rows of trees having drooping branches to close the edge facing the dyke and to make a good appearance also during the dry periods.

The trees are generally planted in a square network, the space between the rows in the wind-breaking zone being 5 to 8 m and 2.5 to 4.0 m in the two other zones. Quickly growing species are preferred, as poplar (Populus) in the former zone, and white willow (Salix alba) in the latter two. To maintain the required number of trees, afforestation and clearing is regularly carried out.

The trees of the shelter forest have to endure occasional overflow without suffering irreparable losses. In addition to the changing biological conditions, even large dynamical forces are expected in the outer zone not merely coming from the winds but from the drifting ice, too.

According to experience the species mentioned above withstand these trials.

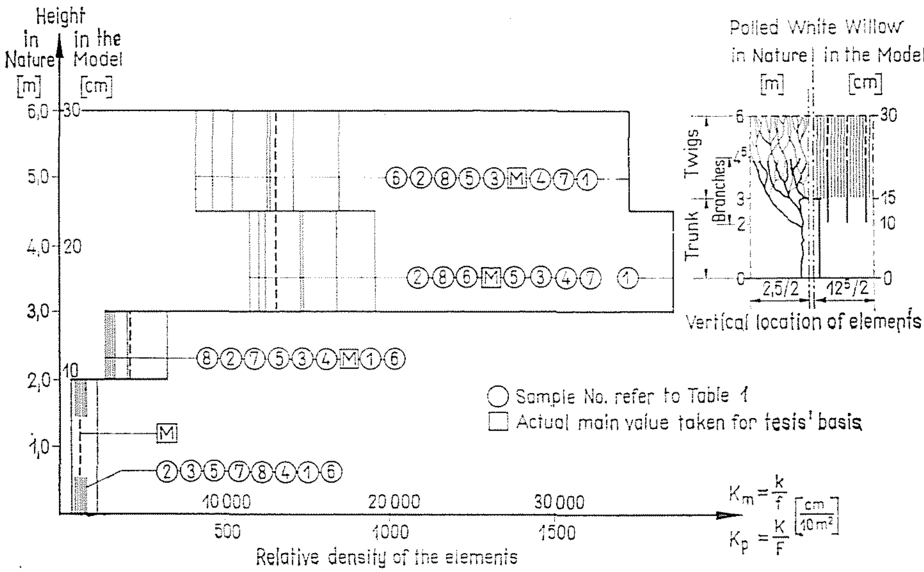

Fig. 2. Analysis of the density in shelter forest

The most striking feature of the trees in the working zone is the sharp vertical detachment of the elements. The relatively short trunks are regularly spaced, branches are springing up on their heads and these again push forth twigs. There is no underwood in the shelter forests in order to allow flow through as much as possible.

The results of measurements on polled willows selected in existing shelter forests are presented in Table 1. The elements were graded to make easier the forming of a unit tree, which represents the average number of branches and twigs at certain levels.

Trunks are not less in diameter than 15 cm, branches are those between 6 and 15 cm and the remainder counts as twigs. In the vertical direction, elements are delimited by the levels of their common boundaries (Fig. 2).

Table 1

Analysis of the density (samples selected in the shelter forest at the Tisza River near Szeged)

		Diam. ⌀ (cm) 1	No. 2	Sum. of Diams (cm) 3	Element ⌀ in 6.25 m^2 horizontal area (cm)	Elements' relative density in 10 m^2 horizontal area (cm/10 m^2)
Sample 1	Trunk	48	1	48	48	76·8
	Branches	20	1	20		
		17	2	34		
		14	2	28	82	131
	Twigs	1	608	608		
		2	102	204		
		3	66	198		
		4	18	72	1082	1730
Sample 2	Trunk	25	1	25	25	40
	Branches	16	1	16		
		12	1	12		
		10	3	30		
		8	1	8	66	105·5
	Twigs	1	120	120		
		2	26	52		
		3	32	96		
		4	6	24	292	467
Sample 3	Trunk	38	1	38	38	60·8
	Branches	14	3	42		
		12	2	24	66	105·5
	Twigs	1	174	174		
		2	38	76		
		3	38	114		
		4	8	32	396	634
Sample 4	Trunk	48	1	48	48	76·8
	Branches	12	3	36		
		10	1	10		
		7	1	7		
		6	2	12		
		5	3	15	80	128·0
	Twigs	1	180	180		
		2	39	78		
		3	39	117		
		4	18	72	447	715
Sample 5	Trunk	38	1	38	38	60·8
	Branches	10	2	20		
		7	4	28		
		6	3	18	66	105·5
	Twigs	1	126	126		
		2	33	66		
		3	42	126		
		4	12	48		
		5	6	30	396	633·0
Sample 6	Trunk	70	1	70	70	112·0
	Branches	14	3	42		
		12	5	60		
		8	2	16		
		7	2	14	132	211·0
	Twigs	1	87	87		
		2	33	66		
		3	18	54		
		4	6	24		
		5	6	30	261	418·0

(Table 1 contd.)

		Diam. ⌀ (cm) 1	No. 2	Sum. of Diams (cm) 3	Element ⌀ in 6.25 m^2 horizontal area (cm)	Elements' relative density in 10 m^2 horizontal area (cm/10 m^2)
Sample 7	Trunk	36	1	36	36	57·6
	Branches	12	1	12		
		10	3	30		
		8	3	24	66	105·5
	Twigs	1	201	201		
		2	63	126		
		3	18	54		
		4	27	108		
		5	9	45	534	855·0
Sample 8	Trunk	38	1	38	38	60·8
	Branches	14	1	14		
		12	1	12		
		8	2	16		
		6	1	6	48	46·8
	Twigs	1	172	172		
		2	20	40		
		3	34	102		
		4	4	16	330	528·0

To describe the thickness of the forest, a factor of relative density was introduced [2]. This factor K shows the sum of the diameters of the elements on a certain level above an arbitrary reference datum:

$$K = \frac{k}{F} \tag{1}$$

k being the sum of the elements' diameter (cm) and F the horizontal area of reference.

The damping effect

It is understood that the force from a passing wave on a submerged cylindrical element is the sum of two components. One is the drag component due to viscous drag and the other is the inertia component due to the combined effect of fluid acceleration from the impact to the element and of the pressure gradient in the fluid, producing the acceleration of the medium. It is shown that for deep-water and small-diameter cylinders the inertia component is predominant [3].

It is further assumed that there is no abrupt change in the wavelength passing through the forest. Then, neglecting the effect of the drag forces, the waves are described by the square of the wave height, directly proportional to the total head of the wave energy. This practical approach was motivated by the lack of proper observations in nature and, after all, it made possible to investigate the wave-damping effect of the submerged trees.

Experimental setup and testing

The experimental equipment consisted of vertical cylinders attached to horizontal discs, namely the elements representing the trunks were fixed on the bottom of the wave channel, and the thinner elements were immersed from above. The existing laboratory glass flume made it possible to investigate 60 m natural width of forest belt to a scale 1 to 20. Then the wave machine was capable of generating model waves corresponding to 1.0 m wave height in nature (this being one of the design data), and the water depth not exceeding 6.0 m in nature matched the height of the channel walls in the model.

Because of the prevalence of gravity forces, Froude's law was used to calculate the hydraulic magnitudes to be used in the model. Let λ represent the ratio of lengths, then the following relationships are to be developed (subscripts p and m refer to prototype and model, respectively):

$$\lambda = \frac{L_p}{L_m} \neq 20 \qquad \text{— ratio of lengths}$$

$$\frac{A_p}{A_m} = \lambda^2 = 400 \qquad \text{— ratio of areas}$$

The ratio of relative forest densities can be derived through the following steps:

The horizontal reference area [F in Eq. (1)] of 10 m^2 will be reduced according to the law of similitude, and in the model it will be

$$f = F \cdot \lambda^{-2} = 0.025 \quad [\mathrm{m}^2]. \tag{2}$$

Sum of diameters of the elements "piercing" this area in the model:

$$k_m = k_p \cdot \lambda^{-1} \quad [\mathrm{cm}]. \tag{3}$$

The relative density K_m at a certain level in the model:

$$K_m = \frac{k_m}{f} \qquad [\mathrm{cm/m^2}]. \tag{4}$$

The natural density values (Table 1) may be converted to scale by using Eq. (4):

$$K_m = \frac{k_p \cdot \lambda^{-1}}{F \cdot \lambda^{-2}} = K_p \cdot \lambda. \tag{5}$$

The relative density of the twigs in the model, for instance, had to conform with that value of the twigs in nature, which was found to average at

$$K_{p(tw)} = 500 \quad [\mathrm{cm/10\ m^2}] = 50 \quad [\mathrm{cm/m^2}]$$

as shown in Fig. 2. The same density in the model will be given by Eq. (5):

$$K_{m(tw)} = K_{p(tw)} \cdot \lambda = 50 \cdot 20 = 1000 \quad [\text{cm/m}^2] .$$

Since in practice, for the construction of the model forest no sticks of less than 3 mm nominal diameter could be applied, the above value was obtained from 49 twig-elements in each model tree. Thus, the effective relative density of model twigs of 3.2 mm actual diameter may be calculated from Eq. (4).:

$$K_{m(tw)} = \frac{64 \cdot 49 \cdot 3.2}{10} = 1003.52 \quad [\text{cm/m}^2] ,$$

slightly over the required value and found suitable for the construction of the model.

Similar procedure yielded relative densities in the model of 112 cm/m^2 for the trunks (∅ 17.5 mm) and 307.2 cm/m^2 for the branches (∅ 6.0 mm), i.e. 56 cm/10 m^2 and 153 cm/10 m^2 in the nature, respectively (Fig. 2). Superposing these values according to the changing vertical position of the elements, the forest density will appear as it is shown in Fig. 2. Although the relative density of the elements in the model follows this diagram, the branches do not end where they do in nature, but reach up to the upper holding disc where they are fixed together with the twigs. This fact was, however, practically unimportant because in the course of the tests the mean water level in the model never reached this disturbed height, similar to the nature, where the water level usually also does not rise above one third or one half of the crown height.

The pattern of the rectangular groups is presented in Fig. 3 together with the picture of the model forest.

The waves were generated by a wave machine of variable frequency and they reached the model forest at point A to be efficiently damped after leaving it at F. No interference due to waves reflected by the end plate of the channel was observed. The wave amplitudes were recorded by a multi-channel rectilinear oscillograph, the observation points — marked A through F — were in the centerline of the wave channel, 60 cm apart. The parallel wire wave-height gauges were zeroed at each measurement location before each test run, by a reading in still water, in order to minimize sources of error such as change of the water conductivity, and the like.

In the initial stage of the model operation the model was adjusted to reproduce occurrences known to have taken place in nature. The damping of waves by the shelter forests at the Tisza River near the town Szeged was measured during the flood in May and June 1970. The data collected there were evaluated as described previously, and these were taken to verify the simulation. After a few modifications — as e.g., stabilizing the required water level, stopping secondary waves travelling across the channel by filters etc. —

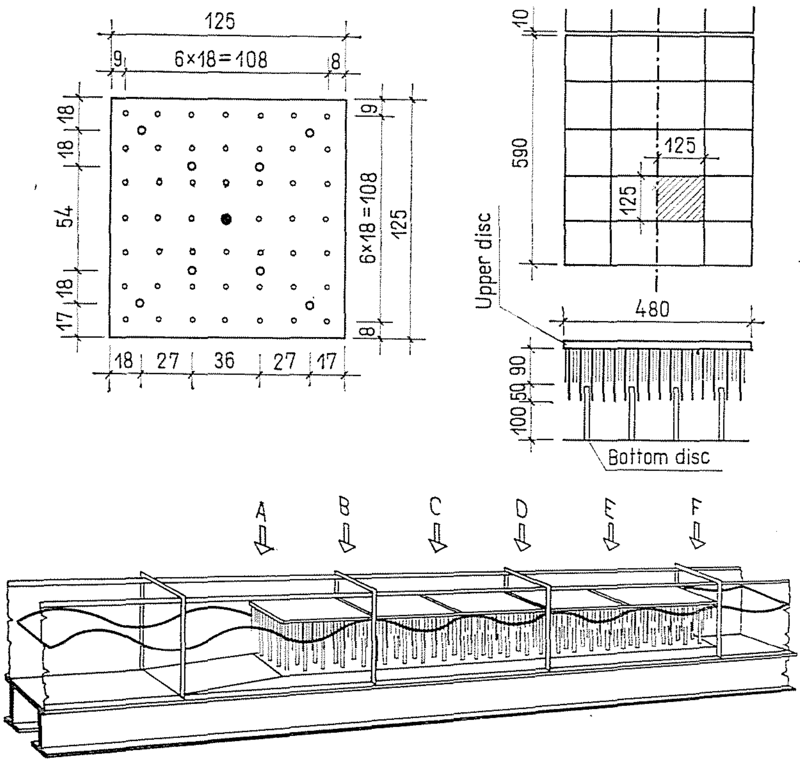

Fig. 3. Model layout of the forests

the behaviour of the model waves in the model forest was found to be dynamically similar, indicating adequacy of the model.

Test results are presented in Table 2. The various runs are identified by groups of numbers. The first two figures give the static water depth in the model [cm], the next two give the immersion of the model branches in still water [cm] and the last figure is the number of forest parts applied in the channel.

In Table 2 also the wave amplitude losses along the channel without passing any element of the model forest are shown. Anyway, the rate of energy dissipation within the boundary layer never exceeded 1/10 of the initial value because of the short distance of travel [4]. In general, this effect was neglected, but in a few cases (runs No. 20, 21, 22) the numerical values were corrected.

The trunk elements were removed in several runs, as it appears from the last column of Table 2, by lowering thus finally to zero the forest density near the bottom in order to assess the role of the elements here — also of a possible underwood — in the damping of waves.

Table 2

Results of the test runs

No.	Ident. No.	Δ(cm)	H_i/H_i^2 mm/mm²						Rel. Dens on SWL (cm/m²)	Trunks
			A	*B*	*C*	*D*	*E*	*F*		
1	23.08.1—5	0.3	26/ 676	22/ 484	20/ 400	17/ 289	15/225	13/169	1310.7	+
2	23.08.1—5	0.6	46/2120	36/1299	24/ 579	20/ 400	16/256	13/169	1310.7	+
3	16.08.1—5	1.1	48/2320	28/ 784	22/ 484	18/ 324	15/225	14/196	1310.7	+
4	16.08.1—5	0.0	34/1156	23/ 556	18/ 324	15/ 225	12/144	7/ 49	1310.7	+
5	34.05.1—5	0.2	40/1600	26/ 676	20/ 400	16/ 256	13/169	11/121	1310.7	+
6	34.08.1—5	0.3	42/1764	32/1022	25/ 625	16/ 256	12/144	9/ 81	1310.7	—
7	34.05.1—5	0.2	42/1764	34/1156	28/ 784	23/ 556	21/442	33/289	654	—
8	31.00.1—5	0.2	38/1420	32/1022	30/ 900	29/ 841	25/625	21/442	154	—
9	31.00.1—5	0.2	42/1764	37/1369	35/1225	32/1022	28/784	26/676	154	—
10	34.05.1—5	0.3	28/ 784	19/ 361	16/ 256	12/ 144	10/100	8/ 64	654	—
11	30.05.1—5	0.0	32/1022	28/ 784	26/ 676	24/ 579	21/442	19/361	654	+
12	30.05.1—5	0.2	38/1420	34/1156	31/ 961	29/ 841	28/784	26/676	654	+
13	37.05.1—5	0.2	38/1420	32/1022	28/ 784	26/ 676	22/484	20/400	654	—
14	37.05.1—5	0.4	28/ 784	22/ 484	17/ 289	15/ 225	12/144	9/ 81	654	—
15	34.00.1—5	0.4	39/1521	35/1225	34/1156	33/1089	31/961	28/784	154	—
16	34.00.1—5	0.1	32/1022	26/ 674	23/ 529	21/ 440	20/400	19/361	154	—
17	34.06.1—5	0.2	34/1156	31/ 961	30/ 900	29/ 841	28/784	26/676	112	—
18	34.06.1—5	0.2	38/1420	35/1225	34/1156	32/1022	31/961	30/900	112	—
19	15.06.1—5	0.4	48/2304	38/1444	29/ 841	22/ 484	12/144	9/ 81	1310.7	+
20	16.07.1—5	0.9	54/2916	36/1296	22/ 484	18/ 324	13/169	7/ 49	1310.7	+
21	17.08.1—5	0.9	54/2916	35/1225	27/ 729	17/ 289	12/144	9/ 81	1310.7	+
22	18.09.1—5	1.0	58/3364	38/1420	24/ 576	14/ 196	11/121	9/ 81	1310.7	+
23	15.06.1—3	—	48/2304	40/1600	28/ 781	16/ 256	—	—	1310.7	+
24	15.07.1—3	—	51/2600	39/1520	27/ 729	16/ 256	—	—	1310.7	+
25	17.08.1—3	—	54/2916	39/1520	21/ 440	13/ 169	—	—	1310.7	+
26	18.09.1—3	—	58/3364	40/1600	26/ 676	16/ 256	—	—	1310.7	+

Examination of the results

At the beginning of the analysis the test results were grouped to demonstrate the similarity between model and natural dampings. The curve in Fig. 4 representing the head of the wave energy (H_i^2) along the model forest is similar in form to the diagram of natural energy losses. The greater the amplitude, the higher were the losses, while smaller wave heights exhibited little change.

To examine the wave damping efficiency of the model forest, the coefficient of damping was introduced in the form

$$C_n = \frac{H_i^2}{H_A^2} \tag{6}$$

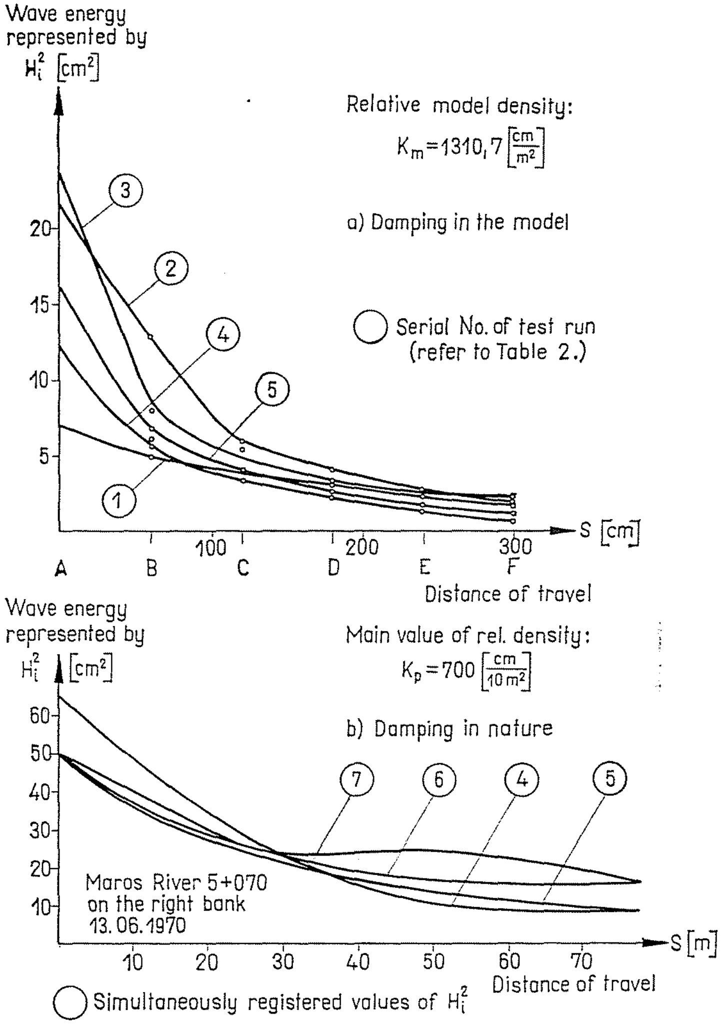

Fig. 4. Damping of waves in shelter forests

where H_i is the wave height (cm) at point i ($i = B, C, \ldots, F$), H_A is the initial wave height at point A, n is the serial number of the test runs referring also to the density applied. The damping coefficient was supposed to depend mainly on the distance of the wave travel and the relative density of the submerged elements. Other factors — as e.g., the change of water depth, or the effect of concentrated suspensions — were held to be unimportant for the final results. Though, their neglect in future investigations may not be recommended, especially if many data of both the model and the nature are to be analyzed.

In the graph of Fig. 5 the rate of the damping coefficient is plotted vs. the horizontal distance of the wave travel. The curves of test results for low

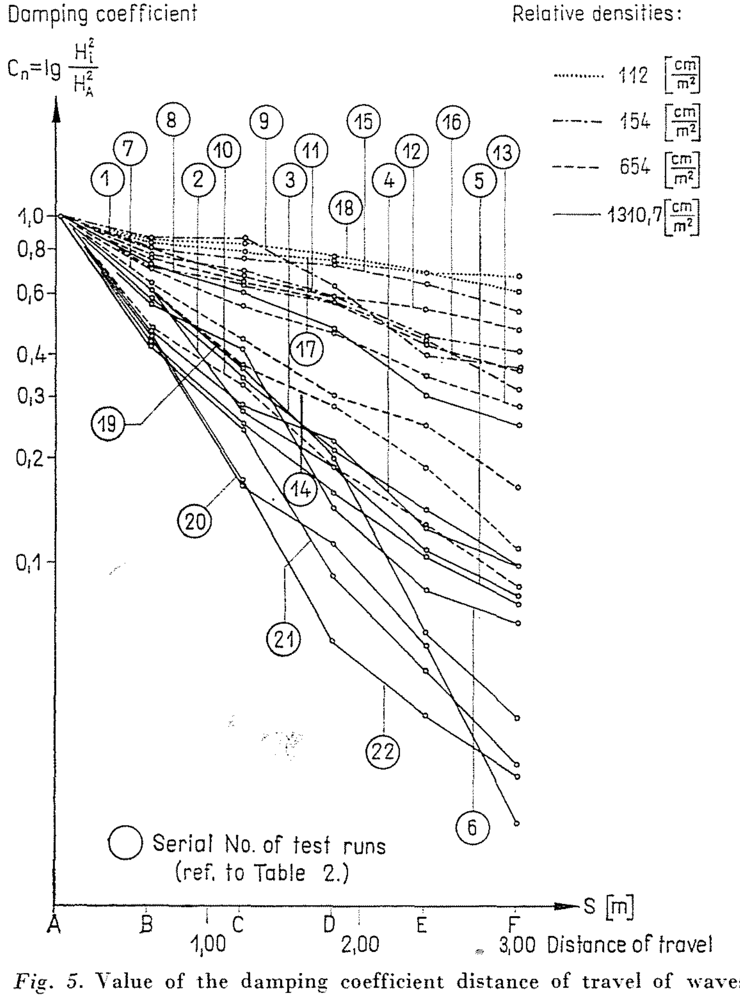

Fig. 5. Value of the damping coefficient distance of travel of waves

relative densities are nearly flat, while for increasing densities they are getting steeper. The slightly circuitous curves refer to irregularities in the model that could not be eliminated, but the polygonal lines may be replaced by straight ones. Thus, the damping coefficient can be expressed in the form

$$C_n = a_a^{si} \tag{7}$$

where a_n is the so-called velocity factor, and refers to the speed of the wave absorption in various test runs ($n = 1, 2, \ldots, 26$), s_i is the distance [m], along which the waves are dampened. To analyze the factor a_n, it has been correl-

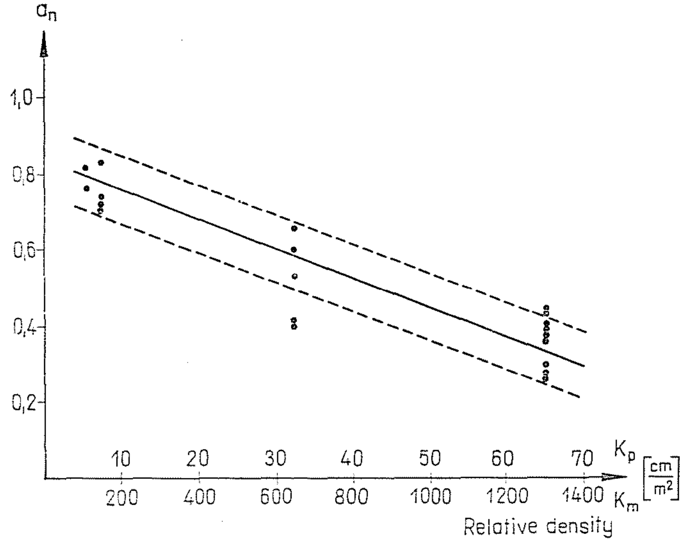

Fig. 6. Conveyance curve for a_n

ated to the relative density, as described previously (Fig. 6). The results of the test runs appear here as single points, and their range can be covered by a stripe. The dashed-line stripe in Fig. 6 can be expressed as:

$$a_{n(m)} = e.0.840 - 0.235 \frac{K_m}{1000} \tag{8}$$

which will give the boundary lines by substituting $e = 0.9$ and $e = 1.10$, respectively.

Rearranging Eq. (6) and substituting C_n and $a_{n(m)}$ from Eqs (7) and (8) gives the damping equation for the model forest of uniform density:

$$H_{i(m)}^2 = H_A^2 \cdot \left(e \cdot 0.840 - 0.235 \frac{K_m}{1000}\right)^{s_i} . \tag{9}$$

For a wave front passing through non uniformly located model elements, the function $H^2_{(im)}$ will take a generalized form:

$$H^2_{i(m)} = H^2_A \cdot a^{s_1}_{1(m)} \cdot a^{s_2}_{2(m)} \cdot \ldots \cdot a^{s_i}_{n(m)} \tag{10}$$

where H_i is the wave amplitude [cm] at point i ($i = 1, 2, \ldots, N$); H_A is the initial wave height [cm] at point A; a_n is the damping rate coefficient for waves passing through various relative densities, as defined by Eq. (8); $s_1, s_2, \ldots, s_i$ are the lengths in the model [m], along which the numerical values of the relative densities ($K_{1(m)}$, $K_{i(m)}$ in Eq. 8) may be considered as constant. Obviously these single lengths add up to the length of the "obstacle" to be passed, i.e. the total distance A to N.

The generalized equations of damping (Eqs 9 and 10) can be converted into natural conditions by using the model prototype ratios of lengths, areas and densities, as shown earlier:

$$a_{n(p)} = e \cdot 0.840 - 0.235 \frac{K_p}{50} \tag{11}$$

and

$$H^2_{i(p)} = H^2_0 \cdot a^{s_1/20}_{1(p)} \cdot a^{s_2/20}_{2(p)} \cdot \ldots \cdot a^{s_i/20}_{n(p)} \tag{12}$$

where H_i and H_0 are the wave heights [cm] at points i ($i = 1, 2, \ldots, N$) and o (entry point of waves), respectively; $s_1, s_2, \ldots, s_i$ are the widths in the shelter forest of uniform density [m], measured horizontally at right angles to the protection line; K_p is the relative density of the elements of the trees in the shelter forest, as expressed by Eq. (1), measured at the design flood water level.

The suggested method enables to analyse numerically the efficiency of existing shelter forests and presents a basis for the increase and proper maintenance of their required damping effect. The results concerning wave phenomena in submerged shelter forests permit to draw valuable conclusions.

As an example, the relative densities needed to obtain the required damping coefficients $C_1 = 0.5$ and $C_2 = 0.2$, respectively, in a forest of 60 m wide active zone, can be determined as follows. Take $e = 1.0$ for average conditions. From Eqs (7) and (11):

$$C_{1,2} = \left(0.840 - 0.235 \frac{K_{p1,2}}{50}\right)^{\frac{s_{1,2}/20}{20}}$$

Hence, the required densities are:

$$K_{p,1} = \ \ 9.6 \text{ cm/m}^2 = \ \ 96 \text{ cm/10 m}^2$$

$$K_{p,2} = 54.2 \text{ cm/m}^2 = 542 \text{ cm/m}^2$$

values corresponding to the experimental data, $K_{p,1}$ and $K_{p,2}$ representing moderate and high relative densities, respectively.

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Summary

The damping effect of partly submerged shelter forests was investigated and formulae were suggested to study this phenomenon as a function of the relative density of the trees' elements. The method gives a direct, practical solution for estimating the efficiency of existing protective forests and may furnish technical parameters for the plantation of new ones.

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