On effects produced by tidal power plants upon environmental conditions in adjacent sea areas

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I ■ INTRODUCTION

Construction of a dam cutting off a part of marine basin, as well as the operation of the Tidal power plant (TPP), may result in a considerable transformation of parameters, structure and energetic characteristics of adjacent tidal oscillations. Therefore the correct assessment of anticipated power capacity, scope of building works needed and possible environmental consequences must be based not on the «natural» data of sea level ranges existing before the start of the building but on the data predicted by numerical modeling taking into account expected transformation effects. These effects must be especially significant when the planned TPP is of a scale great enough for the relevant geometric modification of the basin to be comparable to a substantial portion of local tidal wave length. Some large-scale TPP concepts have been advanced in Russia as potential prospects to be realized in future for the Bay of Mezen (White Sea) as well as for the Bay of Tugur and the Bay of Penzhina (Okhotsk Sea) [1, 2, 3, 4]. For the first two designs the areas of tidal basins detached by a barrage are envisaged to be about 2650 km^2 and 1800 km^2, whereas for the Bay of Penzhina two versions of the barrage position are proposed : the «northern» one with the tidal basin area of about 6800 km^2, and the «southern» when practically all the Bay with area of about 20 000 km^2 is supposed to be cut off. Whilst such designs are hardly realizable in the immediate future, the estimation of relevant possible effects on oceanographic conditions seems to be of some interest.

II ■ ESSENTIALS OF TRANSFORMATION

Some general and important transformation effects can be foreseen even before the modeling by considering the mechanism of transformation following from the long-wave nature of tidal phenomena. The most material of these effects caused by erection of a barrage can be principally studied using an elementary model of a gulf (fig.1a) having length L, constant width b and depth h and energy absorbing end at $x = 0$ (simulating an energy dissipation in the head of the gulf). Under natural conditions a progressive-standing wave motion exists in such a gulf as a result of partial reflection of a progressive tidal wave with amplitude A entering the gulf from the left. The resulting amplitude H and phase g distribution along the gulf can be described [4] as:

$$H = A\,(1 + 2r\cos\beta + r^2)^{1/2}$$

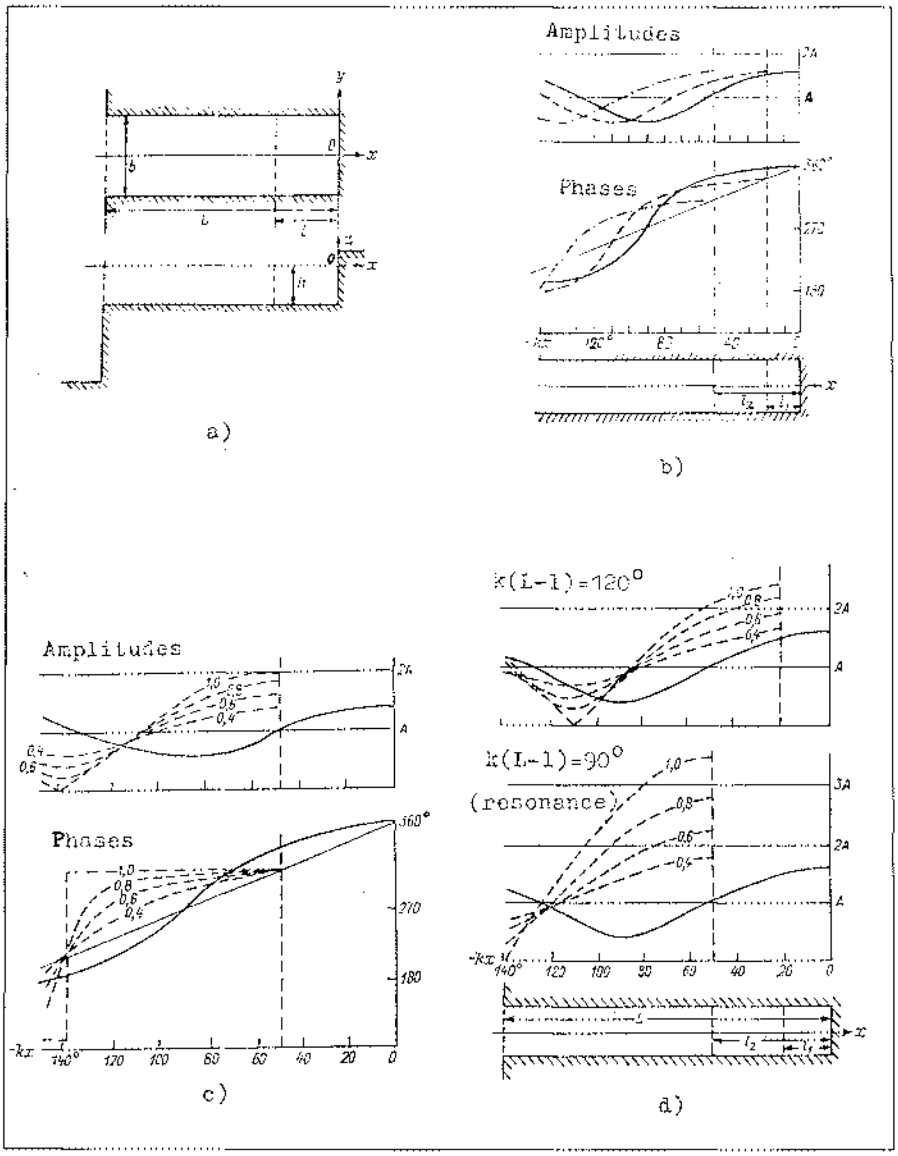
$$g^\circ = \mathrm{arc\,tang}\,\{\mathrm{tang}\,kx\,[(1 - r)/(1 + r)]\}\,; \qquad (1)$$

where $\beta = 2\,kx$ and r is a coefficient of reflection at $x = 0$ (solid lines in fig.1b). If a barrage is created at $x = -l$, the following consequences would take place :

1) *Reflection point shift.* The site of reflection is moved for a distance l from the gulf's head with the phase of reflected wave reduced by $2kl$ ($k = \sigma / \sqrt{g^\circ h}$ - is a wave number, σ and g being tidal frequency and gravity acceleration). It is seen from the Fig.1b (broken and dotted lines) that for $\lambda = \lambda / 2$ ($\lambda = 2\pi / k$ - tidal wave length) this effect leads to increase in resulting tidal amplitude upstream of the barrage.

Les effets produits par les usines marémotrices sur les conditions environnementales dans les zones bordant la mer

Les changements entraînés par la construction et l'exploitation d'une usine marémotrice (TPP) dans les mouvements des marées (amplitudes, phases, composition spectrale des oscillations du niveau de la mer, positionnement des zones extrêmes, largeur de la zone intercotidale, régime de cette zone, transport de sédiments...) peuvent être estimés sur la base d'un modèle mathématique. En général, les effets sont proportionnels aux dimensions de la zone barrée par l'usine. Les résultats présentés concernent les projets de la mer Blanche et de la mer d'Okhotsk.



1. Transformation of tide by a TPP dam in an idealized basin

a) Sketch of a gulf with the TPP dam location

b) Transformation of tide caused by change in position of tidal wave reflection with fixed reflection coefficient r = 0.6. Thin straight lines correspond to a progressive wave (r=0)

c) Transformation of tide caused by change in dissipation intensity. Reflection coefficients are given on curves

d) Transformation of tidal amplitudes caused by change in resonance characteristics of a gulf.

2) *Change in* the *basin dissipativity.* As a rule the barrage erection results in reduction of dissipativity by two causes : (*a*) owing to interception of usually shallow and dissipative gulf's head and its elimination from oscillatory process, and (*b*) owing to origination of an antinodal zone adjacent to the barrage with corresponding reduction of local tidal currents. Resulting oscillations approximate to a standing wave with amplitudes increasing in front of the barrage (anti node) but decreasing (currents increasing) at a distance of $\lambda / 4$ from the barrage (node). In Fig.1c the relevant transformation effects are shown for $k\lambda = 30°$ and dissipation corresponding to incident wave energy losses equal to 84%, 64%, 36% and zero (r equal to 0.4, 0.6, 0.8 and 1).

3) *Change in geometry and resonance tuning.* This effect can be manifested if the open boundary (at $x = - L$) of the gulf is characterized by an appropriate internal reflection (sharp change in cross-section, the shelf border) characterized by reflection coefficient r_L (the power minus index means that it refers to a wave traveling in negative direction). The first reflection of the incident tidal wave occurs now not at $x = 0$ but at $x = - l$ and the length of the basin determining the wave travel time and resonance tuning becomes equal not to L but to $L - l$. In a general way, the coefficient of reflection from the barrage r_b also differs from the 'natural' reflection coefficient r. As a result we obtain for transformed amplitude H_t and phase $g°_t$:

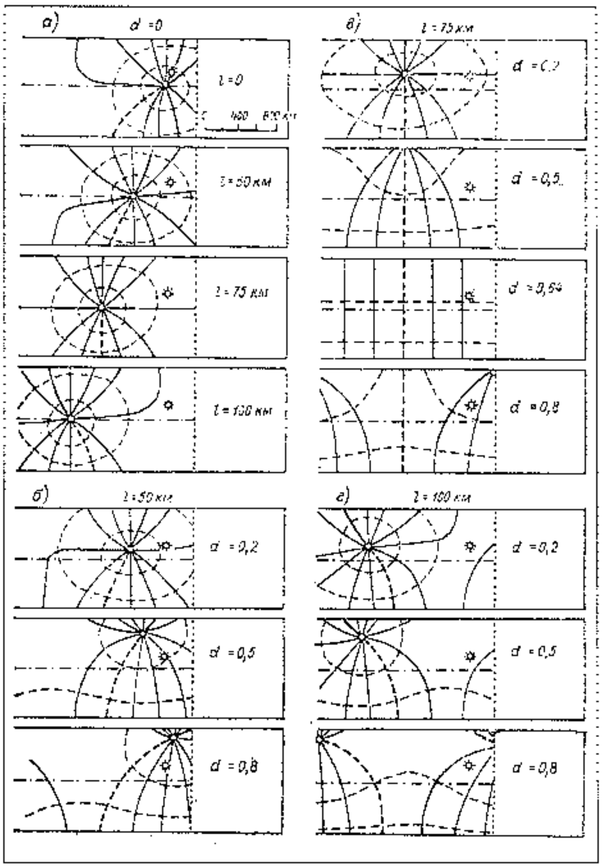
$$H_t = A\{[1+2r_b \cos 2k(x+l)+r_b^2]/[1 - 2q \cos 2k(L - l)+q^2]\}^{1/2} ;$$
$$g°_t = \mathrm{arc\,tang}\,\{[(1-r_b) \sin kx+2kl]/[(1+r_b) \cos kx + 2kl]\}; \qquad (2)$$

where $q = r_b . r_L^-$. In Fig.1d the influence of geometric (L-l) and dissipative (r_b) factors is shown on the amplitude and phase transformation effects (decrements) $\Delta H = H_t - H$ and $\Delta g° = g°_t - g°$ with given value of $r_L = 0.4$. It is seen from this figure that, depending on initial geometry of the gulf, the erection of a barrage can bring the length $L_t = L - l$ of the remaining part of the basin closer both to resonance $L_{res} = (2n+1)\lambda/4$ or to anti-resonance $L_{ant} = (n+1)\lambda/2$ values. The transformed tidal amplitude responds to that with either magnification or reduction. It is also seen that the greater this effect is manifested, the less are the energy losses due to either dissipation or radiation from the gulf.

As some above-mentioned concepts envisage creation of extremely large-scale tidal power plants with severed water areas of some thousands of square kilometers and expected powers of some tens of millions kW [1, 2, 3], a preliminary assessment of transformation effects may be expedient as applied to great ocean-like adjacent water basins demanding to take the Coriolis force into account. It can be shown that in a wide basin of depth h_o adjacent to a shelf of depth h_s with energy absorbing coastal border, the tidal oscillations can be, as a rough approximation, structurally represented by a combination of two oppositely directed (incident and reflected) Kelvin waves. The resulting tidal chart pattern is determined by the amplitude-phase relation between these waves (module and argument of coefficient of complex reflection from the shelf edge) depending in turn on the depth relationship h_s/h_o, the width of the shelf zone L_s and the energy absorption (dissipation) intensity $d = 1\text{-}r^2$ where r is again the coefficient of reflection at $x = 0$ (at the coastal border of the shelf zone). The two last parameters can be perceptibly modified if a great TPP is erected nearby the coast with a barrage detaching the offshore part of the shelf.

In fig.2 the influence of variable barrage positions and energy losses on the tidal chart pattern is given for a tidal constituent M_2 ($\sigma = 1.405.10^{-4}s^{-1}$) at the northern latitude 60° in a basin of width $b = 1200$ km and $h_o = 1000$ m with $L=350$ km, $h_s=62.5$ m. When allowing for the Coriolis force, we restrict our attention to the area of the basin beyond the material manifestation of the Poincare standing waves which are concentrated in the vicinity of the shelf edge inside the zone of order of $\lambda_o/4=\pi(gh_o)^{1/2}/2\sigma$, what permits to represent the resulting tidal oscillations as a combination of two opposing Kelvin waves. In fig.2a the effect of impermeable (without losses) barrage erected at distances $l=0;\ 50;\ 75$ and 100 km from the coast is presented. By the asterisk the «yardstick» position of the amphidromic point is denoted corresponding to the «natural» case when the incident tidal wave loses 50% of its energy after reflection from the coast line (simulation of natural coastal dissipation with $d=0.5$ or $r=0.707$) in the absence of barrage. It is seen that the effect of an impermeable barrage, firstly, puts the amphidromic point on the central line of the basin and, secondly, shifts it from the shelf for a distance far exceeding l. The figs.2b-d illustrate the effect of variable energy losses for relevant distances l showing that displacements of the amphidromic point from its «yardstick» position can reach hundreds and thousands kilometers. The pattern of co-tidal lines is especially sensitive to energy loss with $l=75$ km corresponding to resonance situation for the remaining part of the shelf. In this case the sufficiently great loss may even result in reversal of sign of summary reflection from the shelf zone [4] and interchanging positions of nodes and anti-nodes.

In Fig.3 the analogous amplitude/phase pattern transformation is presented based on comparison of two numerical solutions the first of which corresponds to the «Taylor problem» [5] (supplemented with a bottom friction), and the second one - to a similar problem differing from the first in that the gulf has an energy absorbing (or outward-radiating) portion of the reflecting border positioned at the right (with respect to incoming Kelvin wave) of it [6]. The geometry of the basin ($L=400$ km, $b=275$ km, $h=100$ m) is in a rough agreement with the Gulf of Shelikhov adjacent to the Bay of Penzhina the latter dissipating a great part of incoming tidal wave energy by admitting its energy-laden right wing. According to configuration of this geographical region and existing assessments of dissipation, the value $d=0.8$ was specified for the right one third of the reflecting border. As a result an amphidromic system is formed in the lower left part of the basin. The closing of the appendix-absorber by a impermeable barrier (specifying $d=0$ for all parts of the coast of the gulf) symmetrizes the picture of tidal chart putting the amphidromic point on the central line. In bottom fragments of fig.3 the characteristic features of transformation are shown demonstrating the amplitude amplification/reduction coefficients $\Delta H/H$ and phase positive and negative decrements Δg^o extremely pronounced in the vicinity of the nodal zone and resembling in combination a clubs figure with $\Delta H/H$ and Δg^o opposite areas arranged in pairs lengthwise and crosswise of the nodal line. It is also seen that the negative ΔH area, disposed on the right side, is significantly less in size than the positive one.



2. Influence of barrage position (l) and absorption intensity (d) upon tidal chart pattern in adjacent ocean-like basin. High-waters and low-waters for t=0 are designated with heavy and dotted co-tidal lines. Position of the «natural» amphidromic point (with l = 0, d = 0.5) is indicated with an asterisk.

III ■ PREDICTIVE MODELING

The implementation of mathematical modeling for prediction of expected transformation of tidal characteristics was started about twenty years ago. By now, a fairly great number of predictive tidal models are developed and realized [7, 8, 9, 10 et al.]. Some estimates of transformation related to large-scale TPP concepts proposed for the Bay of Mezen, the Bay of Tugur and the Bay of Penzhina are presented below. The relevant areas are shown in figs.4 and 5.

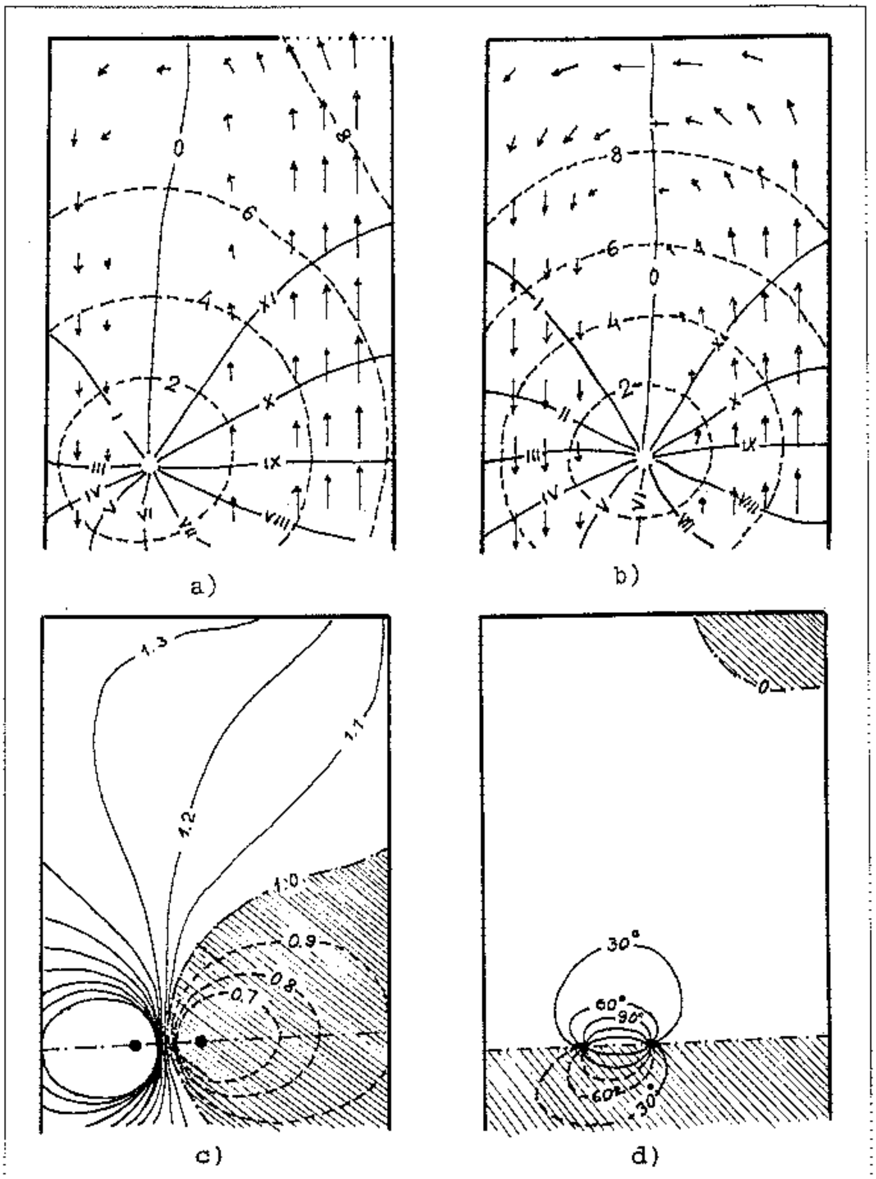
3. Characteristic pattern of amplitude and phase transformation in a rectangular gulf simulating the Gulf of Shelikhov as responded to cessation of energy absorption on a part of the boundary.

a) and b) Tide with and without energy absorption

c) Transformation of amplitudes (ΔH/H)

d) Transformation of phases (Δg°).

Tidal energy horizontal flux is also given.



3.1 Bay of Mezen

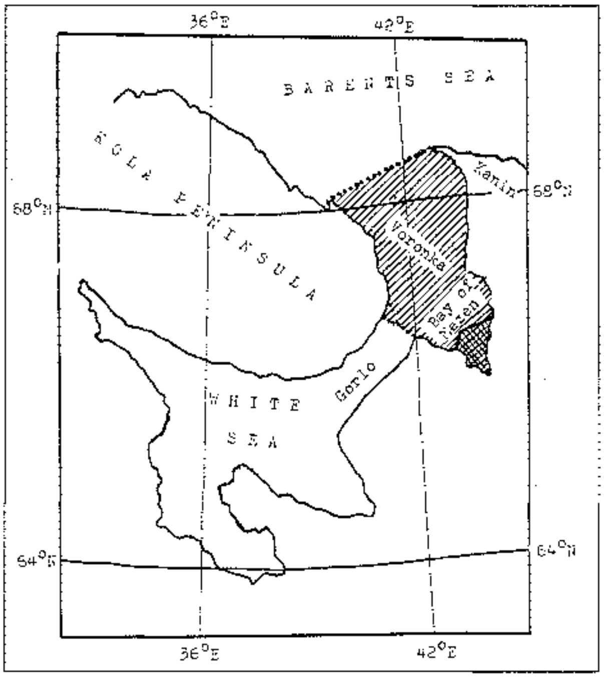
The tides in the Bay of Mezen may have the range reaching 10 m and are of nearly pure semi-diurnal type what makes it possible to restrict the consideration only with the M_2 constituent determining the principal features of summary tidal oscillations in this region. The modeling was performed basing on D. Greenberg's method [8] with the use of the nonlinear vertically averaged hydrodynamic shallow water equations which are to be integrated numerically on a staggered finite-difference grid [9]. The boundary conditions of different types have been employed corresponding :

(*i*) to the coastline (including in turn the «fixed non-permeable boundary» and «moving boundary», allowing for the flooding and drying of inter-tidal zone, versions) ;

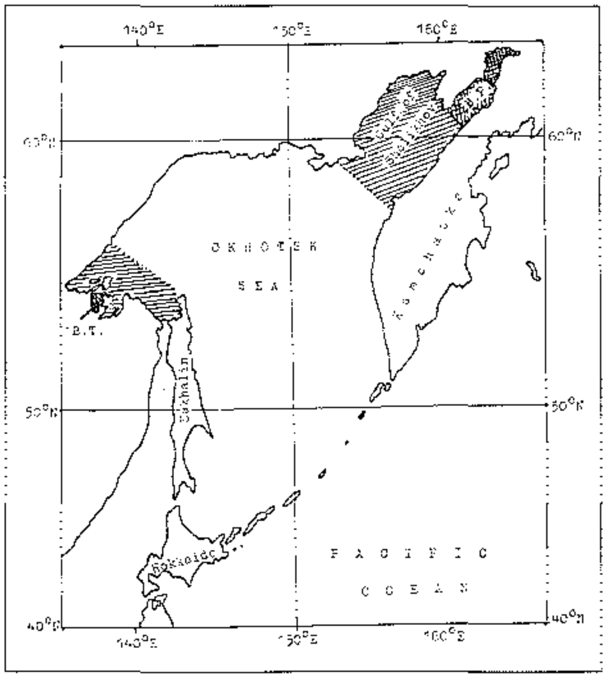
(*ii*) to the open or «liquid» boundary where either specified values of tidal oscillations (sea surface displacements ζ or current components u, v) or so-called «impedance» condition (prescribing not ζ or u, v, but a certain relationship between them) are to be set ; and

(*iii*) to the TPP barrage with specification of the discharge regime through the generating units and sluices or with the non-permeability condition in case of a blind dam. The model area covering the Bay of Mezen with the Voronka region and incorporating the position of the barrage with the site of the tidal station on it is shown in fig.4.

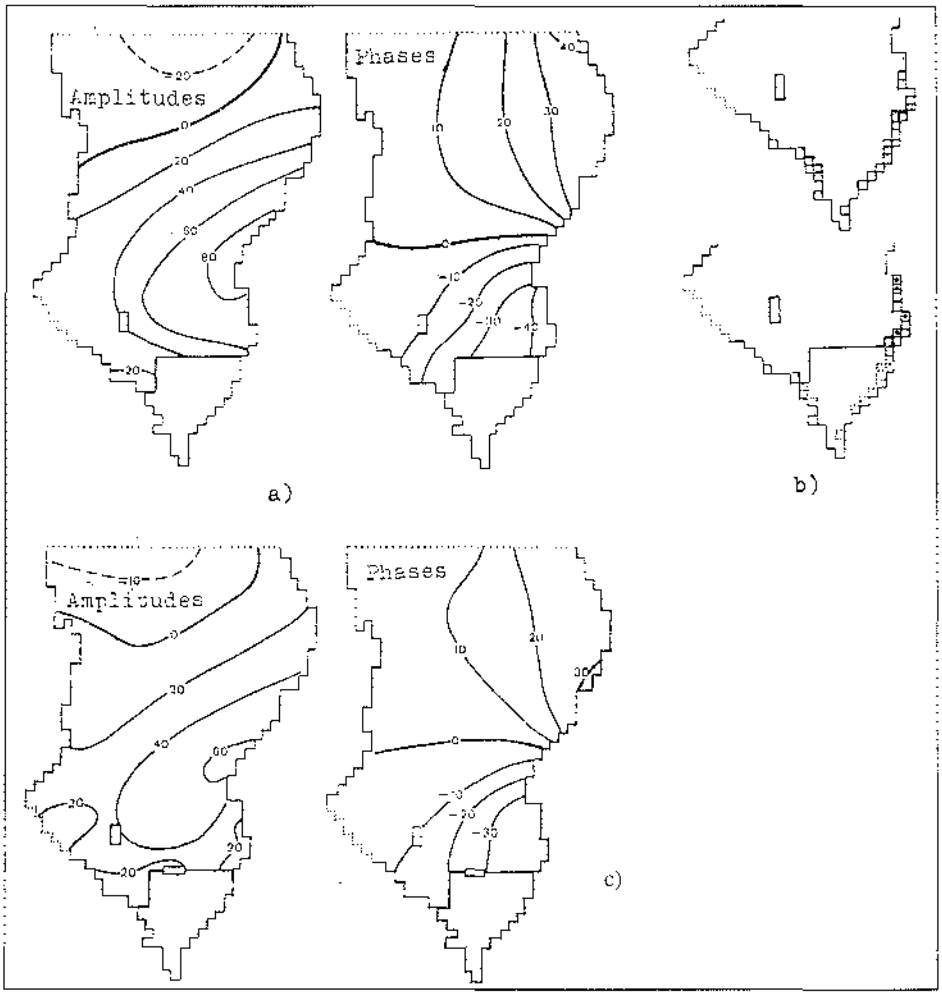
In fig.6 the transformation of amplitudes and phases of the M_2 tidal constituent (predominating in this region) caused by a blind dam and a barrage with a discharge regime specified for one-side «ebb operation» is presented. It follows from this assessment that the erection of a dam would result in rise of tidal amplitudes in the most part of the area considered with the increase greater in the eastern part. The transformation of phases is also greatest in the eastern part exceeding there one hour and with distinct separation into zones of positive and negative increments. The modified pattern of tidal oscillations determines the changes in inter-tidal zone shown in fig.6b. The detachment of the head of the Bay of Mezen excludes a considerable portion of this zone - about 435 km^2 of the total area 715 km^2 - from the area exposed to tidal oscillations (the situation inside the tidal basin, where the changes have very specific character, is not considered here). At the same time certain increase in the



4. Mezen TPP modeling area in the White Sea.
Slant hatching - modeling area,
Cross-hatching - detached tidal basin.



5. Modeling areas in the Okhotsk Sea
BT - Bay of Tugur,
BP - Bay of Penzhina.
Slant hatching - modeling area,
Cross-hatching - detached tidal basin.



6. Transformation of M_2-tide in the Bay of Mezen caused by the TPP.

a) Transformation by a dam of amplitudes (differences in cm) and phases (differences in deg.),

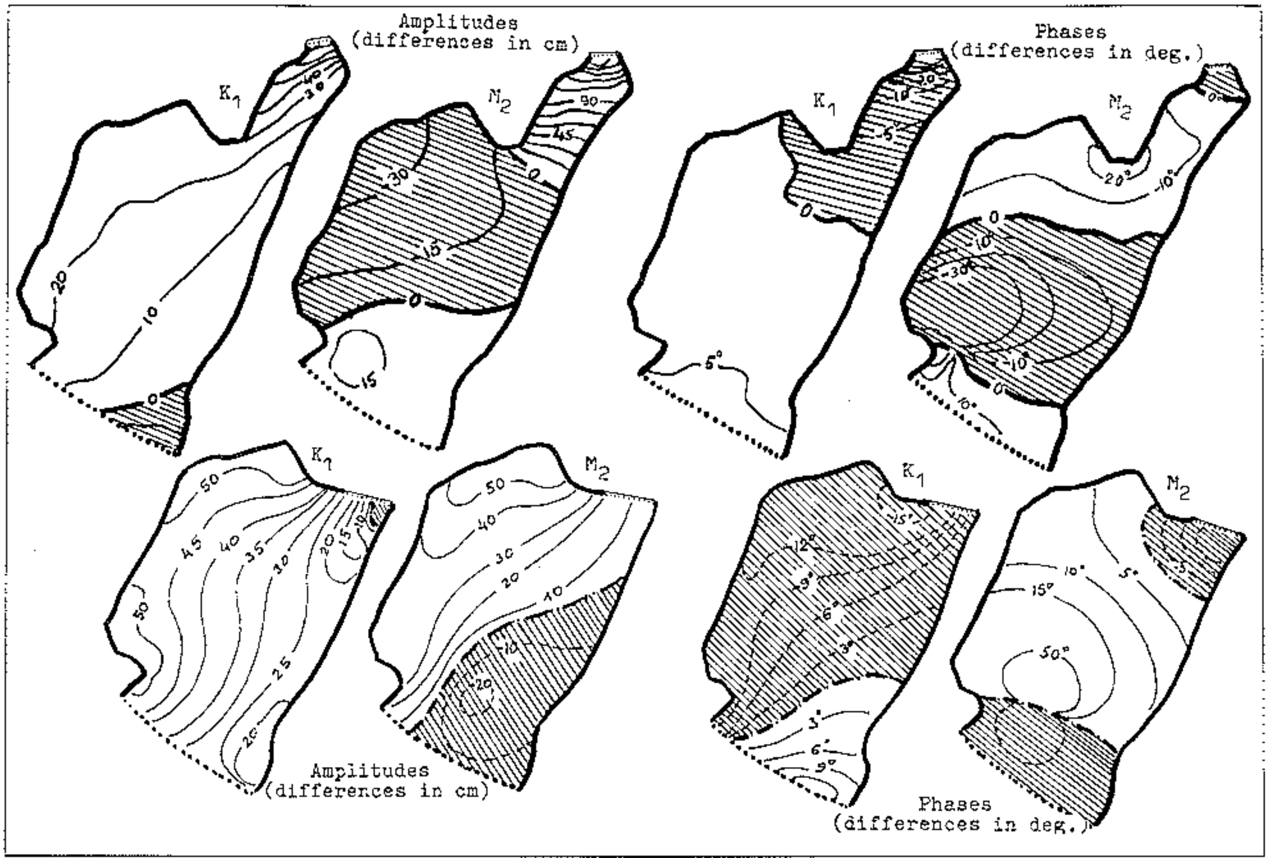
b) Changes in position of inter-tidal zone caused by a dam.

□ a mesh of inter-tidal zone under natural conditions

⬚ mesh excluded from flooding/drying process

☲ new inter-tidal mesh.

c) Transformation by a barrage with TPP in operation.



7. Transformation of tidal constituents in the Gulf of Shelikhov.
Top - effect of the northern dam,
Bottom - effect of the southern dam.

inter-tidal zone area of about 124 km^2 takes place mainly in the region of amplitudes amplification near the eastern coast. Effects produced by a barrage with operating units and sluices are generally similar to those caused by a blind dam but all the changes are manifested a little slower. Additional disturbances produced in oscillations by the TPP action are of secondary importance being restricted within the immediate neighbourhood of the barrage. It is a general rule remaining valid for all the numerical experiments fulfilled in relation with the TPPs under consideration.

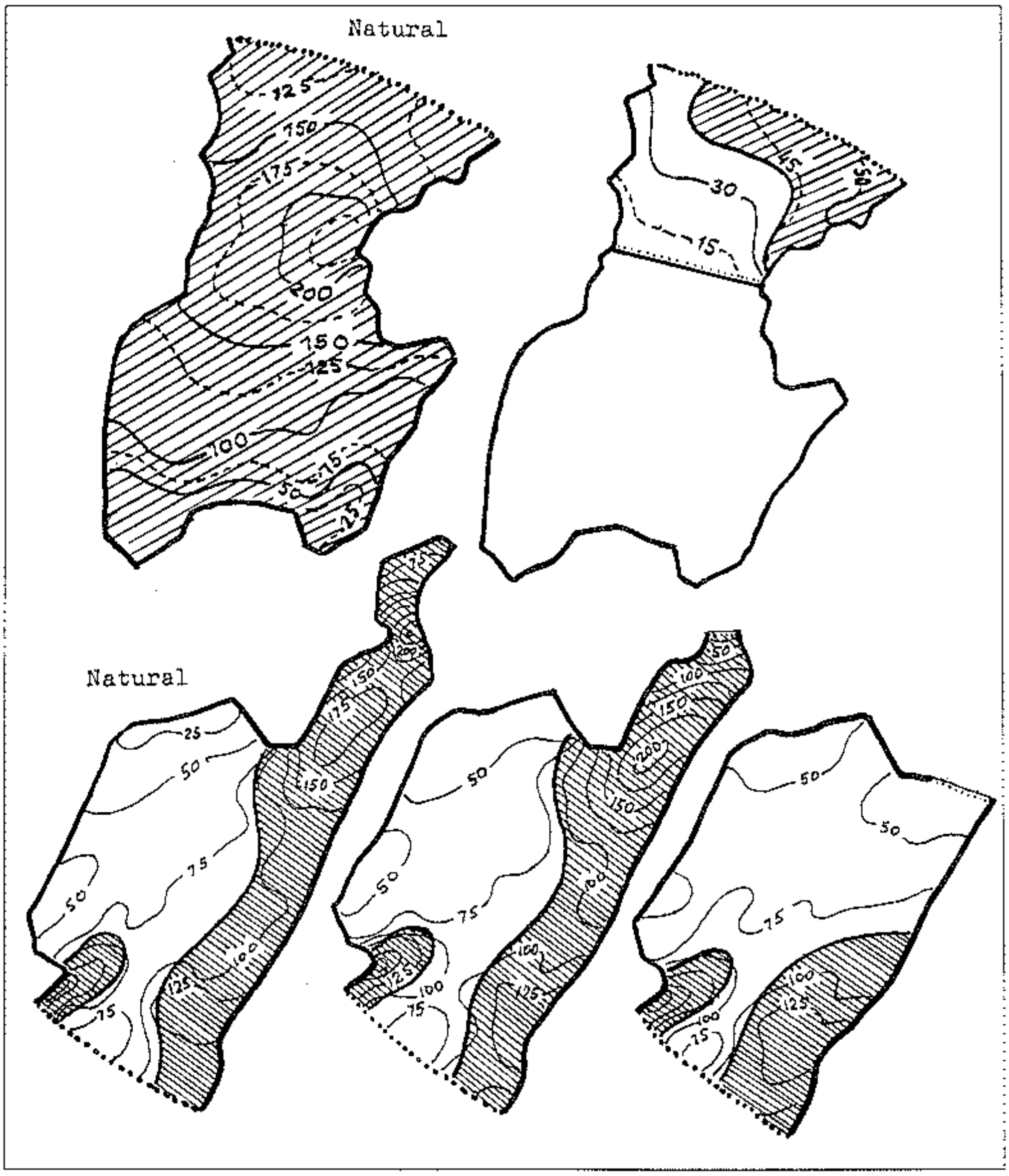
3.2 Bay of Tugur

Though the tidal oscillations in the Bay of Tugur (their range reaches 9 m) also belong to the semi-diurnal type, the role of diurnal components is not negligible and the modeling must include the combination of a number of principal constituents. Actually, 10 principal constituents have been taken into account when modeling. For this basin the method of curvilinear coordinates have been employed permitting to improve the approximation of natural boundaries by coordinate lines and to get higher resolution for regions of special interest. The main subject of matter was the transformation of the summary tide by a dam erected (in accord with the existing concept) in the narrowest part of the Bay bearing in mind that the dimensions of the Bay of Tugur are much smaller than the local length of tidal wave.

As would be expected, the modeling showed that the damming brings to arising of the anti-node area in front of the barrage with an increase of the amplitudes and decrease of tidal currents. The local phase decrease also takes place meaning that high and low waters would occur some earlier due to the dam. The special attention has been paid to effects touching on residual tidal currents and tidal mixing. It is apparent that the residual currents were considerably reduced with their maximum velocity dropping from 13 to 2 cm/s close to the dam. As for the tidal mixing, the calculation of Simpson-Hunter criterion $log_{10}(h/V^3)$ [11] intimated that the reduction of tidal currents from 2.4 m/s to 15-20 cm/s in the vicinity of the dam would result in local decay of tidal mixing and so the formation of a density stratified area becomes quite probable (fig.8).

3.3 Bay of Penzhina

In the tidal oscillations in the Bay of Penzhina (BP) and adjacent Gulf of Shelikhov (GS) the diurnal components dominate over semi-diurnal ones and the type of local summary tide is generally qualified as diurnal with maximum range reaching about 13 m. Attempts to assess the consequences of supposed TPP creation in the BP have been undertaken repeatedly with the modeling based on D. Greenberg's method in the 70-ies and 80-ies [12, 13, 14]. Recently some new results were obtained by using the curvilinear coordinates technique [6] applied to the united BP+GS region as well as to the entire Okhotsk Sea what permitted to study the transformation effects and to trace the range of their action over vast areas beyond the nearest proximity of



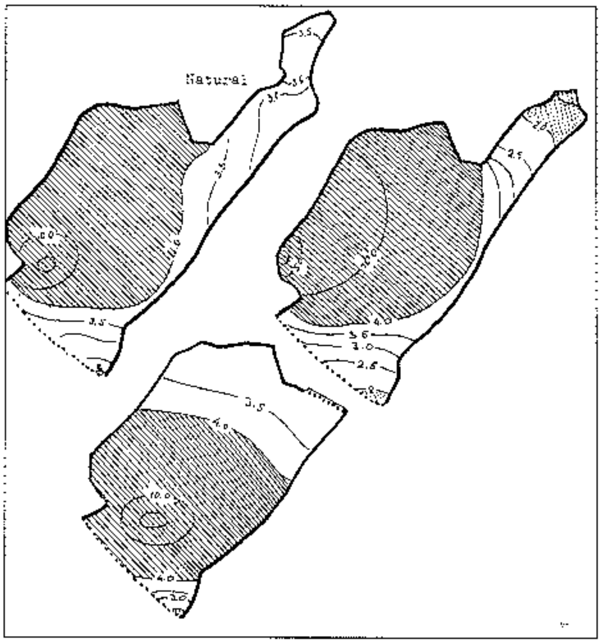
8. Transformation of tidal mixing
Maximum tidal stream velocities (in cm/s) are given (with isolines) as well as supposed mixed (hatched) and stratified (white) zones.
Top - Tugur Bay, Bottom - Gulf of Shelikov and Penzhina Bay.

the TPP dam. The numerical experiments were fulfilled both for summary tide and for separate tidal constituents to facilitate the physical interpretation of results. In this relation, the M_2 and K_1 constituents are discussed below.

The consideration of the amplitude/phase modification (fig.7) makes obvious the great role of the Coriolis force in the mechanism of local tidal regime formation. The character of effects in case of southern version of the dam is structurally quite similar to that displayed in the fig.3 which represents the principal features of transformation caused by the closure of an energy sink placed on the «right hand» side (as regards the incident Kelvin wave) of the reflecting buttend boundary of a gulf. Like in right-angle basin considered above, the positive change (increase) is arranged to the left-hand side of the outside tidal basin exceeding 0.5 m for both the tidal constituents. The distinctive feature of the M_2 constituent is the negative change area occurring on the right-hand side of the GS with extreme values at a distance of about a quarter of local tidal wave length from the dam, i.e. in the nodal zone. As the diurnal tidal wave is twice longer than the semi-diurnal one, the similar nodal line for the K_1 constituent has to be situated much farther from the dam and so the «negative» zone for K_1 is displaced far long to the south-eastern part of the Okhotsk Sea (fig.10) adjacent to the Kuril Island chain with its size and distance from the dam much larger comparing to M_2 because not only of difference due to periods, but also through larger depth and local λ value. In case of northern position of the dam the semi-diurnal tidal component seems to be more responsive than the diurnal one, what can be explained by the resonance effect similar to that shown in fig.1d. This effect, resulting in considerable amplification of M_2 amplitudes within the resting part of the Bay of Penzhina, provides also the total decay of the semi-diurnal wave reflection from the BP due to the phenomenon similar to «clearance» occurring on application of an antireflection coating in optics.

In fig.8 some effects connected with transformation of tidal mixing are shown. Position of mixed and stratified areas, as well as the frontal zones separating them, can be materially changed due to transformation of tidal currents field. This result refers to tide combining ten constituents of different periods.

Different response of tidal constituents to dam construction brings to transformation of spectral structure of oscilla-

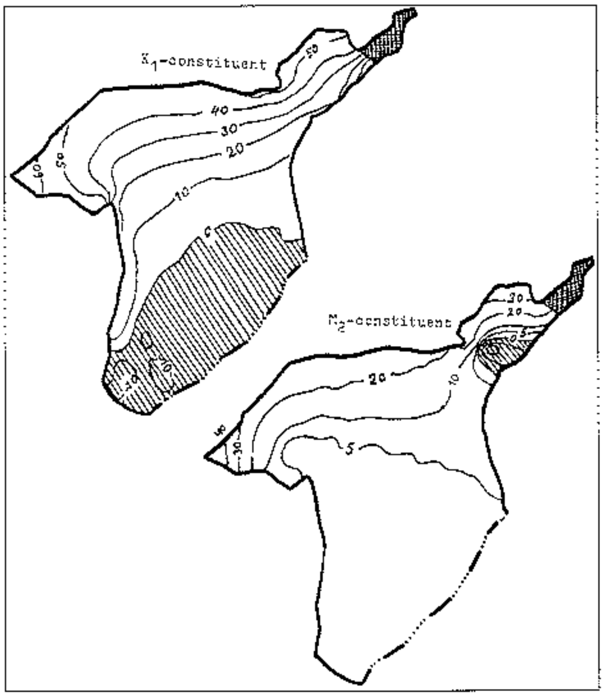


9. Transformation of tidal types (spectral structure) in the Gulf of Shelikhov and Penzhina Bay caused by northern and southern dams. Isolines of tidal type criterion $D = (H_{K1} + H_{O1}) / H_{M2}$ are given,

«regular» diurnal type

«irregular» diurnal type

«irregular» semi-diurnal type.



10. Transformation of tidal constituents in the Okhotsk Sea. Differences (in cm) of amplitudes caused by the southern dam in the Penzhina Bay are given.

positive differences,

negative differences,

detached tidal basin.

tions manifested in modification of the «type of tide» expressed as parameter $D = (H_K + H_O) / H_M$. In fig.9 it is seen that the relevant modification also may be of sensible amount especially in connection with resonance effects in case of northern location of the dam. Effects of this sort may be of particular importance for coastal areas affecting to life regime of organisms inhabiting inter-tidal zone.

The most of transformation effects considered here correspond to general rules treated above what facilitates the interpretation of results obtained by the numerical modeling.

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