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RELATIVE CHANGES OF THE BLACK SEA LEVEL AND IMPACT OF ABRASIVE SHORE PROCESSES

ABSTRACT: SHUISKY Y.D., *Relative changes of the Black Sea level and impact on abrasiveshore processes.* (IT ISNN 0391-9838, 1999).

Most of modern prognosis point to the catastrophic rise of the World Ocean level by the end of the 21th century. In future a number of negative consequences are connected with it, including growth of shore abrasion rates: tantatively by a power of the value. As the Black Sea is a part of the World Ocean, negative consequences are foretold for its shores as well. As a result one must be ready for a change of schemes of planning, management and development of shores in nearest decades which is connected with immense expenditures and risk of damage to natural systems. To check the given prognoses data of long-term observation of the level, waves, rates of cliff abrasion and other phenomena on several hydrological and meteorological stations on the Black Sea shores, mainly in it's Northern part within Ukraine were used. The connection between the average atmosphere temperature rise and level rise was found but these variables are not connected with the growth of wind and wave activity from the sea section of the horizon and with abrasion rates.

KEY WORDS: Sea level rise, Shore abrasion, Black Sea.

RIASSUNTO: SHUISKY Y.D., *Variazioni relative del livello del Mar Nero e impatto sui processi erosivi delle spiagge.* (IT ISNN 0391-9838, 1999).

La maggior parte delle recenti previsioni indicano la risalita catastrofica del livello mondiale degli oceani a partire dalla fine del XXI secolo. In futuro una serie di conseguenze negative saranno da porre in relazione con questo fenomeno, compreso l'incremento del tasso di erosione delle spiagge, probabilmente di un ordine di grandezza del valore attuale. Poiché il Mar Nero è una parte dell'oceano, conseguenze negative sono previste anche per le sue spiagge. Come risultato si dovrebbe essere preparati ad una variazione degli schemi di pianificazione, gestione e sviluppo delle spiagge nei prossimi decenni legata alle ingenti spese e al rischio nei casi di danneggiamento dei sistemi naturali. Per verificare questa previsione sono stati utilizzati i dati derivanti da osservazioni di lungo termine sul livello marino, sul moto ondoso, sul tasso di erosione delle falesie e su altri fenomeni registrati in differenti stazioni idrologiche e meteorologiche poste lungo le spiagge del Mar Nero, principalmente nella sua parte settentrionale all'interno dell'Ucraina. È stata stabilita la relazione tra l'innalzamento della temperatura media dell'atmosfera e quello del livello del mare, ma queste variabili non sono legate all'aumento dell'attività del vento e del moto ondoso provenienti dal mare aperto ed ai tassi di erosione.

TERMINI CHIAVE: Innalzamento del livello del mare, Erosione di spiaggia, Mar Nero.

INTRODUCTION

Optimization of rational nature usage on the coasts of different seas requires consideration of planning and management in the coastal zone must be worked out accordingly. In the given case natural concept of «coastal zone» is meant, i.e. environment of dissipation of sea waves on the submarine (nearshore) slope (i.e. from the the depth equal 1/3 of the length of the average stormy wave) and on the shore to the height of storm wave wash during setup and high tide).

At present information about essential changes of climate towards warming on the Globe is received. They cause natural restruction of water balance in the Ocean towards water mass increase. This natural restruction is increased by anthropogenous factor over and over to the extent when it acquires the features of disaster. The sea level can also rise in the same catastrophic way, which will lead to a number of negative consequences. Among such hypotetical consequences cliff abrasion rate growth, at least by a power of the value in comparison to the last decades of the 21th century as is supposed (Barth & Titus, 1984; Leatherman, 1989; Titus, 1990; Belyaev & *alii*, 1992; Kaplin & Lukyanova, 1992; Kaplin & *alii*, 1993) attracts particular attention. As a result essential damage can be done, taking into account high degree of industrial, agricultural and transport development of the Black Sea coast (fig. 1). To check this hypothesis in the coastal zone of the Black Sea (mainly within Ukraine) studying of the sea water balance,

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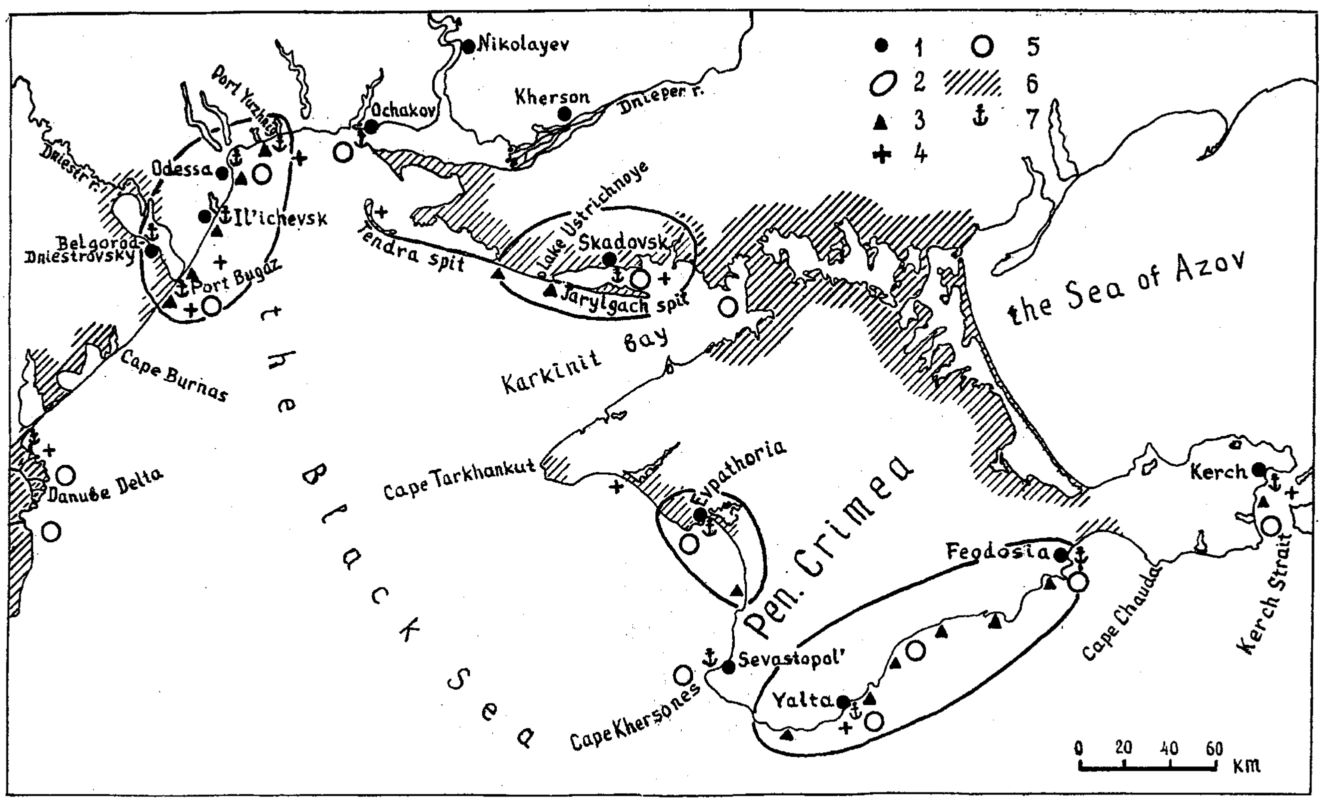

FIG. 1 - Main economical units on the Black Sea coast within Ukraine: 1) big and small cities; 2) recreational regions and areas; 3) shore protective structures; 4) places of sand mining on nearshore bottom; 5) fishering sites; 6) sections of very low shore (less than 2 m); 7) sea ports.

long-term changes of the level and air temperature, modern rates of abrasion, wind and wave regime, relief and tendencies changes was carried out, corresponding calculations were done.

Conditions of the Black Sea coast development are various. Reaction of shores on the possible level rise is determined by their geological composition, reight, supply of sediments and other reasons. Low shores with low wave energetic potential are most likely to be subjected to passive flooding. It seems that high shores composed by very hard crystalline and crystallized indigenous rocks practically will not change greatly, and catastrophic consequences do not threat them. The greatest changes are to be expected along low and moderately high shores composed by weak deposits and sedimentary rocks which are subjected to strong wave influence. Under the level rise impact in connection with «greenhouse effect» in future, this article is mainly dedicated to their development. Here the most important natural conditions in the Black Sea coastal zone, main features of shore dynamics, mechanism of abrasive profile development, modern tendencies of hydrometeorological regime (including the level changes) are considered, correlations of rates of cliff abrasional retreat and level fluctuations are found, calculation of impact of depth increase on abrasional rates is carried out.

CONTEMPORARY DYNAMICS OF COASTAL ZONE

General characteristics of the coastal zone

According to dynamic characteristics the Black Sea coastal zone is diverse. This diversity is the result of geological history of the sea basin and was inherited from previous epochs and stages, especially Pleistocene and Holocene. For this investigation it is important that shores be composed by indigenous rocks and deposits of different compressive strength, coastal cliffs and bluffs being of different height from 0.1-0.5 to 110-130 m. Prevalence of sediment deficit in the coastal zone is absolute (Shuisky, 1993, 1995).

In the process of possible the Black Sea level rise under the impact of «greenhouse effect» very low original coasts (< 2 m) can be subjected to passive flooding. It is connected mainly with the fact that wave energetical potential along them is very low, and therefore such sections cannot correspondingly react on relative level changing in conditions of acute sediment deficit. They are situated mainly in bays, harbours, lagoons and limans, and are seldom met on open even shores (fig. 1). Only in the region between the Danube delta and Bakal Spit the length of very low shores is equal 457 km, which corresponds to about 11% of the length of the Black Sea shores. If low shores in other regions are added, this potential will be longer than 20%.

In general, natural sea conditions are characterized by essential depth (in the average 1315 m) and aquatory area, which allows big waves to develop (Shuisky, 1993a). During storms (wave height h = 1.5 m and more) wave heigth reaches 3-7 m, maximum equals 14 m. The average duration of strong storms on sea constitutes 1300-1450 hours a year for a long-term period. This is enough for abrasive shores to be wide spread.

However, abrasion rates are essentially limited by geological composition of shores. About 20% of their length are composed by very hard rocks (mainly > 500 kg/cm^2), which practically are not destroyed even during very stormy years, which is shown by the diagram of figure 2. Such conditions are sure to influence abrasion rate change in future, when their increase under the impact of relative level rise is supposed. At the same time more than a half of contemporary cliffs are represented by low-durable deposits and sedimentary rocks (for instance, Quaternary talus, alluvial, deltaic, etc.), and abrasion rates on them are maximum. Also about 18% of the shore length are represented by modern wave accumulative forms (barriers, bars, spits, terraces) composed by non-indigenous sedimentary drifts. In conditions of sediment deficit (Shuisky, 1993a, b; Vykhovanets, 1993) the shoreline of these forms experiences long and steady retreat.

During last decades cliffs of different types and composed by deposits and sedimentary rocks of different strength are spread along 2,112 km of the Black Sea shore. This constitutes 47.7% of the total shoreline. In general, more than 62% of the shorelength are retreating in the average for a long-term period, but during especially stormy years about 74% can be subjected to operative abrasion, during non-stormy years about 38%.

Thus first of all the relief of the shores composed by extremely low-durable deposits and sedimentary rocks will react on the sea level rise. If is they that we are going to consider. According to the data of long-term instrumental records now rates of shore-abrasion of sandy and clayey cliffs constitute 1-6 m/year, of loessial cliffs 3-6 m/year, of cliffs composed by crystallized limestone and sandstone are 0.01-0.5 m/year, by eruptive rocks (andesite, tuff, tuff-breccia, diorite, etc.) not more than 0.2 m/year. Therefore the amount of wave energy in the coastal zone is sufficient for cliffs to retreat up to 6 m/year, and that is why in future, when according to the wide-spread hypothesis (Barth & Titus, 1984; Vellinga & Leatherman, 1989; Belyaev & *alii*, 1992; Kaplin & Lukyanova, 1992; Kaplin & *alii*, 1993) storm activity grows and sea level rises 2-3 m and more than the modern one such shores can be subjected to the greatest danger.

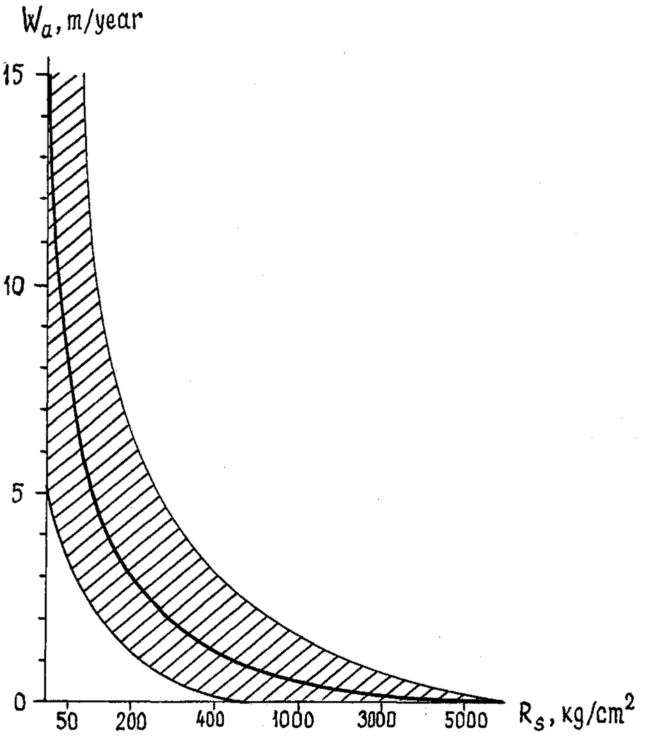

FIG. 2 - Diagram of dependence of average cliff abrasion rates (W_a, m/year) on the average strength of rocks and deposits (R_s, kg/cm^2) received by the results of natural experiments.

Mechanism of abrasional crossing profile development

Let us consider the mechanism of the crossing profile development of abrasive type coastal zone, which develops during current hydrometeorological regime. Most often it is described basing on the principal concepts of «Zenkovich-Bruun Rule» (Bruun, 1962, 1983; Zenkovich, 1946, 1967). Real development determined by drift balance change and beach size showed that in reality the given «Rule» is a specific case not typical for coastal zone of untidal seas (Shuisky & Musielak, 1991). Quickly retreating active cliffs develop in close connection with the dynamics of nearshore bottom and beach size (Shuisky, 1976, 1986), which is not taken into account by «Zenkovich-Bruun Rule». First of all cliff retreat always and synchronously takes place against the blackground of depth growth on the nearshore bottom. Sediments accreating as a beach at cliff base are not the sediments formed by cliff destruction on the point, where the given profile is situated, they come from the adjacent shore sections and from nearshore (submarine) slope.

During the process of abrasive profile formation waves are sculpturing nearshore bottom abrasive terrace. The width of this terrace can increase to the state which leads to essential extinguishing of waves, reduction of drift moving wave power, growth of beach size to the state of wide abovewater accumulative terrace, and then the cliff dies and shore cliff becomes stable.

However, in conditions of drift deficit within the Black Sea coastal zone, only single cases of contemporary formation of abovewater sediment terraces are met and in general this process is not typical. Of course, on the broad nearshore bottom abrasive terrace beach dimentions are greater than on the narrow one. But, in both cases sea slope of underwater terrace is erosed out because it is composed by low-durable deposits and sedimentary rocks. Wide beach covers cliff base and the longer part of the profile on the shore bottom, narrow beach allows wash out of the whole abrasive terrace and cliff. That is why at the stage of narrow beach quick formation of underwater abrasive terrace and accumulation of wide beach take place, and at the stage of wide beach wash out of sea slope of this terrace, decrease of its width and beach dimensions, cliff retreat activization begin. Such cyclic recurrence is typical for the Black Sea shores under consideration. Duration of the cycle constitutes from 15 to 35 years on different sections, i.e. during the time when relative level rise equals from 0.01 to 0.1 m. These values are within typical anemobarographical changes of the level constituting «noise background» of everyday the level state.

The shown mechanism of the coastal zone abrasive profile development in its intensity exceeds slow fluctuations of the level. These are phenomena of different types and refer to categories of different degree of natural systems organization. That is why abrasive profile is able to adjust to slow level change in contrast to the scheme describing «Zenkovich-Bruun Rule» (fig. 3). If the coastal zone is composed by hard rocks, cliff and nearshore bottom abrasion rates turn out to be less than the level rise rates. But in this case storm activity and level uplift growth cannot cause catastrophically quick shore retreat. At least abrasion rate measured by centimetres per year will not be of grave danger for people.

At last it is necessary to pay attention to quick retreat of shores composed by low-durable deposits and sedimentary rocks during the whole Neoholocene, i.e. when relative stabilization of the level in the natural development regime without influence of «greenhouse effect» and anthropogenous impact, took place. During this time cliff was continuously retreating with the rate of the same order as now. The total distance of cliff retreat in Neoholocene constitutes from 1 to 16 km in different regions where clayey and sandy sedimentary deposits occur (Nevesskiy, 1967). Thus shelves of abrasive type were formed (Zenkovich, 1967; Shuisky, 1993).

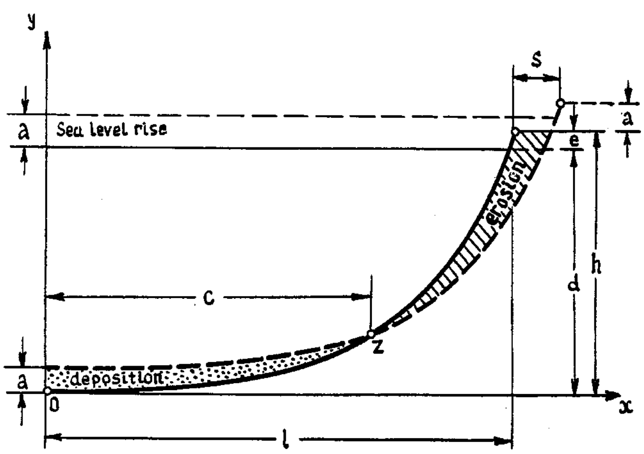

FIG. 3 - Scheme of reaction of see coastal zone crossing profile on sea level rise, reflecting main propositions of «Zenkovich-Bruun Rule» (Zenkovich, 1946, 1967; Bruun, 1962, 1983).

Correlation of cliff and bench abrasion

The sections composed by low-durable deposits and sedimentary rocks abrasive nearshore bottom (bench) spreads seaward to different depths, but usually not more than 21 m even along open oceanic shores (Bruun, 1962; Shuisky, 1976; 1995). On the Black Sea the maximum measured depth of wave abrasion beginning reaches 17 m, and minimum is 3 m, according to repeated long-term surveys (Shuisky & Vykhovanets, 1989). Most often real abrasion starts on the depths 7-9 m, according to the wave regime and geological composition.

If the bench was not subjected to abrasion and remained stable, during cliff retreat process nearshore bottom surface would coinside with sea aquathory surface. But it is not so. For instance at present in Sanjeiskiy Cape area the depth of 3.2 m is in the point where in 1921 the shoreline located (rate of the cliff retreat is 1.4 m/year). In Budaki area the depth of 3.8 m located in the place, where in 1931 was the shoreline (average rate of the cliff retreat is 3.4 m/year), and in Feodosiyskiy Bay the depth of 2.9 m is in the place where in 1928 the shoreline located (average rate of the clayey cliff retreat is 1.5 m/year). Correspondingly bench abrasion rate, without taking into account correction for relative level rise, equals 43.2 mm/year, 59.4 mm/year and 43.3 mm/year. Rates of relative level rise in these areas are within 2-6 mm/year. In these and other coastal regions it was observed that cliff abrasion rates increase when the bottom abrasion rates start to grow (Shuisky, 1976; 1986).

Such dependence is described in different forms and generalization of natural data allows to show it as rectilinear in simplified way. In the given case it becomes appeerent in conditions of direct, even, monotonously going down seaward profile of sea nearshore slope. It is expressed as:

$$I = W_a \cdot \cos \alpha \qquad (1)$$

and taking into account relative sea level changes K_y:

$$I_h = (W_a \cdot i_n) \pm K_y \qquad (2)$$

where I_h = bottom abrasion rate (m/year); W_a = rate of cliff retreat (m/year); i_n = inclination of nearshore slope profile (i = H/L) to the depth n. In comparison to the variable suggested by Belyaev and co-authors (1992), the one suggested by us is more perfect as it takes into account rates of nearshore bottom abrasion. It is very important in connection with the mentioned above process of nearshore abrasive terrace formation and change of dimensions of the bench along the cliff's base.

Formular (2) shows the connection of abrasion of bench and cliff, which made it possible to draw a nomogram to calculate bottom abrasion rates taking into account i_n (fig. 4). It gives abrasion rates of cliffs which are most often met on those sites of the Black Sea shore, which are composed by low-durable deposits and sedimentary rocks: having cliff abrasion rate W_a it is possible to calculate rates of bench abrasion I_h.

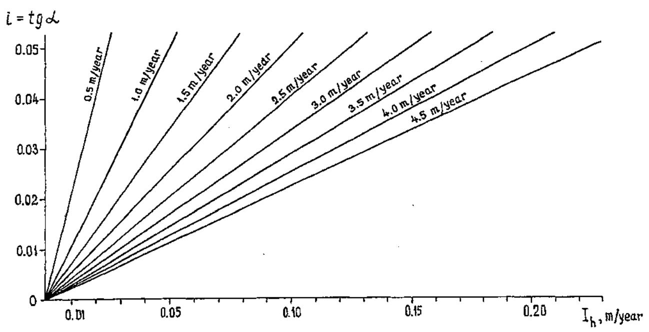

FIG. 4 - Nomogram for the determination of rates of clayey bench abrasion (I_h) in conditions of different inclinations of the nearshore bottom profile ($i = tg\ \alpha$) and cliff abrasion rates (W_a).

At the same time on the nearshore slope of accumulative forms processes of trend erosion are composed of short erosions and accretions, and as a result crossing profile curve on the whole displaces steadily parallelly to itself (Zenkovich, 1967; Shuisky & Vyknovanets, 1989; Vykhovanets, 1993). This displacement is accompanied by accumulation of drifts on the back side of narrow spits and barriers on limanic, lagoonal and bay sides (fig. 5b). The analysis of numerous similar profiles allowed to determine numerical values of wave abrasion on nearshore bottom, on the one hand, and accumulations on the back part of the profile, on the other hand. Algebraic sum of these two groups of numerical values gave magnitudes of resultative drift erosion (DA). Simultenously we took into account the rate of retreat of accumulative form shoreline from the seaside (W_a') on each of the studied sites. This allowed to get the diagrams of connection between DA and W_a'; as the example diagrams for the central site of Burnas Barrier and Eastern Tendra Spit are given (fig. 5a). In the given examples DA is larger on Burnas Barrier in comparison to Tendra Spit as on the Burnas crossing profile is steeper, has a concave form, the depth of abrasion start is 25% deeper, real retreat rate is 30% higher.

Thus intensity of deformations of indigenous relief and sediment layer is several times higher (up to a power of the value) than rates of sea level change on indigenous abrasive sites and is one-two powers of the value higher on accumulative forms. This means that the sea level rise with the rate equal millimetres a year is accompanied by coastal relief deformation on the value measured by centimetres and metres per year. Between abrasion rates and relative level change there are so many intermediate links that they can practically exclude direct connection between W_a and K_y. That is why growth of abrasion rates adequately to the level rise is unlikely, even with the rates determined as catastrophic (up to 15-20 mm/year, according to many authors). Not without reason on the reservours of Ukraine, where clay-sandy soft sedimentary rocks are spread and where the level grows immediately on several metres abrasion profile reached the stable state during 5-20 years.

As to accumulative forms they react on storm activity change and relative level change more sensitively, because

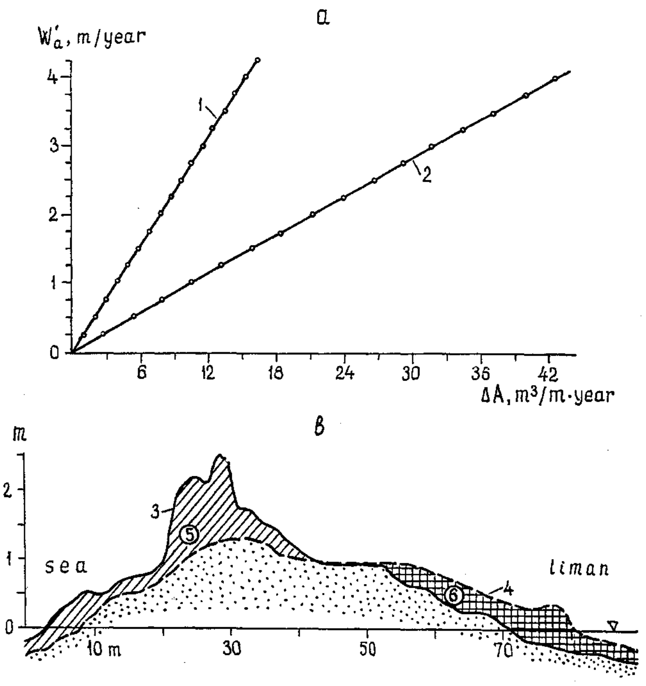

FIG. 5 - Dependence of the average quatity of washed away drifts (ΔA) on the average rate of accumulative form shoreline retreat (W_a') in the process of displacement of nearshore slope crossing profile form: a) diagrams of dependence of DA on W_a' (1 - Eastern side of Tendra Spit, 2 - central site of Burnas Barrier); b) illustration of displacement of the profile of Budaki Barrier abovewater part (according to repeated surveys: 3 - in August 1995, 4 - in December 1995 after two heavy storms in November and December); 5 - erosion; 6 - accretion.

of close interaction of their abovewater and underwater parts, because they are composed of loose and soft sedimentary strata. Storm activity of various strength secures formation of protecting mechanism of preservation and dynamical stability of spits, bars, barriers (Shuisky & Vykhovanets, 1989; Vykhovanets, 1993). The main element of this mechanism is growth of the back shoreline (figure 5b, *6*) simultenously with the nearshore submarine slope retreat, because from 20 to 45% of the sediment washed off the marine profile are spent on the back shoreline accretion. In addition, during gales and corresponding setup the highest part of barriers, bars and spits is erosed off as well. But the stormy profile (fig. 5b, *4*) is very quickly restored, during 0.5-1.5 years, and a ridge of foredunes appears again (fig. 5b, *3*).

Naturally, rate of height regeneration of accumulative forms during such a short time is much higher than of relative level rise during the same time. Therefore, such process is quicker and that is why the height of accumulative forms will grow together with the level rise (even with the rate 15-20 mm/year). This very clearly process took place during Holocene (Nevesskiy, 1997) and now the thickness of contemporary accumulative forms can reach up to 40-45 m, inspite of the fact that during some stages of Holocene the speed of the relative Black Sea level rise was higher than 18-24 mm/year. Apparently, values of erosion of accumulative form submarine slope (fig. 5a) were fully compensated by the supply of drifts from bottom to coastal sources during even such high relative rates of the level rise.

It is necessary to underline once again that everything said here refers to those sections of the coastal zone which are composed by loose and soft deposits and low-durable sedimentary rocks.

MODERN TENDENCIES OF HYDROMETEOROLOGICAL REGIME CHANGE

Rates of indigenous cliff retreat are most closely connected with the wave energetic potential of the coastal zone. As the wind type is the main type of the sea waves, wind velocities are of primary interest. Growth of storm activity in the end of the 21th century is linked with the air temperature rise and air circulation intensity (Barth & Titus, 1984; Vellinga & Leatherman, 1989; Belyaev & *alii*, 1992). The sea level rise in future is determined as synthetic factor of abrasive shore development (Kaplin & Lukyanova, 1992; Kaplin & *alii*, 1993).

At present it is a generally accepted opinion that burning of fossil fuel causes formation of «greenhouse effect». As a result the average annual temperature of the over land air grows: during last 100 years it increased by 0.5°C (Budiko, 1972; Golitsyn, 1986) in the northern semisphere, especially from the middle 60's of the 20th century. This tendency takes place on the Northern coast of the Black Sea as well. On stations Odessa, Skadovsk, Evpatoria and other the average climatic air temperature grew by 0.2-0.3°C during 1960-1995.

Air temperature growth was accompanied by the change of wave regime. During last 15 years on Il'ichevsk station the average wind speed decreased from 4.2-4.3 m/sec to 3.2-3.4 m/sec. At the same time during this period strong (> 15 m/sec) and maximal (18-26 m/sec) winds a little increased. But this took place owing to the decrease of speed and reocurrence of winds of southern directions, causing wave storms and owing to the growth of northern (from land) wind role. Similar regularities were observed on stations Vilkovo, Odessa, Ochakov, Genichesk, Evpatoria, etc. Thus rise of air temperature in over land layer is accompanied by general decrease of wave activity in the coastal zone. This was confirmed by the calculation of seasonal and annual values of wave energy during the period from 1960 to 1988, from 8-11 to 4-7 wave energy units. Correspondingly (fig. 6), rates of abrasion decreased on the majority of experimental sites, composed by soft and low-durable sedimentary rocks. Such regularity is opposite with respect to generally accespted one, and relative level rise is not correlated with the change of the average wave activity.

Besides, the calculated annual values of wave energy (E, t·m/year) allowed to compare them with the annual values of abrasion rates (W_a, m/year). When the average values of energy constitute less than 5 t·m/year, actually

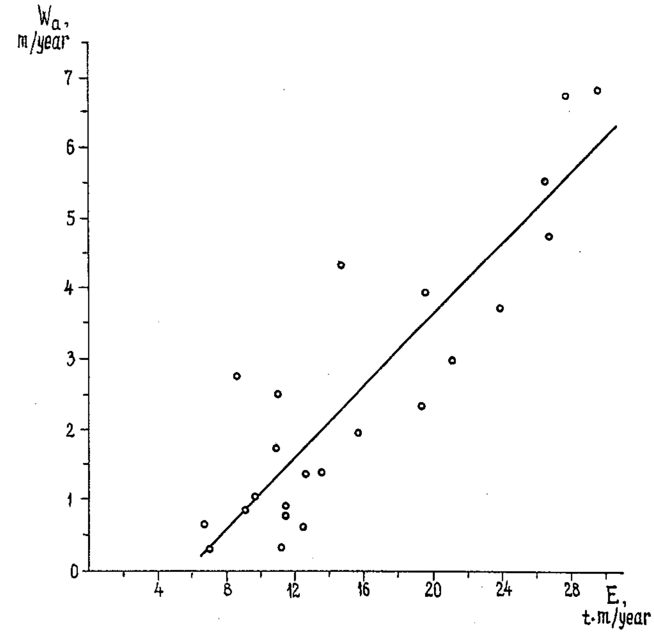

FIG. 6 - Diagram of connection between rate of collapse clayey cliff abrasion (W_a) and sea wave energy (E) based on data of long-term observation on stationary site «Burnas».

existing small beaches along the cliff base dissipate the waves and keep it from reaching the cliffs (fig. 6). Only larger waves are able to cross the beach and cause the retreat of low-durable cliffs. High correlation was found between W_a and E: $r = 0.88 \pm 0.03$; and the error of the arithmetic mean was 1.81% (< 3%). Growth of the depth on the surface of nearshore bottom abrasive terrace increased proportionally (Shuisky & Vykhovanets, 1989).

As it can be seen (fig. 6), rates of annual retreat of clayey cliffs lie in wide range: from year to year they constitute from 0.3 to 6.9 m/year. Rates of botton aabrasion on the whole surface of nearshore abrasive terrace can be from 0.002 to 0.201 m/year in separate profiles and years on the depth 0-5 m, depending on the value of E and sediment supply. That is why inspite of the sea level rise with rates 2-6 mm/year, rates of cliff and bottom surface abrasion tend to decrease (fig. 7) on many sites starting from 1970 (Shuisky & Musielak, 1991; Shuisky, 1993a e b). Thus there are reasons to assert that relative sea level uplift will not be accompanied by adequate growth of abrasion of cliffs composed by low-durable deposits and sedimentary rocks.

In the Black Sea basin rise of air temperature in the nearland layer of atmosphere is accompanied by growth of precipitation. For instance, from 1970 to 1995 the average annual amount of precipitation constituted on stations: Vilkovo 531 mm/year, Belgorod-Dniestrovskiy 471 mm/year, Odessa 502 mm/year, Kherson 462 mm/year, etc. It is in the average 75% more than during 1900-1960. Correspondingly water discharge of the biggest Black Sea basin

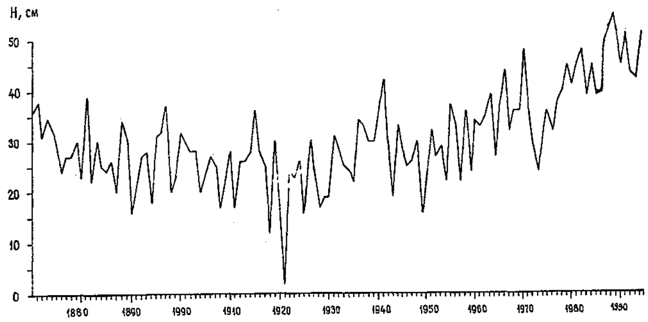

FIG. 7 - Curve of annual values of the Black Sea level on basic station «Odessa» for the period from 1870 to 1995.

rivers grew by 86%. However, water evaporation from aquatory surface of the whole sea decreased in general from 400-450 km^3/year in the first part to 300-350 km^3/year in second part of the 20th century under the influence of artificial pollution of the surface water microlayer. That is why at present sea water balance is significant, positive, which secures the average rate of the sea level rise by 2.7 mm/year (share of water supply). It is 1.8 times higher than in the average for the World Ocean, because the Black Sea is notable for considerable limitation of aquatory.

Besides water supply growth the sea level rise is connected with other reasons (Barth & Titus, 1984; Budiko, 1972; Golitsyn, 1986; Titus, 1987; Belyaly & *alii*, 1992), which intensify this phenomena. Algebraic sum of all reasons conditions different values of K_y in different time periods and in different regions of the Black Sea coast. In partucular till 1921 on Odessa station relative decrease of the level with rate 1.32 mm/year took place, and from 1922 the level grew with the rate 0.1 mm/year till 1949, in 1950-1973 the increase reached 4.5 mm/year, and in 1974-1995 already 6.6 mm/year (fig. 7). During 1945-1995 the rate of the level growth on Primorskoye station equalled 3.94 mm/year, on Bugaz station was 6.51 mm/year, on Il'ichevsk station was 2.79 mm/year, on Khorly station was 3.88 m/year, etc. Almost on all stations progressing increase of relative growth of rates is observed, especially monthly minimal values.

If such tendencies of the level change along the shores composed by low-durable deposits and soft sedimentary rocks remain in future, in the end of the 21th century the level magnitude can become higher than 1.0-1.5 m in comparison with the mark of 1985. In this connection the scenarios suggested by Vellinga & Leatherman (1989) can be taken as basical. They came to the conclusion that during 1985-2100 the level can rise on 0.5 m («low scenario»), on 1.0 m («middle scenario») and on 1.5 m («high scenario»), which we take for the Black Sea. The version in which the level can rise on 2 m in 2100 on some sections is excluded. Thus to calculate rates of cliff abrasion growth we use three scenarios recommended in Vellinga & Leatherman (1989) and one extreme, foreseeing the 2 m level rise.

CORRELATION OF CLIFF ABRASION AND SEA LEVEL RISE RATES

As it was shown above, the grows of the average air temperature and level rise are accompanied by decrease of repetition of effective waves, causing cliff abrasion. This tendency along the Northern Black Sea shores is opposite to the one foretold by other authors (Barth & Titus, 1984; Belyaly & *alii*, 1992; Kaplin & Lukyanova, 1992; Kaplin & *alii*, 1993), but nevertheless it is based on great amount of detailed information and therefore seems trustworthy. The fact of the level rise must not cause any doubts, therefore it is necessary to find out the possibility of depth growth as a factor of corresponding wave energy rise. As it is known (Zenkovich, 1946, 1967; Nevesskiy, 1967; Shuisky, 1986), the higher level creates greater depth on which waves are less destroyed, have greater energy resource and therefore are able to influence cliffy shore more powerfully.

Let us consider base site «Burnas» which is typically abrasive again. At first we studied the correlation betwee the average annual rates of abrasion (W_a) and relative sea level changes (K_y) during 1960-1995. These values were plotted on the diagram (fig. 8). One can observe on it the distribution of both variables in time during the whole period of measurements. Years with higher and lower values stand out clearly, their rhythmicity can be seen. In order to bring all quantities to compatible seals, during calculation abrasion rate was expressed in decimetres, the level was counted from the minimum value equal 464 cm.

Statistical processing of a number of numerical values W_a and K_y confirmed their general character of distribution on figure 8. But at the same time it showed: rhythmicity of K_y is expressed to lesser extent, which is connected not only with wind impact but also with atmospheric pressure change, fresh water discharge from land to sea, change of water temperature, etc. On the diagram four full rhythms clearly stand out, therefore analysis of trends can be used.

Trend-analysis was carried out by linear, logarithmic and exponential dependencies. As a result trends of W_a and K_y change in time were found, separately for the peri-

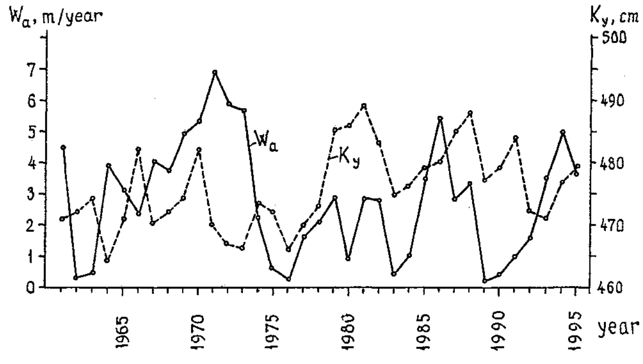

FIG. 8 - Diagram on long-term course of changes of average annual values of abrasion rates (W_a) and sea level (K_y) on the coastal stationary site «Burnas» during 1960-1995.

ods of 1960-1995 and 1980-1995. These tendencies turned out to be approximately the same, which indicates their steady linear trend. That is why calculations by linear dependencies are presented as an illustration (fig. 9). They showed that during the whole studied period of time the rate of relative level change in rising and equals 2.3 mm/year in average. Summary value of level rise constituted 0.08 m for the total period of 35 years on «Burnas» site.

At the same time rate of abrasive retreat constituted 2.826 m/year and against this background stable tendency to its decrease showed itself (fig. 9a). Summary value of decrease was 1.1 m, the average annual increment was negative and turned out to equal –0.032 m/year, i.e. in the average –1.1 % per year. Correlation coefficient of function $W_a = f(K_y)$ is: $r = -0.14 \pm 0.0197$. Therefore relative sea level rise is accompanied by decrease of the rate of abrasion of the cliff composed by low-durable clayey and loessic deposits of Pleistocene, and practically no dependence is observed.

Character of relation between W_a and K_y during last 15 years (1980-1995) turned out to be the same (fig. 9b). Summarily the sea level rise on 0.04 m value (50% of the whole 35 years period). The rate equals 2.7 mm/year which is 17% more in comparison to the whole time of 35 years. Such rise confirms the shown before (fig. 7), tendency towards acceleration of the level rise. As to the cliff abrasive retreat its average rate decreased by 0.027 m/year, the summary value of decrease is 0.4 m. Therefore against the general background of the 1960-1995 period, during the last 15 years accelaration of the level rise and decrease of cliff abrasion rates were observed.

Such regularity is opposite to the one foretold in the Global seale by the majority of authors. But this very correlation between W_a and K_y was found on many other shore sites of the Black Sea composed by clays, sands, loams, loesses («Sanjeiskiy», «Budaki», «Gribovka», «Yuzhniy», «Bolshevik», «Dangeltip», etc.).

That is why in future working out schemes of planning, management and development of coasts it is necessary to base on the fact that cliff abrasion rate depends most closely on sea wave energy, and process of cliff retreat follows process of energy change during long time and with very high correlation coefficient (fig. 6). Correspondingly it is necessary to study the situation when the sea level will elevate and to what extent growth of depth near the shore corresponds to sea wave energy increase, which can make abrasion rate higher, according to figure 6. And only then it will be possible to make a conclusion about abrasion rate change under the influence of «greenhouse effect» consequences.

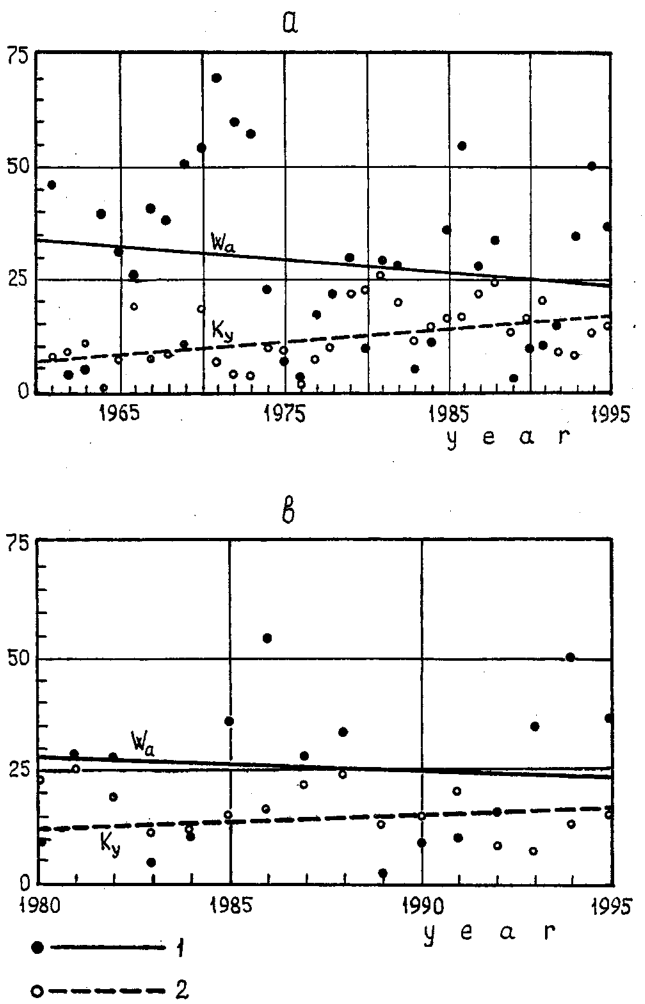

FIG. 9 - Calculated linear trends of abrasion rates (1) and relative level rise (2) during 1960-1995 (a) and 1980-1995 (b).

IMPACT OF POSSIBLE SEA DEPTH INCREASE TO RATE OF CLIFF ABRASION

As in other chapters here we speak about the shores composed by low-durable deposits and soft sedimentary rocks (compressive strength is < 500 kg/cm^2). If any of the scenarios comes true and sea level rises on 0.5 m, 1.0 m, 1.5 m or 2.0 m till 2100 near the cliff base, the abrasion will take place and cliff will retreat. The question is whether this intensification will be catastrophic and whether W_a will grow on a power of the value how a number of cited authors and claim also Titus (1987).

To clear out this question we used methods worked out by Munk (1949) and Sovershaev (1987, 1989). These methods allow to model long-term relative level rise and its influence on windy wave energy with the help of the situations, when the level grows for a short-term during stormy setup.

Calculation of wave energy change was based on the theory of single waves. It follows from it that breaking wave is a crest in the water mass of which more than 90% of the energy of the whole wave are concentrated. Such crests are isolated one from another and do not depend on the distance between their tops, i.e. for a single wave the parameter of wave length does not exist (Munk, 1949). Instead of it concept of effective wave length is introduced

$$\lambda_{ef} = \frac{2\pi}{3\gamma} \quad (3)$$

The main parameter of single wave is relative wave height $\gamma = h/H$ which does not depend on its length, where h = wave height, H = depth on the line of breaking wave. According to [10], energy of single breaking wave is determined by equation:

$$E' = 8/3\rho g H^3\gamma \cdot \gamma/3 \qquad (4)$$

Natural experiments showed that the average relative wave height on the line of breaking can be taken equal γ = 0.78. On condition that wave crest is oriented parallely to the shoreline, the single wave equation acquires the form:

$$E' = K \cdot H^3 \qquad (5)$$

where: $K = 8/3\rho g\gamma$; in (3) and (4): ρ = sea water density; g = gravitation coefficient; wave energy flow is $E_r = E' \cdot t / T$, where t = duration of storm-surge corresponding to the time of shore cliff abrasion; T = period of breaking wave. As single wave energy is proportional to the depth cubed, even small level rise considerably increase impact of wave energy to the shores.

If before the beginning of setup the energy of breaking waves equals $E_1 = K \cdot H_1^3$, during maximum setup on the line of breaking it increases and equals:

$$E_2 = K (H_1 + \Delta H)^3 \qquad (6)$$

where ΔH - magnitude of setup, and in our interpretation it is a summary relative level rise value in future. The difference $E_2 - E_1 = \Delta E$ is wave energy increase, caused by the level rise. According to the character of distribution of storm-surge level on the crossing profile, the greatest wave impact should be expected in the upper part of bottom abrasive terrace and along the cliff base, i.e. as it is foretold during the long-term rise in the end of the 21th century in conditions of each scenario.

According to drawn by Sovershaev (1989) curve of wave energy change depending on the value of the level rise (fig. 10) in the strip of wave breaking the energy can increase 8-10 times, when the rise reaches 2 m above zero-level. This very cause explains why there is such a great difference between annual values of W_a: from 0.17 to 6.88 m/year (figures 6 and 8) on the same site with small beaches near the cliff base (up to 15 m wide and 16 m^3/m of volume).

However, the energy increase during storm-surge taken place quickly during several hours or days. And if the calculation is done for a long-term relative level rise, the value of the energy will stretch for many decades. Besides, the diagram of figure 10 is drawn for constant value of relative wave height γ. But it, and therefore coefficient K, can change within a wide range: according to natural observation, K = 0.92-0.31 as limits. But the matter is, that with slow rate of level rise and adaptation of changing abrasive profile, variable γ remains in its present form or decreases, which does not increase coefficient K and therefore E'. Taking into account all substantiation given, the calculation of energy E_r for base site «Burnas» was carried out

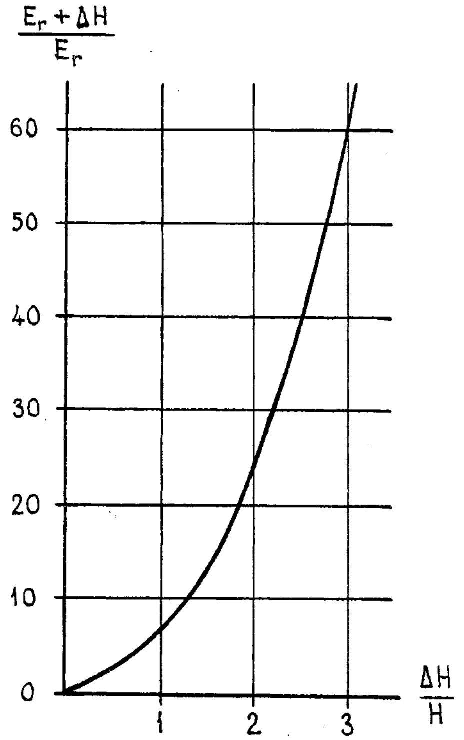

FIG. 10 - Change of wave energy on the wave breacking line depending on storm-surge sea-level rise.

(tab. 1). For given average salinity and temperature of sea water dencity ρ = 0.014. Gravitation coefficient is g = 9.81 m/sec^2. During storms, waves from 0.5 to 5.1 m high are acting from opened sea in the entrance to the coastal zone. The average relative height of wave on the breaking line is taken equal γ = 0.78. Inclination of nearshore bottom slope is not more than 0.020.

According to the content of table 1, with the scenario with maximum level rise 2 m, the average energy increment DE constitutes 1.1-2.5% a year and 0.5-1.2% a year correspondingly during periods of 50 and 100 years. If themselves these values and much lower than natural rhythmic and observed (fig. 6), when rates of cliffs retreat from year to year can differ by > 4,000% under the influence of E_r and ΔH, as it is seen on figure 10. Therefore resource of natural adaptation of abrasive shores composed by low-durable (< 500 kg/cm^2) deposits and sedimentary rocks is big enough for momentary reaction on very slow relative changes of the sea level in conditions of possible wave activity decrease by realization of corresponding mechanism of coastal zone profile evolution. This type of development, as it is seen, has very high elasticity in contrast to the sections composed by very hard crystalline and crystallized rocks (fig. 2). High changeability under the sea wave influence and comparatively low positive increment of relative level values in themselves are protection against disastrous growth of abrasion rates in conditions of quick formation of underwater abrasive terrace, rather big beach,

TABLE 1 - Calculation of wave energy increase given a rise in sea level at various heights above ordinary

Number	Height of setup, ΔH, m	Height of wave, h, m	Depth at which wave breaking line, $H_1 = h/\gamma$	Values of wave energy in relative units		Increase of energy of wind waves during setup (storm-surge)		Relative increases in energy during raised sea level per unit of measurement of setup		
				before the beginning of setup, E_1	during maximum setup, E_2	relative units ΔE	%% of E_1	In depths interval from 0 to H_1, in %	Yearly average over 50 years, %	Yearly average over 100 years, %
1.	0.10	0.5	0.64	5.349	8.269	2.920	54.6	1.95000	1.1	0.5
2.	0.25	1.1	1.41	57.199	93.338	36.139	63.2	0.74353	1.3	0.6
3.	0.50	2.3	2.95	523.840	837.895	314.055	60.0	0.50000	1.2	0.6
4.	0.75	3.2	4.10	1406.319	2327.864	921.545	65.5	0.30896	1.3	0.7
5.	1.00	3.7	4.74	2173.038	3858.940	1685.902	77.4	0.30313	1.6	0.8
6.	1.25	4.2	5.38	3177.453	5946.657	2769.204	87.2	0.25647	1.7	0.9
7.	1.50	4.6	5.90	4190.717	8268.514	4077.797	97.3	0.23167	1.9	1.0
8.	2.00	5.1	6.54	5707.758	12708.840	7001.082	122.7	0.24880	2.5	1.2

corresponding inclinations of nearshore bottom profile. As a result dissipation of sea waves simulteneously wih slow relative level rise, even with the rates of 15-20 mm/year is constantly supported.

CONCLUSION

As the basical theoretical concept we accept that by the end of the 21th century diastrous rise of the World Ocean level is expected, connected with warming of the Earth's climate, anthropogenous activity impact and «greenhouse effect» formation. The given data of the investigation point to the rise and acceleration of rise of the Black Sea level during the past decades till 1995. Three scenarios of relative level rise by the end of the 21th century are most probable: on 0.5 m, on 1.0 m and on 1.5 m above the zero-level mark of 1985. The scenario of 2 m uplift was worked at as an extremely high one.

On the studied sections of the Black Sea coast we foretell passive flooding of low (< 2 m) indigenous shores, with low wave energetic potential. Shores composed by very hard rocks (strength is > 500 kg/cm^2) will remain practically stable, very little changed by sea wave actions. The greatest destroying changes are supposed to take place along indigenous low and moderately high cliffs, composed by low-durable and soft deposits and sedimentary rocks, and also along accumulative coastal forms of the World Ocean and the Black Sea in particular. On the example of the Northern Black Sea shores basic features of possible reaction of such low-durable and soft shores on the level rise by the end of the 21th century were considered.

Comparison of rates of relative changes of the level and cliff abrasive retreat showed that on the majority of stationary sites between them there is no reliable correlation during modern relative rise of the sea level. On the contrary, level rise is accompanied by decrease of abrasion rate. This tendency has particularly clear features during last 15 years, when acceleration of level rise took place. At the same time clear dependence of abrasion rates on wave energy values was found. During last decades general trend of energy amount reduction along the shores under investigation was observed and at the same time in general abrasion rates decreased.

Overwhelming majority of researchers are explaining the level impact on shores by machanically. They put more height level, according to various scenarios, on modern profile of coastal and nearshore bottom slope. However, this is not correctly. Indeed from end of 20th century to 2100 within sections with soft deposits and low-durable sedimentary rocks the coastal profile will undergo the essential changes, and wave regime will change according to different rhythmicity ways. Therefore, for reliable estimation of the possible influence of sea level on coastal zone (according to the various scenarios), we ought to estimate sea level position with transformed (but with not today) profiles on long-term observation sites. And such new profile we can forecast correspondingly to the contemporary diversities of the coastal zone position along time and within different alongshore lithodynamical cells.

On the basis of the methods worked out by us, we worked at the question whether the level rise and corresponding growth of depth will bad to the disastrous rise of abrasion rate by the end of the 21th century. It turned out that possible growth of depth according th the accepted scenarios cannot essentially increase abrasion rates within the studied Black Sea shores. Natural rhythmical fluctuations of annual values of abrasion rates under the impact of wave energy are much more effective. And it is they that lead to the development of the mechanism, which favours shore adaptation and its protection against all foretold values of level rise in the end of the 21th century. That is why disastrous rise of abrasion rates and cliffs retreat is not expected.

The obtained conclusions must be taken into account in schemes of planning, management and development of coastal territories and use of their resources. Probably, conclusions of this elaborations must drow attention of experts from other countries and regions, where natural and human impact conditions are similar to those which we studied, for more detailed and critical investigation of the problem «Climate Changes and Shores».

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