XI.

U. S. S. R.

The Compressed Air Breakwater. (1)

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I. — Introduction.

The protection of water areas from the force of the waves is admittedly a very difficult problem, while it is at the same time one of the most important links in the chain of questions connected with harbour construction. The difficulties of the problem are mainly due to the fact that the nature of sea waves has so far been but inadequately investigated. It is on record that in some instances the outer harbour structures, built to protect the aquatory of the port from the action of the waves, fell short of their purpose owing to their imperfect configuration in the horizontal plane. There are also numerous instances of such structures being damaged and swept off. These facts are due to the vagueness of our notions as to the laws governing the propagation of sea waves, their force, the conditions of their breaking, interference, diffraction, etc., and also to inadequate observation and experimental data.

Experimental data, inseparable from any study of natural forces, become of particular importance, when it is sought to devise new methods of overcoming such forces that have not yet been sufficiently investigated to warrant scientific generalizations.

The compressed air breakwater, which is the object of the present

(1) This research was carried out at the Central Scientific Research Institute for Water Transport.

article, supplies a vivid illustration of the above statement: the artificial conditions of the interaction of compressed air and the motion of the waves, under which the calming down of the waves takes place, must be experimented with, not so much in order to verify theoretical assumptions, as because the study of the effect of compressed air on the waves (even if the waves be artificially created) demands the same plenitude of practical investigation, from observation down to experimenting strictly speaking, as the study of natural phenomena.

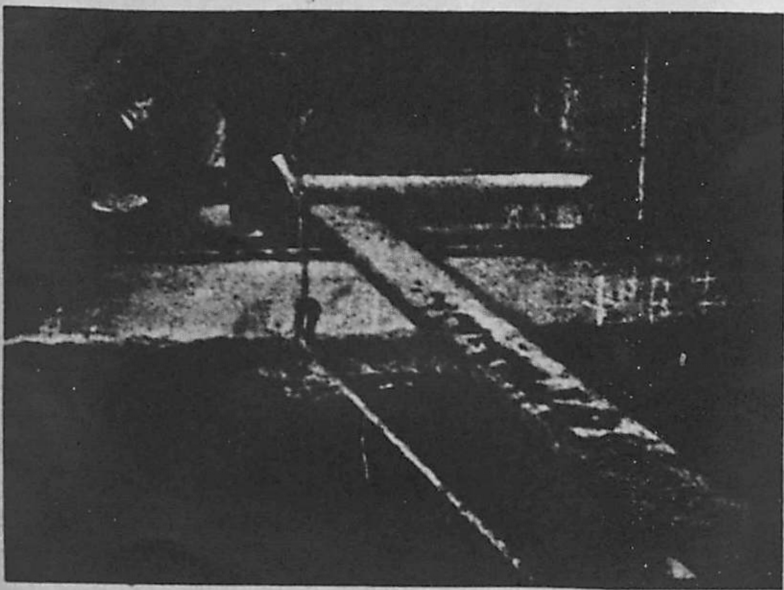

Fig. 1.

1. — The Principles of the Compressed Air Breakwater.

To the contrary of the familiar type of stationary protective structures, as used in harbours, the compressed air breakwater is apt to possess some of the advantages peculiar to those mobile structures that can be rapidly erected at a comparatively low cost. It consists of a series of pipes (in this particular case of one single pipe — Fig. 1), connected by flexible hose to a compressor plant on shore and forming a more or less closed circuit round the aquatory to be protected from the waves. The air supplied by the compressors is forced out into the surrounding water through the holes made in the pipes, and, rising to the surface, breaks the rhythmic motion of the waves, thus preventing the latter from penetrating within the enclosed area.

The pipes may be either laid along the bottom (Fig. 2) or suspended on floats at a depth corresponding to the maximum draft of the vessels entering the port.

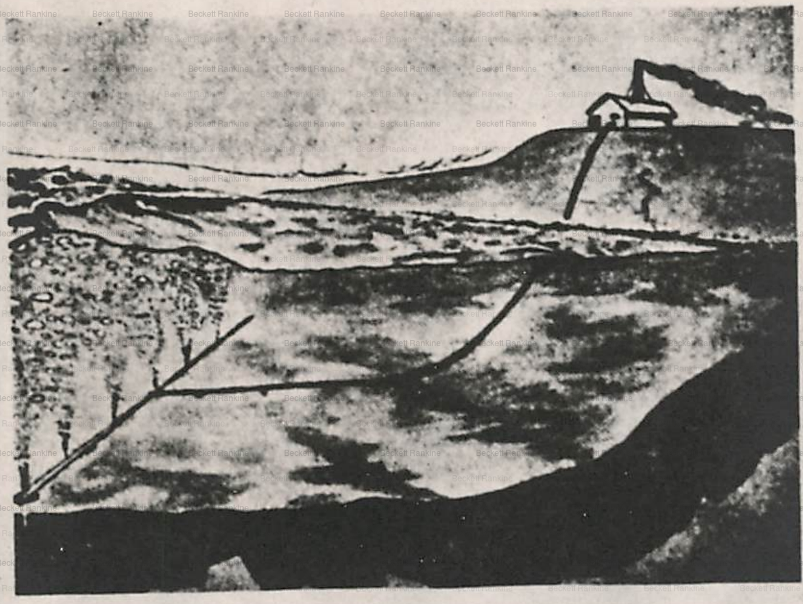

FIG. 2.

It is obvious that the compressor plant need not be brought into operation, unless this is rendered necessary by a storm or a rough sea.

The configuration of the compressed air breakwater being easily adjustable, none of the difficulties mentioned above as to the choice of the best outline in designing stationary protective structures apply in this case; moreover, should it be neccessary to erect a protective structure of a stationary type, the most satisfactory configuration may be determined by successively shifting the air

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breakwater pipes. Owing to the high cost of stationary protective structures, sometimes amounting to as much as ten thousand roubles per linear metre, and their considerable length, the use of the compressed air breakwater for a judicious selection of the configuration of a stationary structure may result in considerable saving through the avoidance of changes and readjustments after the structure has been completed.

In addition to the subsidiary value of the compressed air breakwater, as outlined above, the latter may be of interest as an independent structure to be used wherever stationary structures are technically impracticable owing to some peculiarities of the operating conditions.

We allude to conditions similar to those prevailing in the port of Tuapse, where the closing of the western entrance of the harbour by means of protective structures of the usual type would be unthinkable, as it would interfere with fire protective measures. At the same time, a closure of the western entrance would be extremely desirable, as it would secure a quiet anchorage for the vessels within the harbour. A compressed air breakwater, permitting of a free passage of vessels, would meet the case better than any other type of structure.

In oil-shipping ports, the air breakwater might be used to control the fire in case of fire, by placing consecutive rows of pipes at the bottom of the sea and by turning on different sections in succession, which would drive the oil into a restricted area and prevent its diffusion.

A laboratory experiment made by the staff of the Port of Tuapse Authority has confirmed the possibility of thus controlling oil fires on the water.

If harbour construction work is conducted in an unprotected water area, the sea waves may interfere with the work done afloat both in dredging, in operating floating cranes and in loading and discharging operations.

In this connection, the use of the air breakwater would do much towards rendering this kind of work less dependent on weather and the conditions of the sea.

It is also possible to assist a ship in distress by surrounding it with a system of pipes, and thus facilitating salvage operations. The mobility of the structure and its rapid adjustment make it possible to contemplate the use of the air breakwater for harbouring seaplanes. Another useful field of application would be the use of the air breakwater in fishing grounds to prevent the tearing of fishing nets and the tossing out of the fish.

The range of application of the air breakwater therefore bids fair to be a very wide one.

Under these circumstances, the necessity to investigate the possibilities of quelling the waves by means of the air breakwater becomes imperative, and every attempt should be made to solve the problem by scientific methods.

2. — The Development of Principles of the Air Breakwater in the U. S. S. R.

In 1930, Prof. V. E. Liakhnitski kindly drew my attention to some references to the above problem in foreign literature. Later on, it came to my notice that this question had also attracted the attention of V. M. Makkaveyeff and Prof. V. E. Timonoff (of whom the latter had been the first to touch upon that question in Russian literature in his article on « Maritime Transport », one of a series of monographs on protective measures). The above persons have also subsequently assisted me again and again with their advice.

The soundness of the principle underlying the air breakwater and the fact that it has attracted the attention of the leading experts in the U. S. S. R. has induced the Central Scientific Research Institute for Water Transport to include this question into its program and to map out far-reaching vistas of experimental and theoretical investigation.

In the process of investigation it proved impossible to utilize any data of home or foreign technical experience, and the problem had thus to be set in all its unexplored vastness. Such information as it had proved possible to find in literature was of a general descriptive nature, sometimes suggestive of advertising, and did not testify to the scientific treatment of the problem.

The earliest reference to the air breakwater that I have succeeded in tracing was in the April issue of the « Compressed Air Magazine » for 1907, in an article by Brasher, who appears to be the first to have put forward the principle of the effect of compressed air on the waves.

The same magasine for March, 1915, contains another article on the same subject under the title of « The Brasher Air Breakwater ». Almost at the same time, an article by Robert G. Skerret under the heading of « Fighting the Sea with Compressed Air » appeared in the « Scientific American » for January 30, 1915.

There is one more article on the subject, the only one I have not succeeded in obtaining, namely « Die Pressluft als Wellenbrecher » by F. H. Wisselingh, published in the « Die Pressluft » magazine for February, 1921.

The main characteristics of these articles (with the exception of the last one) are given above.

They contain, however, some interesting data on the use of the air breakwater, as quoted below.

The particulars contained in the table below are all we could find in foreign literature; further work conducted abroad in this direction is unknown, in spite of the satisfactory results obtained in some instances, and the fact that, as may be gathered from the same sources, a « Brasher Breakwater Company » has been organized (1).

Several attempts to put into practice in the USSR the principle underlying the airbreakwater were made off the port of Mahatch-Kala on the Caspian Sea, in the port of Tuapse in the Black Sea, and also at Vladivostok. All this work was done practically within the same period of time, about 1930.

Leaving out of account the experiments at Tuapse, already mentioned above, and those at Vladivostok as to which no particulars are available, we give below some particulars of the experiment at Mahatch-Kala, which seems to be the most interesting amongst them.

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(1) In reply to our inquiries, The American Association of Port Authorities and the Hafenbautechnische Gesellschaft have stated that they have no data available as to the air breakwater, with the exception of some of those quoted above.

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This experiment, due to the initiative of the Daghestan Fisheries Trust, and carried out by the Institute of Fisheries of the Turalinsky Fisheries, had for its object to ascertain the possibility of preventing the tossing out of the fish out of the fishing nets when landing in rough weather, and of protecting the nets from tearing.

The air breakwater pipes, of a total length of about 45 metres, had a U-shaped configuration, thus forming a half-closed circuit. The outlets were 5.5 mm. in diameter, their spacing 15 cm. The diameter of the working portion of air breakwater pipe was 75 mm. (3"). The consumption of air was about 15 m^3 per minute (1), with a gauge pressure of 0.35 — 0.40 atm. As may be seen from the official record of the experiment, the Commission did not observe any considerable effect of the current of air (forced through the outlets) on the heavy waves prevalent in the coastal zone, while the wind and the waves were at 5 — 6 points; when, however, experiments were made in a less rough sea, the damping action of air blowing on the breakwaters was more noticeable; the general opinion of the Commission is that the blowing of a greater volume of air at a higher pressure might produce an adequate effect.

It may be added that in the case under consideration, at a depth of 3 metres, the motion of the waves was a forward motion as mentioned in the record, involving the actual displacement of masses of water, and this inevitably rendered the desired result more difficult of attainment than under the conditions prevailing at great depths where the waves preserve a more or less oscillatory motion.

3. — Scientific Research in U. S. S. R. The First Series of Laboratory Experiments.

A scientific treatment of the air breakwater problem involves the consideration of all the factors that may affect the results of the experiment, including a differential study of every separate factor and of the joint effect of two or more combined factors. The absence of such methods in the pioneer work outlined above, showing the complexity of the problem and the difficulties in-

(1) There is discrepancy between the consumption of 500 cub. ft. of air per minute as shown in the record, and the capacity of the motors supplying power to the plant.

TABLE I.

Cons. Nos.	Place of experiment.	Date of experiment.	Particulars of installation.	Results.
1	New York Bay. Dry repairing dock.	1907	No data available.	Unknown.
2	Million Dollar Pier. Atlantic City.	1908	Length of pipes, abt. 1 *km*. whereof 200 *m*. of pipes of 25 *m m*. diameter. Air consumption 14—28 m^3 per min.	Damping of heavy ground swell.
3	Crotch Island. Maine. U. S. A.	Date unknown.	Length of piping abt. 100 *m*. Diameter of pipes 100 *m m* Diameter of air outlets 6 *m m*; spacing of air outlets, 15 *cm*. 2 compressors of a capacity of 75 m^3 per minute. Depth of submergence, 14 *m*.	Damping within 15 min. of heavy waves rolling so high that the spray was flying over the tops of the trees on shore.
4	Buzzard's Bay. Mass., U. S. A. Salvage of s s. « Yankee ».	1908	Length of piping abt. 30 *m*. Diameter of pipes 100 *m m* Diameter of outlets 6 *m m*; spacing between outlets 15 *cm*. 3 compressors. Capacity not stated.	The waves which had been rolling over the vessel were converted by the action of the air into a long low swell.
5	Brighton Beach. Long Island.	unknown	Length of piping unknown. Breakwater designed to protect from waves 180 *m*. of open coast. Depth of submergence 5 m. Other particulars unknown.	Unknown.
6	Off Gloucester. Mass., U. S. A.		No data available as to size of pipes and capacity of compressors. The breakwater had been laid to protect the pier which sometimes could not be used for landing owing to a heavy swell.	

Note. — These data, given in English measures in the original and converted into metrical measures, are quoted here in round numbers.

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volved in its systematic study, as well the presence of a number of contradictory data in the particulars of the experiments described above, rendered it necessary to ascertain as fully as possible the very fact of the effect of compressed air on the force of the waves.

With this end in view, the Central Scientific Institute for Water Transport organized a series of experiments at the Prof. V.-E. Timonoff Hydrotechnical Laboratory (1).

The experiments were made in a trough 24 m. long by 2 m wide and 40 cm. deep.

In order to produce a surge, a wave producer was used, constructed after the Danzig Laboratory design.

The air breakwater model was a tube 2 m. long, with a diameter of 24 mm. and 2 mm. air outlets drilled at 50 mm. intervals. The outlets were plugged with screws when necessary, the spacing between them being thus increased to 10, 15 and more centimetres.

Air was supplied by means of flexible hose from jars containing compressed air. By using the reduction valve it was possible to generate a current of air in the tubes at so low a pressure as 2 — 4 atmospheres, with an initial pressure in the jars of up to 150 atm.

The air breakwater pipe with the air holes pointing upwards, was placed at the bottom of the trough parallel to the crest of the waves, i. e. across the trough.

The experiments were conducted alternately with one and with two tubes, the spacing between the air outlets being alternately 5 and 10 cm. In the experiments with two tubes, a variable factor also was the spacing of the tubes, which varied within the range of 0,45 m. to 2 m. The elements of the waves generated in the trough and the air pressure in the tubes also varied.

The experiments with one tube did not produce a complete lull, the best results obtained being the reduction of the height of the waves by about one half.

A better result was obtained when using two tubes placed at a distance of 1 m. 8 from each other, with a spacing of 10 cm. be

(1) Cf. « Transactions of C.S.I.W.T. » No 1. I. A. Bogolepoff and N. D. Loghinoff : « The Use of Compressed Air for the Protection of Water Areas from Sea Waves ».

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tween the air outlets, the air consumption being about 0,6 m³ per minute, and the pressure 3,5—4 atm. In this case, a regular wave of 5,5 cm. in height was broken up and reduced to a slight ripple, with occasional splashes of up to 1,5 cm.

4. — Hypothetical Effect of Compressed Air on the Motion of the Waves.

Besides establishing the possibility to control the destructive force of the waves by the action of compressed air, the first series of laboratory experiments yielded another important result, namely the possibility to frame hypotheses explaining that phenomenon.

It became evident at that early stage that the mode of action of compressed air on the waves, in the presence of an actual displacement of masses of water (advancing waves) differs radically from its mode of action in the case of oscillatory waves. If, in the first alternative, the moving mass of air is to be considered from the point of view of the live force it represents, which is to be opposed to the live force of the waves, in the second alternative an adequate explanation would be supplied by the possibility of breaking up the rythm of the oscillation of the water particles. From this it may be inferred that, granted identical conditions as to the elements of the waves, the air consumption would be greater in the case of advancing waves. Would not this supply an adequate explanation of the failure of the experiments at Mahatch-Kala ? Taking into account the great energy that may be contained in the advancing waves, it would hardly be warrantable, from the economic point of view, to construct powerful compressor plants of a capacity determined by a comparison of the energy of the waves and the energy of the air issuing from the air outlets. It may easily be seen that the live force of moving air $\left(\frac{mv^2}{2}\right)$, if its mass *(m)* is inconsiderable, can have a high value only with an increased velocity *(v)*, which would require a greater air consumption and greater velocities at the air outlets.

We should arrive at similar results in comparing the energy of moving air and that of oscillatory waves. To make the matter

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clear we give below such a comparison in figures, for an imaginary concrete case.

The energy of an oscillatory wave per unit width is equal to (1):

$E = \rho \pi h^2 v^2$ kg. m.

where ρ is the density of water $= 100 \frac{kg.sec^2}{m^4}$.

$2h$ the wave height in metres.

v velocity of wave propagation im m/sec.

For waves of a height of $2h = 4.0$ m we may assume, for instance, as probable, the following values of length and period (2).

Length $2L = 27.0$ m.

Period $2T = 4.2$ sec.

Then $v = \frac{L}{T} = \frac{27}{4.2} = 6.5$ m/sec.

and $E = 100 \pi 2.0^2 \times 6.5^2 = 53.093$ kg. m $\sim$ 53.1 tn. m.

If we assume the velocity of the air issuing from the oulet to be $v = 200$ m/sec., which velocity may be considered high among those practically attainable we may, from the equation:

$$\frac{mv^2}{2} = 53.093 \text{ kg. m.}$$

determine the mass of air (m) required, per unit of breakwater, to generate an energy equal to that of the waves; thus

$$m = \frac{2.53093}{v^2} = \frac{106186}{40.000} = 2.66 \frac{Kg/sec^2}{m.^4}$$

The consumption of air in units of weight per linear metre would be:

$Q_g = mg = 2.6$ kg. sec.

which, at a pressure of $P = 4$ atm. and a temperature of $t =$ 15° C, corresponds, in units of volume, to

$Q = 5$ m³/sec. per linear metre, or 300 m³ per minute.

Thus, with a length of the breakwater of, say 100 metres, the capacity of the compressor plants should be over 50.000 m³ per minute, which would require about 240.000 H. P. Taking into account the resistance of medium through which the air would

(1) Cf. Flamant « Hydraulique ».

(2) I. A. Bogolepoff. « Comparative Characteristics of Empirical Formulae for the Determination of the Elements of Waves. » Report No 67 to the IV Hydrological Conference of the Baltic States.

move the necessary capacity of the compressor plants would amount to a still higher figure.

It may thus be seen that the hypothesis as to the necessity to oppose the energy of compressed air to that of the waves, which purports to explain the action of the air breakwater by the assumption that the air currents form a barrier of forces, does not seem likely to warrant its practical application. At the same time it is at variance with the facts described above, when a satisfactory result was obtained with a consumption of air of about 5 litres per m/sec. in a rough sea.

Other conclusions suggest themselves if it is assumed that in order to shatter oscillatory waves by means of compressed air it suffices to break the rythm of such oscillatory ondulation, and this does not by any means require an energy equivalent to that of the waves. In this case, a positive result can obviously be obtained with a comparatively low consumption of air. The question as to the correctness of this hypothesis became a cardinal one in the subsequent laboratory tests of the Central Scientific Research Institute of Water Transport.

5. — Second Series of Laboratory Experiments (1).

The second series of laboratory experiments had for its object not only to elucidate the problem of the effect of compressed air on the waves but also to supply some data for the quantitative estimate of the value of every factor contributing to the ultimate effect. The installation was on a considerably larger scale than in the experiments of the first series.

It may be characterised by the following figures :

Width of reservoir : 6.7 m.

Length of reservoir : over 100 m.

Depth of reservoir : (max.) 3.5 m.

The model of the breakwater was a metal tube of 50 mm. diameter (Fig. 3).

The air outlets were 2, 3, 4 and 6 mm. in diameter. The spacing of the outlets varied within the range of 5 to 40 cm.

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(1) Carried out by a brigade of the Central Scientific Research Institute composed of : N. D. Loghinoff, B. N. Grenhammer, E. I. Hadji-Panayoty and C. N. Ovchinnikoff.

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During the experiments, the breakwater pipes were laid in one, two or three rows.

With a view to reproducing waves, a mechanical wave producer had been constructed (after the design of I. V. Bazilevsky), which could generate waves 10 to 30 cm. high.

The air was supplied by a compressor of a capacity of 2.2 m³ per minute, at a pressure of up to 6 atm.

The air consumption was controlled by a regulating device.

The experimental data were recorded both visually and automatically, including photographing and filming.

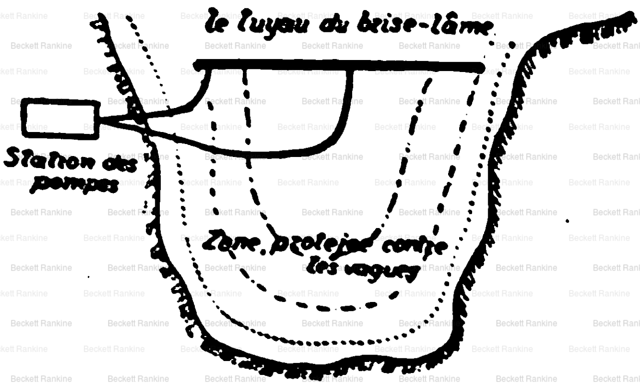

FIG. 3.

Sation des pompes .... = Pump station.
Le tuyau du brise-lames .... = The pipe of the breakwater.
Zone protégée contre les vagues ... = Zone protected against the waves.

The best effect, accompanied by a complete damping of 22 cm. waves within 15 — 20 sec., was obtained with one tube, submerged at a depth of 2.8 m., with the air outlets turned downwards. The diameter of the air outlets was 2 mm. and their spacing, 5 cm.

An idea of the results obtained may be gathered from photographs 4, 5 and 6, forming part of the film. Photograph No. 4 shows a foreshortened wave taken against the background of a screen, so as to give an idea of its initial size before breaking. Photograph No. 5 shows the same wave after the action of the air breakwater. Photograph No. 6 shows another wave taken against the screen after breaking up by compressed air. The cinema films were taken at a time when there was some hitch in the work of the

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compressor; therefore the effect of the air breakwater as appearing in the films is somewhat below the result actually obtained.

Thus, a low swell is discernable in photograph No. 8, while under the conditions outlined above, the surface of the water was generally projected as an almost ideally straight line.

The experiments were very numerous, including as they did over 500 variants (Table 2), and yielded extensive experimental data, the study and systematization of which have already begun.

It is therefore impossible for the present to consider anything but some preliminary conclusions that may be drawn from these series of experiments.

In an attempt to confirm the hypothesis that the rythm of the undulatory (oscillatory) motion is broken up by the compressed air issuing from the air outlets and that it is therefore not necessary to give high values to the issuing velocities of air and to erect a barrier of forces, a comparison was established between the effect of the air breakwater with the air outlets pointing upwards and the same effect with the air outlets turned down-

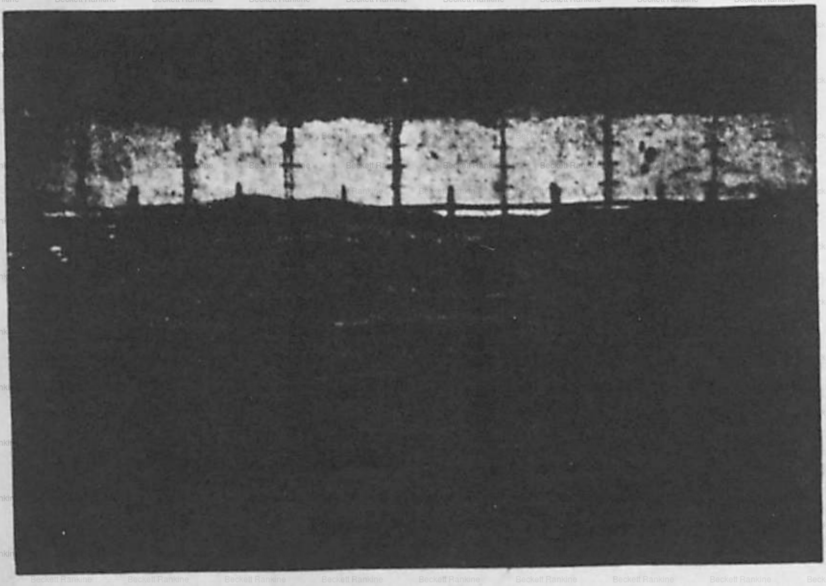

FIG. 4.

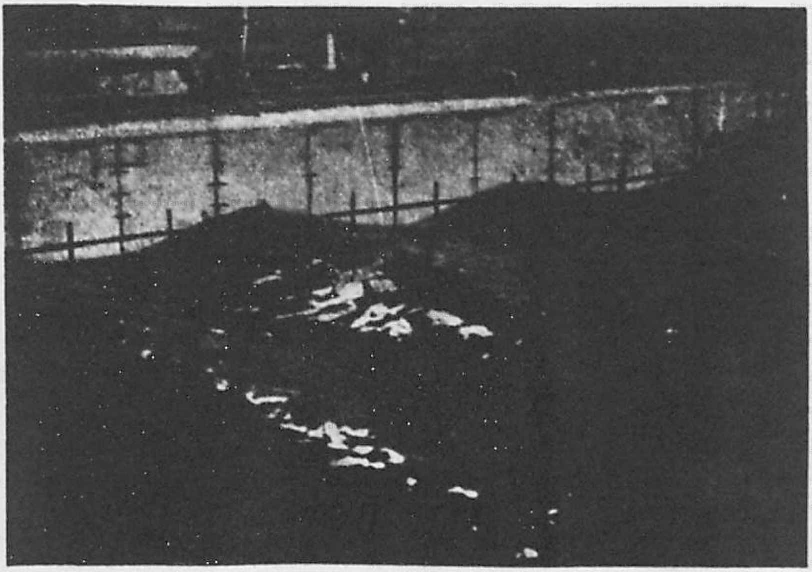

Fig. 5.

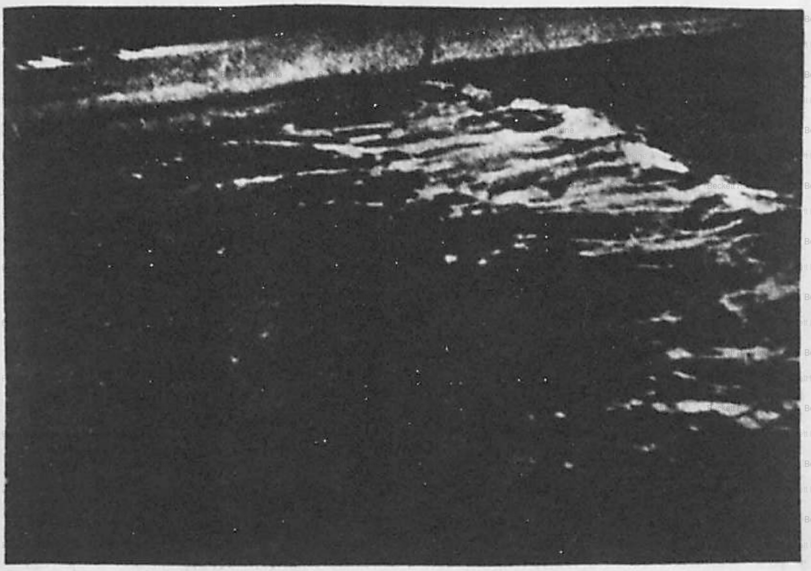

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Fig. 6.

wards. In the latter instance, the air issuing from the outlets had to pass in its ascent through the position of zero velocity, having altered the direction of its motion; the effect of the issuing velocities of air on the progress of the experiment had therefore been left out of account.

Numerous experiments have shown that the effect of the air breakwater, with the air outlets pointing downwards, far from being inferior to that with the contrary position of the outlets, gave rather better results. The hypothesis of a barrier of forces can therefore be abandoned. At the same time, the possibility of obtaining the desired effect with the air outlets pointing downwards has another and a very essential advantage. This position facilitates the blowing of the pipe with a view to purging it of water that may have got inside during the inaction of the breakwater; there is also no doubt that, under natural conditions, the downward position of the air outlets prevents their clogging with sand and slime.

It is remarkable that, contrary to the experiments of the first series, the best results were obtained with the air breakwater pipes laid in one row; attempts to place the pipes in two rows, with the distance between them varying within a very wide range, failed to give a better result than that obtained with the single-row breakwater. With a distance of 8 — 10 m. between the two rows, the effect, however, was quite satisfactory.

Since the best results were obtained with a single row breakwater and with the air outlets pointing downwards, not to mention the other advantages of this installation as compared with a multiple-row breakwater with the outlets turned upwards, the greatest attention in handling the experimental data is necessarily given to the results of those experiments that were conducted with a single row breakwater with its air outlets pointing downwards.

In this case, the main factors determining the effect would be in the first place air consumption and air pressure. Fig. 7 illustrates the effect of these factors.

The experiments have also shown the importance of deeply submerging the pipe. An increase of the depth improved the effect (Fig. 8).

Principal Experimental Variants. TABLE N° II.

Elements of waves				Particulars of breakwater model. Diameter of tubes—500 m/m.; length of tubes—6.5m.							
Height of wave	Length of wave	Velocity of wave propagation	Period of wave	Air consumption	Pressure	Diameter of air outlets	Spacing of air outlets	Depth of submergence of tubes	Number of breakwater tubes	Spacing of tubes	Remarks
2h / cm	2L / m	v / m/sec	2T / sec	Q / m3/min.	P / atm.	d / m/m	e / cm	H / m	n	a / m	
15.0	1.84	1.69	1.09	2.5	4 & 1.75	2	5	2.5	1 & 2	0; 2; 4; 6; 8; 10; 12; 14; 16; & 30;	The experiments were made with air outlets turned both upwards and downwards.
16.6	1.42	1.51	0.94	2.2	4 & 1.75	2	5	2.5	1 & 2		
14.0	1.96	1.77	1.11	2.2	5 & 2.75	2	5	2.5	1 & 2		
13.0	2.35	0.94	2.50	2.2	6 & 3.75	2	5	2.5	1 & 2		
15.3	1.65	1.62	1.02	2.2	6 & 1.75	2	10	2.5	1 & 2		
14.8	1.40	1.51	0.93	2.2	6 & 1.75	2	15	2.5	1 & 2		
16.0	1.63	1.61	1.01	2.2	6 & 1.75	2	20	2.5	1 & 2		
14.7	1.40	1.50	0.93	2.2	4	2	40	2.5	1 & 2		
15.2	1.48	1.59	0.93	2.2	4	4	10	2.5	1 & 2		
14.8	1.20	1.43	0.84	2.2	4	4	20	2.5	1 & 2		
16.0	1.17	1.39	0.84	2.2	4	4	40	2.5	1 & 2		
15.0	1.84	1.69	1.09	2.2	2	6	5	1 & 2.5	1 & 1		
14.0	1.96	1.77	1.11	2.2	2	6	10	1 & 2.5	1		
15.2	1.46	1.59	0.92	2.2	2	6	20	1 & 2.5	1		
18.0	1.81	1.69	1.07	1.5	4	2	15	2.5	1 & 2	0; 2; 4; 6; 8; 10; 12; 14; 16; & 30;	
16.0	1.37	1.51	0.91	1.5	4	2	10	2.5	1 & 2		
15.0	1.42	1.54	0.92	1.5	4	2	20	2.5	1	—	The experiments were made with air outlets turned downwards
14.0	1.91	1.69	1.13	1.5	4	4	10	2.5	1 & 2	—	
16.0	1.17	1.39	0.84	1.5	4	6	20	2.5	1	—	
14.6	1.40	1.50	0.93	1.5	3.5	6	10	2.5	1	—	
15.0	1.42	1.54	0.92	1.5	3.5	6	10	1.0	1	—	
15.2	1.48	1.59	0.93	1.0	3	2	5	2.5	1	—	
15.3	1.65	1.62	1.02	1.0	3	4	10	2.5	1	—	
15.0	2.35	0.94	2.50	1.0	4	6	15	2.5	1	—	

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This result confirms the assumption of an analogy between the energy of rising air bubbles and the energy of a falling body.

This conception gives a greater precision to the problem of the velocity of issuing air, with the air outlets turned upwards. If the idea of opposing the energy of compressed air to that of the waves is abandoned, and the hypothesis of the breaking up of the rythm of the undulatory (oscillatory) motion is adopted, it would seem that a better result might nevertheless be expected from an acceleration of that velocity. The experiments show, however, that this is not the case, no improvement having been attained by an acceleration of the initial velocities. This would appear to be due to the resistance of the medium, which speedily hampers the motion of the air currents as such. By using divers' lanterns to light the water depth during the experiments it was possible to observe that with the air outlets turned both upwards and downwards, the upward motion of the air issuing from them does not form any jets, but assumes the shape of separate bubbles, following one another at certain intervals and increasing in volume with their rise. Calculations show that the air issuing from the air outlets of the installation described above forms air bubbles having an internal pressure many times as great as the hydrostatic pressure at the depth of the submergence of the pipe; this pressure may be roughly estimated at, say, 4 atm., the losses along the length of the pipes for friction and local resistances being comparatively negligible.

Since that pressure is greater than that of the surrounding water, the air bubbles expand, their expansion proceeding simultaneously with their rise. It has proved possible to measure the velocity of the rise; it amounts on an average to 2 m/sec. Computations are now being made to analyse the energy of the issuing air by splitting it up into the following components:

1) The energy of the expansion of the air bubble from some initial volume (W_0), i. e. the volume it assumes at the moment of issuing from the air outlet, to the volume (W_1) corresponding to the hydrostatic pressure, and, 2) the energy of the rise of the air bubble as that of a body of a lower specific weight than water.

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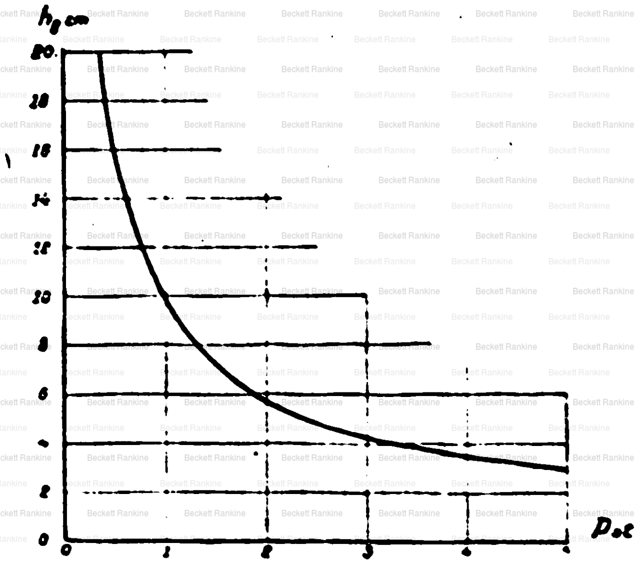

Fig. 7.

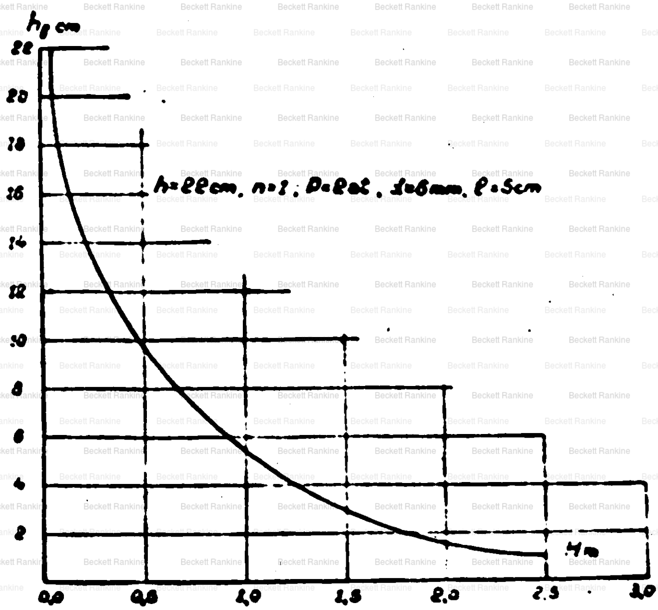

Fig. 8.

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N. D. Loghinoff, who carried out laboratory experiments jointly with the brigade, is of the opinion that the energy of air, i. e. of that part of it which is spent in breaking up the waves, ought to be divided into the following constituents :

1) The energy of the rising body (air bubble) of a *constant initial volume*, under hydrostatic pressure.

2) The energy of *the additional hydrostatic pressure* due to the expansion of the air bubble owing to the excess of its internal pressure over the hydrostatic pressure.

3) The energy spent in work during the expansion of the bubble from volume W_0 to volume W_1, as expressed by the formula :

$$R = P_0 \, W_0 \ln \frac{W_1}{W_0}$$

where : P = initial pressure,

W_0 = initial volume of air bubble,

W_1 = ultimate volume of air bubble.

4) The energy spent in overcoming the resistance of the medium.

Such is the path mapped out for the determination of the mode of interaction of compressed air and the motion of the waves. The experimental data having not yet been sufficiently studied, it is premature to subject the question to a more searching analysis.

In the course of the experiments an interesting observation was made, namely that, as the air was issuing out of the water, currents were formed on the surface running in opposite directions. The velocity of the current having the same direction as the current running in the opposite direction did not exceed 0,25 m/sec.

As regards the configuration of the breakwater in the horizontal plane the experiment proved its effect to be independent of the angle formed by the axis of the breakwater and the direction of the propagation of the waves. This fact has a practical value.

Fig. 9.

since it is difficult to conjecture the direction of the propagation of the waves which the breakwater is to ward off.

From the standpoint of the outline of the breakwater in the horizontal plane, there is thus but one requirement that the configuration of the air breakwater is to meet, i. e. that the pipes of the breakwater should form a more or less closed circuit round the water area to be protected.

Table 3 is a summary of the data of those experiments which gave the best results (Table 3).

Below we also give some sample records taken by automatic recording instruments on the aquatory both outside and inside the breakwater.

The process of quelling the waves and the operation of the automatic recorder were filmed; the film shows clearly that the undulating curve on the drum of the automatic recorder becomes, after the air has been turned on, an almost ideally straight line.

Conclusion.

The data yielded by the 1st and the 2nd series of experiments carried out, as stated above, on widely different scales, may be utilized, after adequate study, to elucidate to a certain extent the question of hydrodynamic similitude, in as much as it is desirable to utilize these experimental data not only for a qualitative, but also for a quantitative characterization of the action of every separate factor. One of the most important aspects of the problem to solve is the capacity of the compressor plant that would be needed, in natural conditions, to quell natural waves, say, 4—6 metres high, i. e. greatly in excess of those reproduced at the laboratory, the length of the structure measuring at least some scores or hundreds of metres.

Until the experimental data have been adequately studied it is difficult to make any definite statement in this respect. All we can do at the present time is to compare the results set forth below, whereof one was obtained during the first series, and the other during the second series of experiments.

With a depth of the trough of 40 cm., a height of the waves of 5—8 cm., a diameter of air outlets of 2 mm., a spacing of outlets

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Characteristics of the most

No.	Date of experiment	Number of breakwater pipes	Spacing of pipes	Particulars of breakwater ... Position ...	Diameter ... [illegible]	[illegible]	[illegible]
1	3 I	1	—	Air holes pointing downwards.	2.30	2.44	6.0
2	23 II	1	—		2.40	2.22	4.0
3	16 I	1	—		2.40	2.50	5.5
4	16 I	1	—		2.40	2.22	not meas.
5	17 I	1	—		2.40	2.22	6.0
6	14 I	1	—		2.30	2.22	4.0
7	4 I	2	0		2.50	2.44	1.75
8	16 I	2	0		2.40	2.22	1.75
9	3 I	2	10		2.30	2.44	1.75
10	7 I	2	10		2.50	2.22	1.75
11	23 II	3	0	»	2.40	2.22	4.0
12	23 II	3	0	Air outlets pointing downwards.	2.40	2.22	4.0
13	14/II	1	—	»	2.30	2.22	4.0
14	17 I	1	—	Air outlets pointing upwards.	2.40	2.22	unmeas.
15	14/II	1	—	Air outlets pointing downwards.	2.40	2.22	4.0
16	4/I	2	0		1.83	2.44	unmeas.
					2.26		1.75
17	10/II	2	0	»	2.40	2.22	5.0
18	20/II	2	0	»	2.40	2.22	4.0
19	5/I	2	8	»	2.50	2.22	1.75
20	16/I	2	8	»	2.40	2.22	1.75
21	16/I	2	10	»	2.40	2.22	1.75
22	16/I	2	12	»	2.40	2.22	1.75
23	16/I	2	12	Air outlets pointing upwards.	2.40	2.22	1.75
24	20/II	2	2	Air outlets pointing downwards.	2.40	2.22	4.0
25	15/I	2	12	»	2.40	2.22	1.75
26	15/I	2	14	»	2.40	2.22	1.75
27	15/I	2	10	»	2.50	2.22	1.75
28	16/I	2	10	»	2.40	2.22	1.75
29	20/II	1	—	»	2.40	2.22	4.5

4	10	20	1.96	1.69	1.16		Very good results 100 [illegible] quelling of waves
4	10	[illegible]	2.14	1.78	1.20	[illegible]	Very good results (2 lines of hose).
2	5	20	1.45	1.48	0.98		Very good results Absolutely smooth surface
2	5	[illegible]	1.45	1.48	0.98		Very good results
2	5	20	1.72	1.67	1.03	—	Very good results.
6	10	18	1.53	1.59	0.96	—	Very good results Surface slightly rippled.
4	10	29	1.87	1.82	1.03	—	Very good results. Occasional wavelets.
2	5	20	1.45	1.48	0.98	—	Very good results Absolutely smooth surface.
4	10	20	1.96	1.69	1.16		Occasional slight heaving of the whole mass of water.
4	10	25	1.76	1.71	1.03	—	Pipes laid at an angle of 17° and 32° to the crest of the waves. Very good results.
6: 4 & 4	5: 10 & 10	18	1.64	1.61	1.02	—	Very good results.
6: 4 & 4	5. 10 & 10	18	1.64	1.61	1.02	—	Pipes laid at an angle of 45° to crest of wave. Very good results
4	10	18	1.53	1.59	0.96	—	Good results (2 lines of hose).
2	5	20	1.72	1.67	1.03	—	Very good results
6	10	15	1.84	1.69	1.09	5-8	Violent issue of air Good results.
4	10	20	1.96	1.69	1.16	—	Occasional swells.
2 & 4	5 & 10	18	1.53	1.59	0.96	—	Occasional ripples. Good results.
4 & 2	10	18	2.14	1.78	1.20	2-3	Waves nearly quelled. Good results.
4	10	25	1.76	1.71	1.03	2-8	Occasional heaves. Good results.
2	5	20	1.45	1.48	0.98	—	Good results.
2	5	20	1.45	1.48	0.98	—	Pipes laid at an angle of 45° to crest of waves. Good results.
2	5	20	1.45	1.48	0.98	2-4	Slight ripples. Good results.
2	5	20	1.45	1.48	0.98	3-5	Results slightly inferior to the preceding experiments.
4 & 2	10	18	2.14	1.78	1.20	—	Results slightly inferior to N° 18.
4	10	18	1.92	1.72	1.12	4-5	Satisfactory result rather superior to N° 27.
4	10	18	1.92	1.72	1.12	4-5	Same as in preceding experiment.
4	10	18	1.92	1.72	1.12	—	Slight waves. Satisfactory results.
2	5	20	1.45	1.48	0.98	—	Satisfactory result.
4	10	18	1.72	1.20	4-5		Satisfactory result.

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of 10 cm., the consumption of air required amounted to 5 litres per second per linear metre of the width of the trough, at a pressure of about 4 atm.

In the second instance we have a consumption of air approaching the first, viz., about 6 litres per second per linear metre, at a pressure of 6 atm., the depth of the reservoir being 3,5 m., the depth of sulmergence of the pipes 2,8 m., the air outlets 2 mm., the spacing of the outlets 5 cm. and the height of the wave 22—24 cm.

In view of the comparatively low values of the air outlet spacing, ranging as it does from 5 to 10 cm., all we can do in this instance, is to establish a dependence of the specific consumption of air on the depth of the submergence of the pipes and on the values of the wave elements. As may be seen from the example quoted, the specific consumption of air was practically unaffected by the almost threefold increase of the wave height and the sevenfold increase of the depth of submergence. It may therefore be assumed that the air consumption and the wave height and pipe submergence are mutually opposed in their dependence. It is, however, difficult, at this stage, to formulate this dependence.

Let us assume, that in the course of study of our laboratory data we may (as we certainly will) evolve an empirical formula to express the quantitative effect of the above factors on the process of breaking up the waves. Will it be possible to use the experimental formula so evolved for a study of natural phenomena ?

This question must so far be answered in the negative, in spite of the fact that a great progress has lately been achieved in the study of the law of modulation owing to the work of Camichel, Escande, etc. As a matter of fact, the laws governing the effect of compressed air upon the waves remain so far undiscovered. Admitting the hypothesis of the breaking up of the rythm of the wave motion by means of compressed air, we solve the problem merely qualitatively. We cannot modify the atmospheric pressure, which therefore remains practically unchanged during the experiments, nor can we establish the proper ratio between the values of the consumption of air and the air pressure in the pipes, being unable to reduce them to the desired scale; finally, we do not possess such data on the functional interdependence of the determining factors of the phenomenon as would enable us to trace the influence of the elements not subject to modification. We are therefore compelled to confine ourselves for the time being to an indirect estimate of the experiment from the quantitative point of view.

It is therefore imperative to aim at a further extension of the scale of the experiments, including the performance of the latter in natural surroundings.

It is intended to carry out some of the experiments in one of the bays of the port of Sebastopol. The data thus obtained will, together with those yielded by laboratory experiments, supply the material that will make it possible to extend the statistical study of the experimental data, but also to subject the phenomenon under consideration to a more searching functional analysis, providing a sufficient number of facts to warrant theoretical inferences.