CHAPTER 53

PROTECTION AGAINST WAVE ACTION BASED ON HYDRO-ELASTIC EFFECT

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ABSTRACT

The author's conception on the mechanism of continuous slope protection under wave action (elements of flexible screen theory) are given in the paper in brief. Slope structures with continuous revetments are widely used in the Soviet Union, not only in canals but even in large reservoirs where waves reach nearly sea wave height.

When ordinary design methods are used, strength and stability of the revetment is provided by its thickness increase, and an expensive filter layer is placed under the revetment, Though continuous revetments were expensive, slope structures proved to be cheaper and more reliable than other measures of protection against wave action.

Now it appears that the revetment's stress conditions may be improved by reducing its thickness and eliminating the filter layer. There are types of coverings, the flexibility of which contributes to the self-consolidation of sand soil, filling the voids, and reducing the effective wave pressure.

There exists however a definite thickness minimum (critical rigidity) below which dangerous slope deformations occur. The various attempts to determine this critical rigidity are shortly reported below.

Results of laboratory and field tests are given, permitting to get knowledge of physical processes occurring under the revetment and of structural features improving their reliability.

I. PRESSURE UPLIFT AND DISPLACEMENT

For many years the revetment behaviour was explained as follows (fig. Ia): the slabs are subjected to severe hydrostatic uplift PTK, which at stagnant water is balanced by water weight PSR and slab weight, but at each wave roll back the uplift remains partially unballanced and tends to tear the covering off. This conception led to the construction of extremely thick revetments, in spite of corrections made in view of empirical data. The coverings about 50 cm thick were used for waves of 3-3.5 m high. Revetments were placed on crushed stone layers of 15-20 cm thick.

Quite different conception was taken as a basis for the theory of flexible screen (R-I). It was assumed that the slabs lay tighly on the compacted soil (as a result of the self-consolidation process, see § 2) and deflected upward by the uplift (fig. Ia).

In these conditions the uplift PUR taken up by the revetment is considerably less than the hydrostatic pressure PTK. It is created by the water in the voids between the slab and the soil and in the soil pores. The water from the voids and large pores of filter or crushed stone layer immediately effects the slab. But the effect of water originating from soil pores is a function of the amount of water, which has time to flow out filtrating during the wave roll back.

A certain part of the revetment bends, passing from the position MN to the MQN under the water action. But in fig. Ia this displacement is many times increased. The water roll back lasts no more than for 2-3 sec, and the amount of water inflowing during this period and causing the revetment to deflect is very limited.

The more revetment is flexible the more it may be deflected without cracking. It might be said that thin slabs "move away" from the uplift. This explains the high characteristics of revetments without filter at the action of wave of 3 m high with revetment thickness several times less than previously used of 50 cm. Since 1959 underreinforced concrete revetments of 20 cm thick and slightly prestressed revetments of 8 cm thick behave satisfactorily under these conditions.

Analytical determination of uplift decrease is related with mathematical difficulties. To overcome them, experimental data which describe physical processes more exactly are needed.

On the other hand, too high flexibility is also not permitted, as there is a definite critical rigidity, below which slope deformation begins, leading to its failure (R.-2). At maximum wave roll back a very thin slit is opened between the slab and the soil. The width of this slit is determined by the amount and the distribution of water, which at this moment is under the revetment, as well as by flexible properties of the slab (R. -I). If the covering is close to the soil, the volume of water under the slab, which may raise the revetment, consists of water in voids and water flowing by filtration during wave roll back.

The first formulation of the flexible screen theory stated-and this was confirmed by preliminary calculations (R-I)-that the uplift may not be taken into consideration as a working load, and the minimum thickness was determined by the slit width corresponding to the critical rigidity.

It was supposed that, if the revetment was too flexible and the slit width prooved to be larger than the average size of the soil particles, these particles were able to move, and this may result in the slope deformation: a hillock could appear under the water level (fig, 4a), what, as a rule, leads to the revetment failure, as we can see further (§ 2).

Such was our conception of critical rigidity up to I965.

Some data of one of the first test zones were used for determination of slit width (R.-I). This test zone was constructed on the breakwater of the Kaohovskaya power station. Measuring instruments were not placed in the zone, and the results of test were taken by visual examinations. The absence of soil upheaval and the presence of only slight signs of initial piping led to the conclusion (R.I2) that maximum seepage gradients were of the order of unity. It was shown that seepage flow could be considered as corresponding to the Darcy law (R.-I). Some observations also led to the conclusion that water under slab never rises in the slit above the water edge level.

Under these conditions (R.-I) a tentative scheme of raising of the slab by seepage flow up to the position MQN (fig. Ia) was proposed. According to it (fig. Ic), it is assumed that wave roll down occurs with constant velocity, and that in the points with abscissae increasing from 0 to X the duration of seepage decreases according to the linear law from T to zero and the gradients of seepage J increase from zero to I. By assuming that the slit length is equal to the length of wave roll down, the mean slit width δ_m may be expressed

$$\delta_m = \frac{kT}{X^2}\int_0^X (Xx^2 - x^3)\,dx = \frac{kT}{6} \qquad (I)$$

where k - Darcy coefficient.

If we take into consideration the amount of active water in the voids between the slab and the soil (BKL, fig. Ia) and in the filter pores (if there is a filter) we receive:

$$\delta_m = \frac{kT}{6} + \frac{V}{F} \qquad (2)$$

where V - water volume in voids of BKL type and in filter pores;

F - the area of the corresponding strip MN long.

Laboratory tests carried out by I.A. Jaroslavtzev in I964 in order to check the theses of the flexible screen theory (R-I-2) (fig. 2a) confirmed formula (I) concerning the initial stage of the revetment's behaviour, when the revetment laid close to the soil.

The formula (2) has not been directly checked, but judging by several measurements, we can suppose it might be justified in analogous cases.

In these experiments (fig. 2a) and also in similar tests and field measurements carried out by the Research Department of Anti-wave Structures and Slope Protection of "Hydroproject" Institute, the following phenomena have been checked up: (earlier these phenomena were taken as a basis of flexible shield theory) (R-I-2).

Self-consolidation. As a result of wave action, below water-edge the soil is compacted, and voids between the revetment and the soil are closed (R. I,2) (§ 2).

"Sinuous" movement of revetment. The revetment moves up and down following the movement of the waves (R.2) (fig. 2b).

Unfavourable filter action. As a result of the large quantity of water in filter pores and its free movement, slab deflections considerably increase. Thus, revetment stresses are larger when using a filter than without it (R-I) (fig. 2a).

Pumping effect. By its sinuous movement, the revetment "pumps" water out of soil and carries water under it up the slope (ascending slit flow, fig. 2b).

It was also supposed that there existed a constant descending slit flow on higher levels of the slope. However, this supposition was not confirmed, as it will be shown further.

"Roller" effect (R-2) - Each oncoming wave acts on the slope as a roller and prevents soil sliding and rolling down of its particles under the revetment. (This phenomenon seems rather clear, however special measurements have to be carried out).

The afore-mentioned experiments and especial measurements carried out in 1965 at the test zone of Taburische Cape (Krementchug Power Station) confirmed the presence of these phenomena, but made clear that conditions assumed in the derivation of formula (I)and (2) not always take place, especially when at high levels there are large voids under the slab (fig. Ib). Actual conditions of the revetment behaviour in this case prooved to be more severe than it was presumed earlier. The results however appeared favourable and are very important for application of the flexible slab theory.

Main tests at Taburische Cape in 1965 were concentrated in the alignment shown in fig. Ib, It is situated on slabs 8 cm thick placed directly on a sand slope without any crushed stone layer. The slabs are fixed to soil in the point E at the depth of about 2 m below T.W.L. The fixation in the point E creates an obstacle to water movement between the slab and the soil and hinders seepage.

In fig. Ib you can see distribution of voids between the covering and the soil during the tests. The voids depth is relatively 100 times enlarged.

In the site we had closely spaced pressure pick-ups, uplift pick-ups, quasistatic displacement gauges (for slit width measuring), vibrographs, void probes and levelling bench marks.

In 1965 oscillograms with synchronous recording of active pressure of wave (P), uplift (S) and displacement (D) were taken for the first time. In the previous years (since 1962), voids and revetment levels were measured.

In the present paper some data of two series of the tests carried out in 1965 is given (fig. Ib):

Ist series:Reservoir water level 81.04 m. Wave height up to 90 cm.

2nd series: Reservoir water level 81.46 m. Wave height up to 1.2 m.

In 1965 waves of 3.1 m high were measured in the zone. The highest waves in the previous years were the waves of 2.8 m high noticed in 1962.

The analysis of such synchronous oscillograms shows that, from the point of view of its beahviour, the revetment can be divided into two distinct zones A and B, and the border between these two zones is near the level of the main impact of the breaking wave (approximately in the point 205).

In the zone A the curve of active pressure reflects the wave progress. And the uplift curve is similar to the smoothed pressure diagram. On fig. 2d oscillograms of another experiment are given; pressure curves are shifted downward, till their lower points coincide with the corresponding lower point of the uplift diagram. These two diagrams for the points 202 and 204 never intersect, but for point 207 they superimpose, and the uplift begins to rise earlier than pressure and lasts longer. The same is shown by fig. Ib.

This shows that in the zone A the uplift is reactive and due to foundation reaction to the active pressure, that reaches the soil distributed in a certain zone by a relatively rigid slab. In the zone B on the oontrary hydrodynamic factor (movement of seepage water and slit water) contributes considerably to the uplift formation. From fig. Ib it is evident that, before pressure increase, ourves of pressure and uplift as a rule draw nearer to each other; that means that the effective uplift (S-P) increases. This fact reflects the moment of uplift increase at the simultaneous decrease of water layer on the revetment due to wave roll back.

The wave impact and the water remaining bring a sharp rise of active pressure. Nevertheless, after this rise, often for a short time the curves of pressure and uplift draw again nearer to each other.

When deflections of the revetment are taken into consideration, we get still more interesting and definite results.

The cause of the deflection in the zone A is undoubtedly the "pumping" effect. Oscillograms of the point 202 show that in fact there are no deflections here, as this point is near the fixed point E and the revetment in its "sinuous" movement had no time to collect water under it. Then the pumping effect comes into action: the amplitude of the "sinuous" movement becomes larger in point 204, when enough water has been already pumped into the slit and is lifted up the slope.

Though velocities have not been measured, there exists doubtless in the zone A a oonstantly directed ascending slit flow. This flow, and the roller effect represent outstanding phenomena, which prevent slope deformation (particle roll down and a hillock formation).

An important factor is the fixation of the point E. In tests when this fixation was not firm, or when it was deep under the water level (fig. 6o), an alternatively directed slit flow was noticed in the zone A, and this leads to dangerous slope deformations. At the present time we may say that best depth to make the fixation is about one wave length under the water level.

The deflections in the zone B originate at upper elevations (probably near the point 208 for the I-st series of tests and above the point 2I0 for the 2-nd series). The pulsating slit flow reaches these points. This flow was distinctly noticed during laboratory tests carried out on transparent models (fig. 2a and 6c) and its influence is reflected in the uplift pulsation. The slit water is evidently collected in the upper void (especially in the 2-nd series of tests). This strengthens its action, but at a certain extent darkens the features of the process.

When the curves of pressure and uplift draw nearer (the curve S-P in the points 208 and 2I0), the slab rises (the curve D) and lowers again with reducing S-P. Such deflections (fig. Ib and 2c) are almost immediately transferred to the point 206 through revetment rigidity. The deflections in the point 206 are not related to the S-P changes, and they cause the inflow of the slit flow and an intensive seepage flow because the gradient is equal not to unity, as it was expected for the zone A in deriving the formula (I), but is of the order of 50.

In the point 204 (zone A) displacements are not related to the upper elevations,but are created by the ascending slit flow.

The deflection amplitudes were large. The observed maximum deflections at the action of the wave 0.9 m high were equal to I.83 mm and at the wave height I.2 m - 2.6 mm. It is supposed that at the action of waves 3 m high, which were observed in I963 and I966, deflections have reached 6-7 mm; such slit is 30 times larger than the average soil particle size. And nevertheless dangerous slope deformations did not occur (see § 2).

In the points 204 and 205, after the wave impact and its remaining pressure, the revetment slowly lowers, but the measured amplitudes do not exceed a millimeter for a 3-meter wave. This magnitude coincides with revetments deflection at the maximum effective pressure for a wave 3 meter high (fig. Ia and 2e), assuming that the slab lies on an elastic foundation. The deflections are expressed by the formula (R-3):

$$w_0 = q_0 \frac{a}{kd} \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \frac{\sin\frac{n\pi}{2}\left(1-\cos\frac{m\pi d}{2a}\right)\cos\frac{m\pi x}{2a}\cos\frac{n\pi y}{2a}}{m^2 n\left[\frac{\pi^4 D k}{16a^4}\left(m^2+n^2\right)+1\right]} \qquad (4)$$

The afore-mentioned tests (fig. Ib) have contributed to a considerable progress in the attempts to develop thinner flexible screens. It was previously supposed that dangerous deformations can be avoided only when the following conditions are fulfilled:

I) the slit between the slab and the ground should not become larger than the average size particles;

2) the water in the slit should not rise higher the reservoir level;

3) seepage gradients should not be large;

4) water should not collect in the slit but should flow into the soil after each wave.

These conditions significantly limited the possibility of revetment's becoming thinner. Now we have learned that if the point E is fixed at a convenient depth (there are types of fastening, that if not placed deep enough, may be useless and even harmfull) slit water rising to higher elevations and slit width many times exceeding the paticle size may not necessarily lead to distinct slope deformations.

Nowadays we presume that the cause lies in the following.

I) When the point E is fixed, the critical rigidity is very small, because the soil can not lower in the zone of wave impact and below it: a constant ascending slit flow in the zone A, roller effect and the impact of the breaking wave - all these factors direct water upward and contribute to soil compaction.

2) As the water rises up the slope it is absorbed by the soil, but some part of it reaches higher elevations. At these elevations roll down of waves takes place not only on the revetment facing, but in the slit as well. In this case however the water pushes the revetment off, and creates high gradients for reverse seepage which prevents particle settlement. "Roller" effect reaches higher elevations, contributes to soil compaction and re-establishes the former situation. At the present time research work is carried out directed towards exact definition of the process nature and the derivation of the design formula of the critical rigidity.

Finally we can point out an interesting phenomenon, connected with the behaviour of the zone A. In painted prisms of fig. 3a" there is as a rule some shade in the left side. There is no doubt (fig. 6a): seepage water flows downwards and the pumping effect directs it upward along the slit. Thus the circuit closes.

2. SELF-CONSILIDATION PROCESS. FILTER EFFECT.

When the study of the flexible shield theory was in its initial period, it was stated that the wave action itself compacts the soil and closes the voids between soil and slab. This phenomenon was named the "self-consolidation process", and its nature may be explained as follows:

I. In the voids between the revetment and the soil there appear water currents at wave impact (fig. 3a) and at its roll down (fig. 3a'), hence there is some erosion with succesive settlement of the soil particles in the lower part of the void. The void moves upward along the slope.

2. The wave impact also leads to the soil compaction, sometimes at its "initial surface liquefaction" (R.-2) and here gravity plays also a definite role: the upper soil layers are slightly moved down along the slope, fill the voids and create a compacted upper slope layer. Roller effect completes the process.

In some tests described in fig. 2a and later in the tests of fig. 6c vertical soil prisms were dyed, and after a certain period of wave action, they had the shape shown in the fig. 3a", where the results of these three effects is evident, as well as of the "roller" effect, which stabilizes the form attained by the slope.

Under these conditions, maximum soil density should be below the level of wave impact. So it was confirmed by the measurements carried out by L.A Jaroslavtzev on a laboratory flume (fig. 3b) and by V.M. Leschinsky in field tests (fig. 3b').

Self-consolidation process has important consequences (fig. 3c). During the initial reservoir filling (I, II, III), in the progress of which wave agitation takes place often enough, the voids move up the slope and concentrate above the zone of wave breaking: in the "zone of natural void" /strip AB/ (fig. 3c).

As a result of self-consolidation, the slope can come to different configurations:

I) flat;
2) with a depression in the zone of maximum wave roll down (fig. 4b);

3) with the depression in the zone of impact and a hillock below (4a).

The first case is hardly probable with a flexible revetment; the second - results in a gradual stabilization of the slope as it took place in fig. 4b; the third - in the detachement of the revetment from the soil and its failure due to the wave impacts. The third case (unfavourable self-consolidation) is the result of a lack of rigidity (under the critical rigidity) or of the presence of water in high elevations. So in the example given in fig. 4a oblique waves forced water under the revetment at high elevations in November 1963 as a result of the failure of the adjoining revetment, hence there was a long lasting severe uplift, constant descending slit flow with considerable particles transfer and the formation of the hillock and cracks at low elevations (fig. 4d). Failure took place in 1965.

The initial self-consolidation leads to unfavourable results when voids move up more slowly than reservoir level and when, owing to a too great initial volume of voids and pores, the zone of natural voids is fixed at the level of wave breaking or below it.

Favourable factor preventing unfavourable self-consolidation and permitting to design the slab as lying on an elastic foundation is also the fact that wave agitation develops gradually, and self-consolidation completes prior to formation of large waves. This is particularly effective in thin revetments.

The self-consolidation process was often checked in the laboratory and field measurements. On the Krementchug test zone the levellings of the revetments (diagrams of the type of fig. 4 a, b) and probing of the voids were carried out twice a year. The results of the probing of I2 alignements on thin prestressed revetments with fixed point (three alignments in each of next sections) are shown in fig. 4e.

I - section of 8 cm thick on filter of low porosity.

II - section of 8 cm thick directly placed on sand slope (its levelling is shown in fig. 4b).

III - section of 5 cm thick on sand slope (its levelling is shown in fig. 4a).

IV - section of 5 cm thick on filter of low porosity (soon destroyed by wave action).

The scale of voids depth and normal deformations is in fig. 4e I00 times more than the scale in which the revetment is represented. The values of depth are given in the scale in centimeters.

The revetments have operated in severe conditions, that take place in many of the power stations situated in the Soviet Union plains. The filling of the net storage volume was completed in the two months of spring flood. Then the water line lowered every autumn and rose again the next spring.

In the revetments without filter (sections II and III) voids of considerable size, which remained after the construction, shifted practically to the zone above TWL (El. 8I m) just after the first reservoir filling in I96I, although the filling was completed only to El. 80.50 m. In the consequent years the situation in fact remained unchanged.

In the revetments with a filter of low porosity (section I) the self-consolidation process also took place, but in this case regularity was not so clear. In contrast to the revetment without filter ,the revetments with filters failed in I965 under the action of waves.

In the revetments I2,I5 and 20 cm thick with coarsly porous filter without the fixed point E, according to available preliminary data of visual examinations, the self-consolidation process did take place as well. The soil shifted downward through filter pores, but, during the autumn water level lowering, the soil moved deeply down the slope, and in spring the process commenced again.

Different factors influenced the revetment deformation and mainly the revetment rigidity and ground water level under it. In section 3 (fig. 4a) 5 cm thick, there was a construction defect -a depression at mean elevations (fig. 4e). In I96I in this section a hillock was formed at low elevations. After the failure of the neighbouring revetment (section IV), in I962 inclined waves collected water at high elevations. And as a result of constant uplift and downward flow this hillock increased, cracks were formed (fig. 4d) and in I965 the revetment broke down.

The section II, where the phenomena mentioned in §I took place, had a similar construction defect, that probably affected the nature of phenomena described in §I. However this section (fig. 4b,c) kept a most favourable profile.

When in I965 the 3d section broke down, inclined waves brought water at the level 82.5 from the direction of the 3d alignment, and it collected on the upper depression of the second alignment (fig. 4e and 5). Thus these waves created constant uplift which caused a slight hillock formation and a short crack in this alignment below the TWL. We shall not dwell upon the details of this process for the sake of brevity - it is rather clearly represented in fig. 5. It will be said only that in lateral alignments this process led to favourable results and that during I966 unfavourable consequences were eliminated.

These examples (some others could be given) show that for continuous revetments with the fixed point at the base of it, a relatively low rigidity is suficient for a reliable behaviour. However, at a lower rigidity the revetments get an unfavourable deformation and break down.

x x
x

It is important to construct revetments in which local ruptures spread slowly, because such revetments can be repaired before the slope fails.

Multiple observations showed an outstanding difference between various types of revetments in this aspect. Some break in a few minutes, others remain in an emergency state for several days and even months. In this paper we cannot describe the details of our experiences, and only restrict to summarizing them as follows:

I. Favourable factors for operation, durability and repairability of revetments are

a) equal strength (no weaker joints, R.-5);

b) large dimensions of separate slabs in plan;

c) fixing at a depth near to one wave height below TWL;

d) no filter.

2. Watertightness of expansion joints and abuttments should be to a certain degree ensured; requirements should be established experimentally. Slabs edges should be surcharged.

3. Prestressed revetments are in essence the most favourable type, but one should abstain from using thin high-strength wire (R.-5) till measures and designs be developed ensuring the absence of cracking which lead to simultaneous corrosion of several wires in one horizontal line.

4. Maximum initial soil density and tight lying revetment are desirable.

5. "Dowels" under the revetment in the zone of wave action are unfavourable because they disturb the self-consolidation process. Below the "dowels" a deep depression is formed (fig. 6a) leading to destruction from the wave action, particularly if there is a joint below the "dowel" (fig. 6b).

6. Prediction of disruptive soil liquefaction under a strong wave action based on calculations and field measurements (R.-8,9) and indirect generalization of some laboratory experiments of slope protection consisting of small slabs, is not confirmed by experience of continuous revetment. This evidently is partially explained by the following reasons:

a) Large accelerations originating at the peak of high wave impact are not transferred to the soil because continuous revetments are extremely inertial (R.-3) and create a certain dynamic filter;

b) Liquefaction and compaction of soil depends on the number of impacts rather than on their intensity (R.-I3), water agitation develop gradually, and when wave height is sufficient for loose soil liquefaction, the soil prooves to be rather compacted;

c) After numerous impacts, each soil liquefaction lasts a very short time and is restricted to the slope surface (R-I3).

7. Thin revetments in fact lay directly on an elastic foundation or on a thin water layer. They can be calculated by the scheme of fig. 2e (the shape of the triangular load has to be determined more exactly, R.-IO, II). The revetments calculated by such scheme withstood the active pressure. Load peak should be taken into consideration with a dynamic coefficient, which depends on the ratio of peak duration to the oscillation period of the system revetment-soil-water (R-3). The more durable load of the water remaining after the peak (R.-IO, II) is assumed quasi-statical.

3. PECULIARITY OF CONTINUOUS REVETMENT BEHAVIOUR WITHOUT FILTER ON EARTH DAMS

Do the water retaining structures present more favourable conditions for flexible screens and continuous revetments in general than structures without level drop? Up to now there were different points of view concerning this question.

The results of laboratory tests and field observations, carried out in I964-I965, gave to this question a favourable answer. They are as follows:

Previous points of view about the behaviour of continuous revetments on water retaining structures.	Actual condition of the first laboratory specimens, tested in I965 without fulfilling similarity criteria.
The first assumption. There is no screen effect (fig.6d)	I. There is a deep level drop (in prototype up to 8 m).
The second assumption. Screen effect exists (fig. 6f) at calm water; with the waves it dissapears (fig. 6g)	2. In the flume, seepage line begins to rise at each wave series, and soon takes a fixed position (fig. 6h). Self-consolidation is provided by a thin pulsating water layer between the slab and the soil (the upper border of the layer oscillated between M and N). The fig. 6i shows the rising of the origin of the seepage line in three tests as the number of waves increases (from 0 to 2000 waves).

The third assumption. There is a screen effect. So there is no uplift, as there is no water (fig.6j), but lack of water excludes the self-consolidation (fig. 6k). The revetment does not lie on an elastic foundation.

3. There are no points where uplift S exceeds pressure P at face (fig. 61)

4. Self-consolidation character (favourable or unfavourable) is determined by the revetment rigidity and the degree of the contact with the slope. It may be improved by means of a right choice of fixed position points.

These results show that a correct choice of the revetment structural parameters may permit:

a) to eliminate uplift as a design load;

b) to consider the revetment as closely lying on an elastic foundation.

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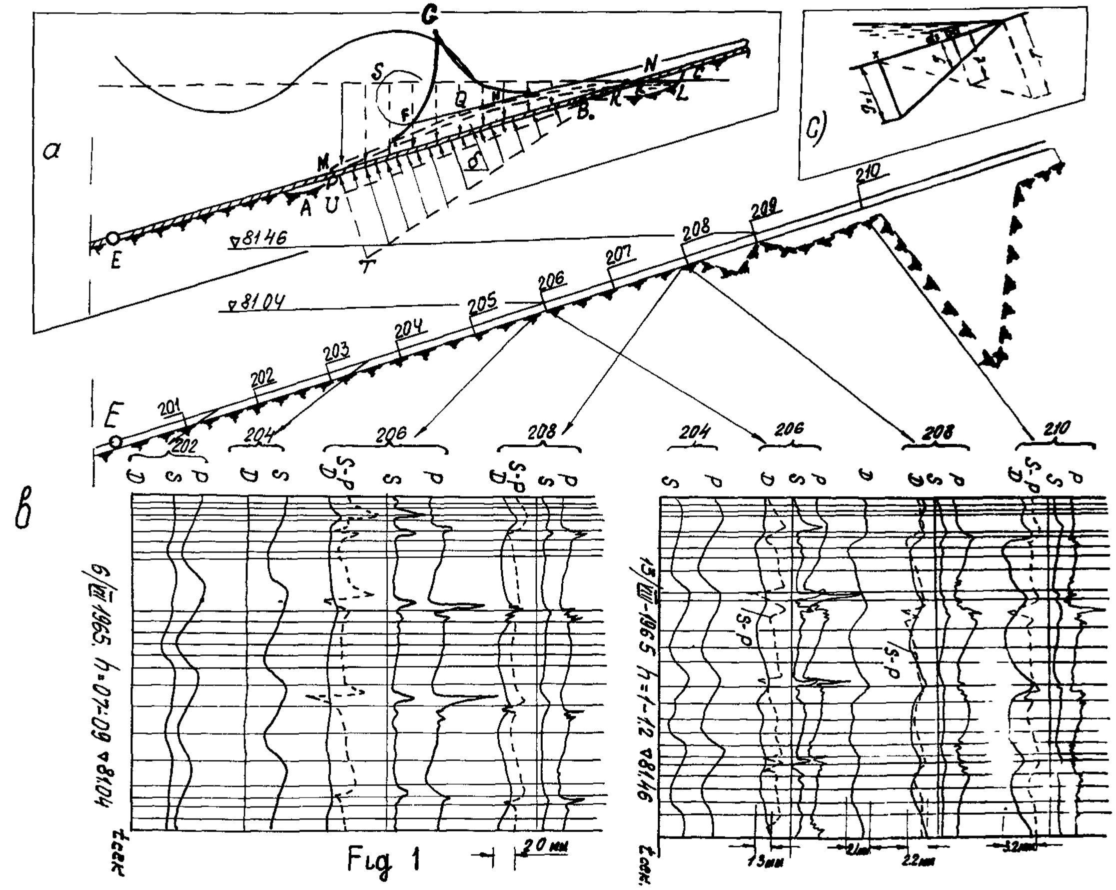

Fig. 1. Flexible screen under wave action. a) Scheme of revetment behaviour. b) Oscillograms of pressure P, uplift S and deflections D. c) Initial scheme for determination of slit width.

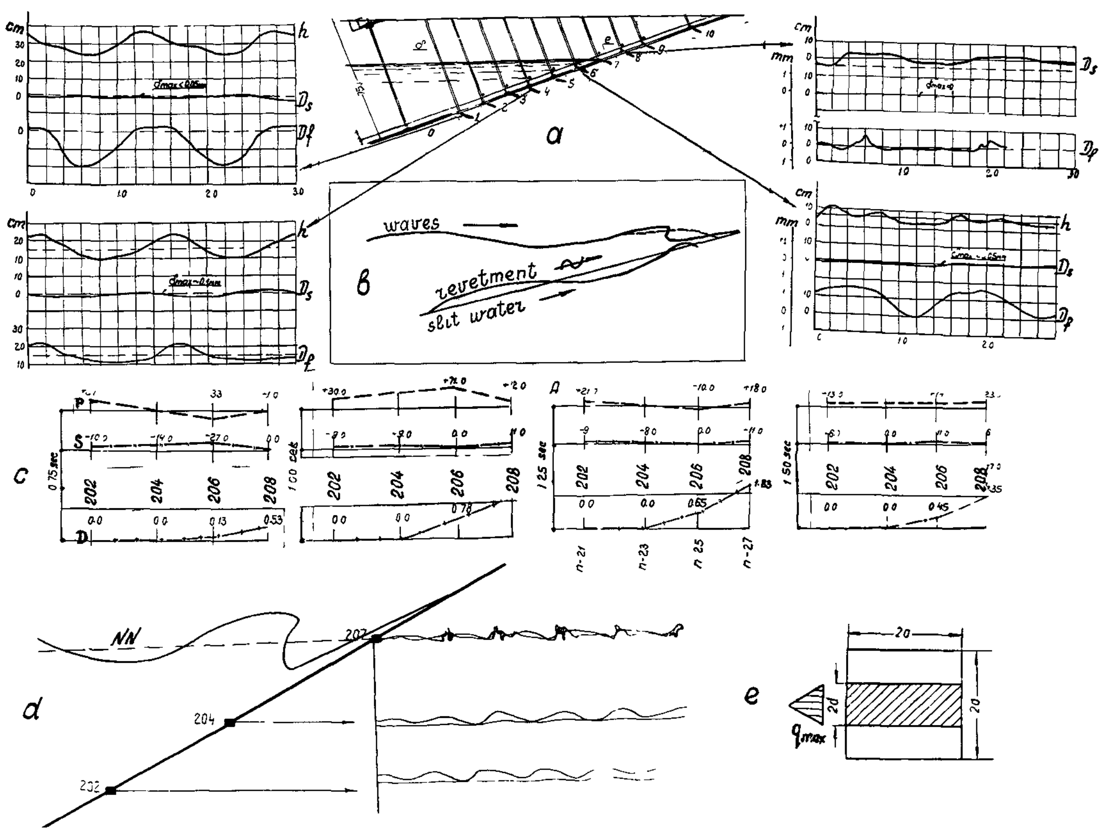

Fig. 2. Phenomena in slit between slab and soil. a) Experiments carried out by Yaroslvtzev for checking the theses of the flexible screen theory. h - wave, Df - lateral deflections with filter, D_s - the same without filter. b) Sinuous movement of the revetment in zone A. c) Sinuous movement in zone B. (Treatment of diagrams of fig. Ib on alignments). d) Uplift nature. e) Scheme of slab design on wave impact (load FGH, fig. Ia).

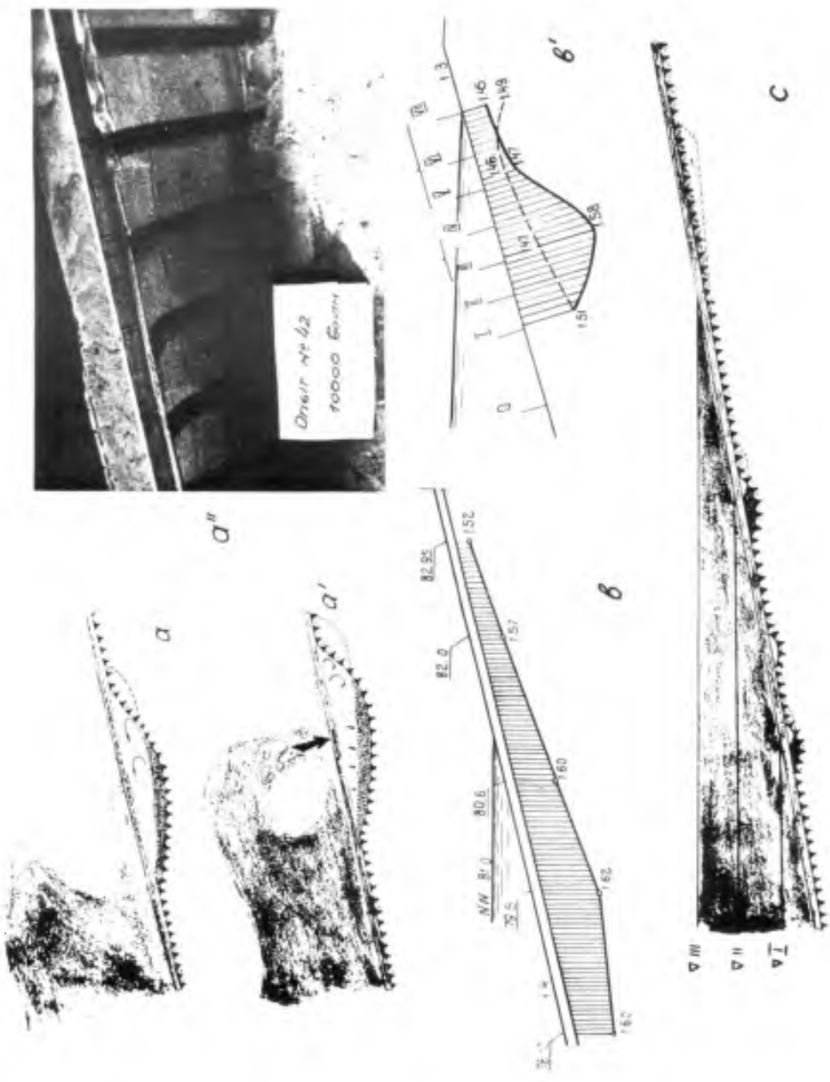

Fig. 3. Self-consolidation process. a) Soil particle movement at self-consolidation. b(Soil density after self-consolidation (b - prototype, b' - laboratory). Formation of depression V-VI-VII and hillock IV-III. c) Location of voids at successive variations of reservoir levels I, II, and III.

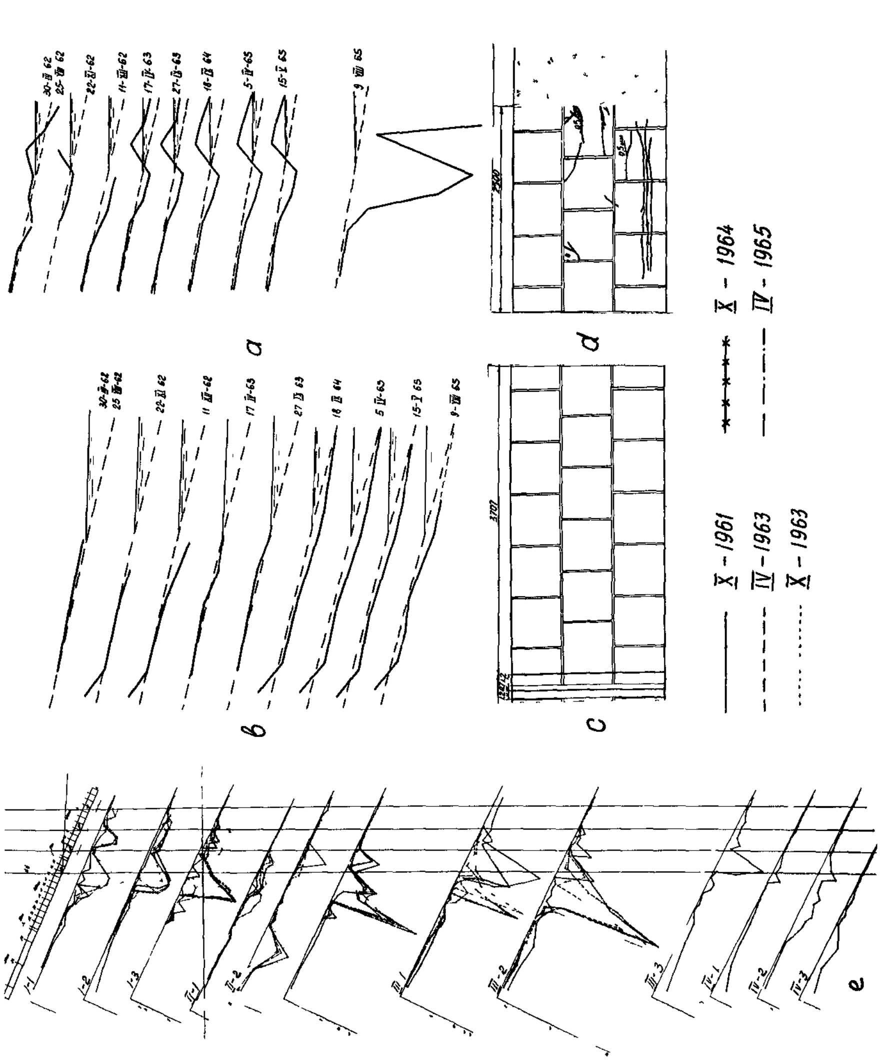

Fig. 4. One of the complexes of self-consolidation measurements. a) Levelling of slabs of 5 cm thick without filter. b) Levelling of slabs of 8 cm thick. c) Cracks in slabs of 8 cm thick. d) Cracks in slabs of 5 cm thick. e) Void dynamics in different thin slabs.

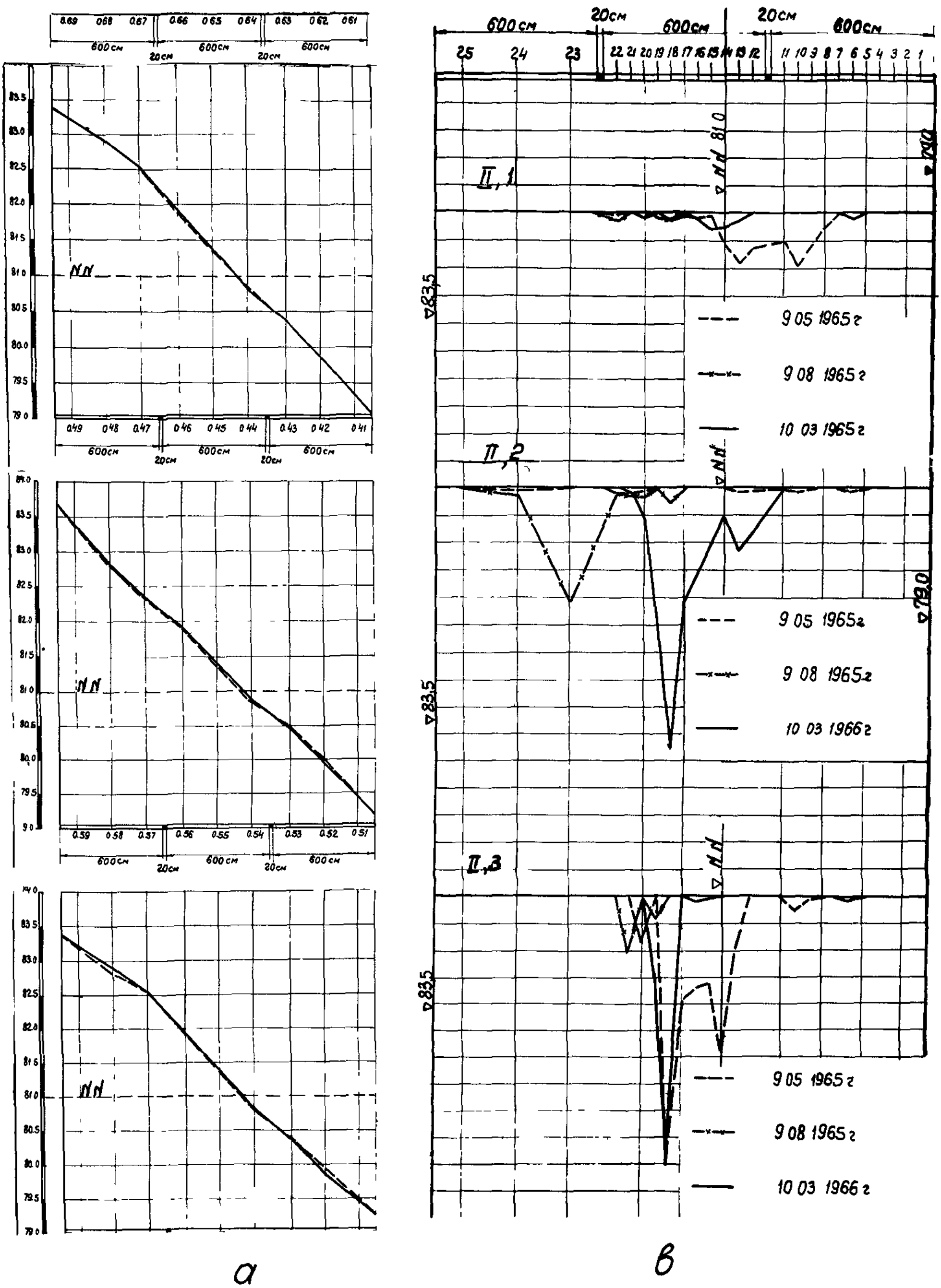

Fig. 5. Variation in revetment of 8 cm thick after lateral erosion of upper elevations.
a) Levellings. b) Voids.

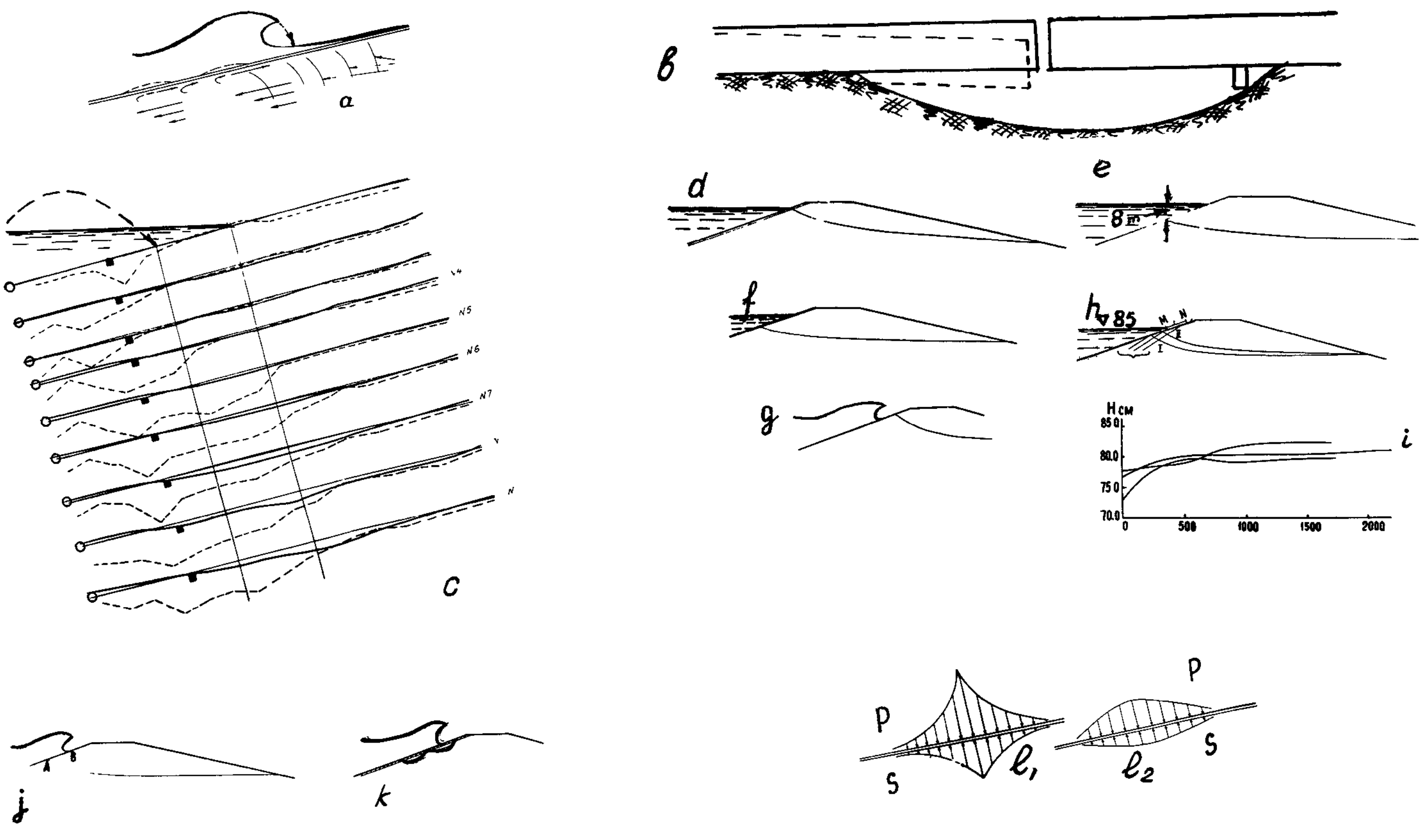

Fig. 6. Results of laboratory experiments of Department of Slope Protection against Wave Action in 1965. a) Closed circuit of ground water and silt water in zone A. b) Self-consolidation with dowel in the zone of maximum wave roll down. c) Erosion on prototype through joint with dowel. d-m) Revetment behaviour on water retaining structures (laboratory and prototype) (see the text).