Collection of Marine Research Works, 2002, XII: 9-18

DYNAMICS AND ANALYTICAL MODELS OF SHORT-TERM COASTAL CHANGES IN THE CASE OF STORMS

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ABSTRACT Many occasions of violent coastal erosion along the coasts of Vietnam in the last years, especially the catastrophic destruction of the coasts of Thua Thien – Hue province, have presented themselves first of all as a direct consequence of powerful attack of storm waves upon the coastline plane. Repercussion of such attack is absolutely certain to create instantaneous crack of the coast, some big material masses have to split and separate from the coastline and either momentarily collapse right in front of collapsed position or hurl further in the wave acting direction. These dynamical processes make the coastline destroy quickly and move backwards to the main land, by that way and create a strong short-term change of the coast. In this paper the author wishes to present the dynamics of these processes and relative analytical models for numerical determining an individual broken material bodies when the waves rush to impinge upon the coastline plane during storms. Such calculations could be applied in the technical problems of shore-protection and relative basic investigation

ÑOÄNG LÖÏC HOÏC VAØ NHÖÕNG MOÂ HÌNH GIAÛI TÍCH CUÛA BIEÁN ÑOÅNG BÔØ BIEÅN CAÁP THÔØI DÖÔÙI TAÙC ÑOÄNG CUÛA SOÙNG LÔÙN TRONG BAÕO

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TOÙM TAÉT Nhöõng naêm gaàn ñaây hieän töôïng xoùi lôû bôø bieån ôû Vieät Nam xaûy ra raát nghieâm troïng, thaäm chí ñöa ñeán nhöõng tai hoïa lôùn nhö ôû khu vöïc bôø bieån tænh Thöøa Thieân – Hueá. Veà maët ñoäng löïc hoïc hieän töôïng xoùi lôû bôø bieån nghieâm troïng aáy tröôùc heát laø haäu quaû taùc ñoäng ñaäp tröïc tieáp cuûa soùng lôùn trong baõo hoaëc gioù muøa leân bôø bieån coù ñoä doác ñaùng keå vaø coù chaát löôïng caáu taïo bôø khaùc nhau, trong ñoù coù loaïi hình vaät lieäu vaø chaát löôïng keát dính cuûa chuùng. Chòu taùc ñoäng tröïc tieáp cuûa löïc doäi laïi khi soùng baõo ñaäp vaøo bôø ñaàu tieân seõ xaûy ra hieän töôïng nöùt bôø thaønh nhöõng maûng lôùn vaø ñi lieàn theo ñoù laø söï saït lôû nhanh choùng nhöõng maûng aáy hoaëc quaêng xa chuùng theo höôùng löïc taùc ñoäng cuûa soùng. Ñoàng thôøi treân baõi ngaäp nöôùc lieàn vôùi bôø xaûy ra tình traïng soùng loâi cuoán vaät lieäu lôû ra-vaøo lieân tuïc theo höôùng tröïc giao vôùi bôø taïo neân söï oån ñònh taïm thôøi cuûa baõi trong vaø sau thôøi gian baõo toá. Taát caû nhöõng ñieàu ñoù laøm cho bôø bieån nhanh choùng luøi vaøo trong ñaát lieàn, roài quaù trình xoùi lôû laïi tieáp tuïc cho ñeán khi khoâng coøn taùc ñoäng cuûa soùng lôùn nöõa. Trong baøi naøy taùc giaû trình baøy moät phöông phaùp luaän ñoäng löïc hoïc cuûa caùc quaù trình nöùt ñaát va sat lô bô va tö ño dan ñen nhöng mo hình giai tích dung ñe tính toan ñònh löông nhöng mang bô bò xoi lô tao nen sö bien ñong bô va tính chat cua chung. Cac mo hình nhö vay co the öng dung trong cong tac tính toan ky thuat phong chong xoi lô va bao ve bô cung nhö trong nghien cöu cô ban nhöng van ñe co lien quan.

INTRODUCTION

In direction towards the sea, a seashore has been able to be distinguished by two parts: coastline and beach parts. The first of them presents itself as a highest and most steep (some time vertical) area of seashore (Fig. 1). The second one is a continued low area characterized by some extent incline and curve surface. Relatively to the mean sea level a seashore includes two different hydro-dynamical zones: upper sea level zone and under water zone. Approaching from relatively deep sea the storm waves often cause either a breakage at the beach or strong attack directed right to the coastline in direction perpendicular to the coast. In this paper wave attack on the coast has attracted the author's attention more than a breakage at the beach.

In response to the attacking waves during storms there are happened following processes of coastal object, first of all a steep shore instantaneously cracks and some individual big masses (later on big pieces, big bodies) of coastal materials have to split and quickly separate from the main land. Then depending on their weights these big masses have been able either to fall-off (collapse) and on-the-spot accumulate right in front of collapsed position or to hurl further in the acting direction. These processes make the coastline destroy powerfully and move backwards to the land, by that way they have created a quick change of the coast. Just after that there are the sediment motions dragging the collapsed materials up and down the slope (cross-shore) for reaching an equilibrium shape of coastal beach. The above mentioned mechanism of coastal migration and cross-shore sediment transport plays most important role in morpho-dynamics of coastal changes during storms. Many occasions of violent coastal erosion along the coasts of Thai Binh, Nam Dinh, Thua - Thien - Hue, Quang Ngai... provinces in the last years had presented themselves as the direct consequences of just described processes and had carried dangerous catastrophes along the coasts of Vietnam. For that very reason they have been attracting serious government and public attention and presenting themselves to the forefront problem which we have to solve first of all. Litho-hydrodynamical processes of these occasions had been considered in some author's works [4, 5], following them this work is carried out. In coastal zone of Vietnam there are usually happened single hurricane and monsoon storms, durations of which restrict themselves in some days or some weeks (such periods are named by climatic time scales). The longshore transport of accumulated materials has a basic difference comparing with the cross-shore one, it is connected with variations in its magnitude and caused long-term changes of a beach slope (some months and often some years). Thus the main aim of this paper is to find out the analytical model for determination of the quantitative characteristics and examination of typical motions of individual broken bodies of the coast when the waves rush to impinge upon a shoreline during storms.

Propagating in coastal zone storm waves transport their energy per unit area E (= $\rho gh^2/8$, where ρ - density of sea water; g – gravity acceleration; h – wave height) at the group velocity c_g and by that product the power per unit crest length e (or energy flux in wave direction):

$$\vec{e} = E\vec{c}_g \qquad (1)$$

This power is the most significant factor creating a cross - shore destruction and longshore sediment transport in surf zone, in result of the last there are happened also occasions of sustained beach erosion and accumulation. In order to study the longshore sediment transport in coastal zone, Longuet-Higgins had proposed to insert into problems the simultaneous factor of wave transmission – the water momentum flux [6]. Here it's not necessary because the only present concerned problem is coastal destruction resulting from power blows of storm waves right on the coastline.

1. The components of acting forces

Storm waves rightly attack the coast and if the waves are losing no dissipative energy in the time of approaching so pressing force carried by devastating energy under impingement is formulated by:

$$\vec{P} = E\vec{c}_g T\cos\theta \qquad (2)$$

where T – the wave period; θ - angle of incidence to the coastal normal in local direction of wave propagation ($Ec_g.\cos\theta$ shows the energy flux toward the coast per unit distance parallel to the coastline).

Paying attention to the main forces, having an effect upon the coastline and the certain material big masses when the waves rush to impinge on, we can bring into consideration the wave force $\vec{P}$ pressing on the coast and the individual big pieces, the corresponding weight $\vec{W}$ of each piece (the force of gravity), reaction force $\vec{R}$ and friction force $\vec{F}$ (including internal and sliding elements) directed oppositely to the tendency of material motion. The origins of them have been put to gravity center O of the certain body. After Newton's second law the main equation of motion of each material big piece can be written as follows:

$$\vec{P} + \vec{W} + \vec{F} + \vec{R} = M\vec{a} \qquad (3)$$

where M is the mass of each individual big piece; $\vec{a}$ – its acceleration. The allotment of acting forces, which the coastline and certain big pieces stand against under the wave attack, could be illustrated in the Fig. 1 (situations A & B) for a section perpendicular to the coast (i.e. $\theta = 0^o$), where the axes of co-ordinate system are so laid out that one of them (the axis Ox) coincides with the inclined plane of the coastline part and keeps positive direction of the beach side.

It is supposed that under any blow of the wave a certain material body of the coast, which will be in crack afterwards, continues its motionless position (situation A, Fig. 1) so we have the vector $M\vec{a} = 0$.

Projecting the left members of (3) on the Ox, Oy axes we get two equations:

$$\vec{P}_x + \vec{W}_x + \vec{F}_x = 0 \qquad (4)$$

$$\vec{P}_y + \vec{W}_y + \vec{R} = 0 \qquad (5)$$

As soon as some next blows have intensified sufficiently (t > 0) the given material body must crack suddenly and sets out from the coast, speed and acceleration of its motion have appeared and the condition $\vec{v}_{t>0} \uparrow\uparrow \vec{a}$ takes place (symbol $\uparrow\uparrow$ denotes unidirection) [4, 5]. The compo-nents of acting forces have changed and complicated right away and they are shown in situation B, Fig. 1. Analyzing this picture we can see that, first of all, the wave force $\vec{P}$ pressing upon the coastline plane has been comprising the absorption part $\vec{P}_{ob}$ and the reflection part $\vec{P}_r$ $\left(\vec{P} = \vec{P}_{ob} + \vec{P}_r\right)$. Projecting these particulars on the axis Ox we have the components $\vec{P}_{obx}$ and $\vec{P}_{rx}$ ($\vec{P}_x = \vec{P}_{obx} + \vec{P}_{rx}$). As for the axis Oy we have the components $\vec{P}_{oby}$, $\vec{P}_{ry}$ and reaction force $\vec{R}_{ob}$ $\left(\vec{R}_{ob} = -\vec{P}_{oby}\right)$. The component $\vec{P}_{ry}$ plays most important role for creation of a crack of the coast during wave attack, it could be named by repercussion force. In fact, to confront coastal collapse is right to confront this harmful component of acting force. When $\vec{P}_{ry} = 0$ the coastline usually is in unchangeable situation. Then, let turn attention to the gravity force $\vec{W}$ of certain material body standing rightly against the wave influence. On the axis Ox, it has the component $\vec{W}_x$ having a significance at all over dynamical processes, as for the axis Oy it denotes two aptitudes: when the coast hasn't been cracked yet (sit. A, Fig. 1) the component $\vec{W}_y$ has been balanced by its reaction opposite force $\vec{R}_W$ at the coastline plane, but as soon as the body has been at a cracked position the reaction force $\vec{R}_W$ disappears momentarily (sit. B, Fig. 1). Lastly, in spite of both situations of the body (sit. A & B) the friction force $\vec{F}$ has only one component $\vec{F}_x$ and its role is obstructing a motion at Ox direction. Therefore, under coastal crack the equations of motion of individual big piece become in forms as follows:

$$\vec{P}_{obx} + \vec{P}_{rx} + \vec{W}_x + \vec{F}_x = M\vec{a}_x \qquad (6)$$

$$\vec{P}_{oby} + \vec{R}_{ob} + \vec{W}_y + \vec{R}_W + \vec{P}_{ry} = M\vec{a}_y \qquad (7)$$

where

$$\vec{P}_{ob,y} + \vec{R}_{ob} = 0;\ \vec{R}_W = 0;\ \left|\vec{P}_{ry}\right| = \omega\left|\vec{P}_y\right|.$$

In the left side of equation (7) the components $\vec{P}_{ry}$ of wave repercussion force and $\vec{W}_y$ of gravity force remain in force, the other respects have been either balanced at the coastline plane or disappeared. Reflection coefficient ω standing before $\vec{P}_y$ shows that only percentage of the last has created repercussion effect, it makes the absolute value of $\left|\vec{P}_{ry}\right|$ become smaller than $\left|\vec{P}_y\right|$, i.e. $\omega < 1$. Reflection effect completely depends on intense degree of wave action (h_b ; T_b). In addition, in the ω there are also real effects of substantial and morphological structures of the coast, for example, the effect of roughness of a coastal structure's plane, etc. In principle, coefficient ω has to be determined either in laboratory or by nature experiments.

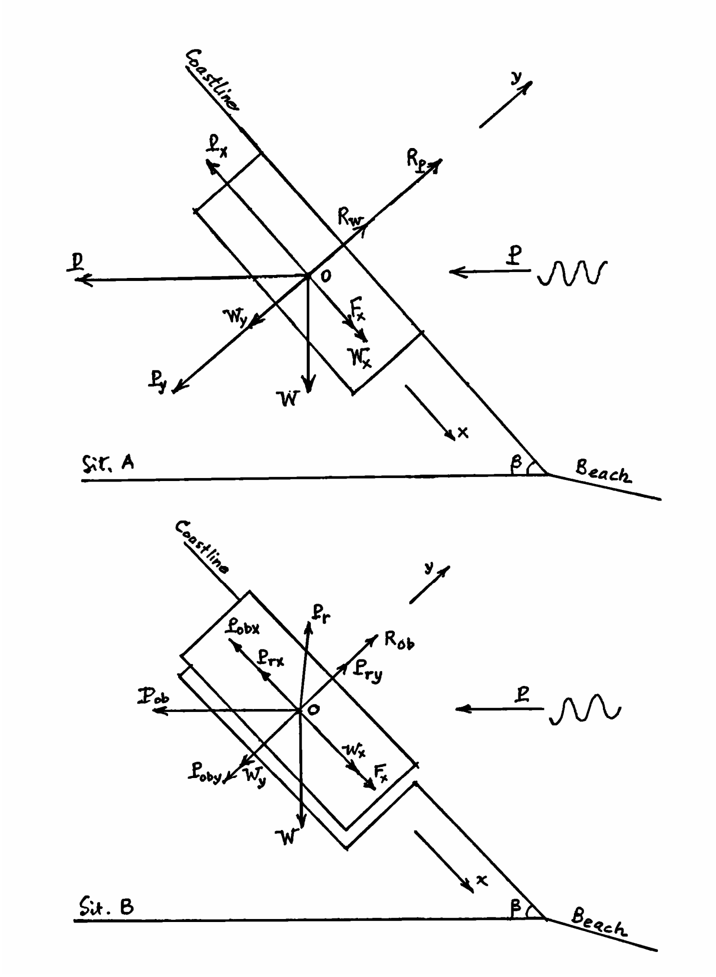

Fig. 1: Allotment of the forces acting on the coastline during storms.

Situation A: Non – Cracking
Situation B: Cracking

2. Analytical model of coastal crack

As above introduced the notion of coastal change in this work has been limited by the following composite processes. First of all, it is the process of sudden crack of the coast from that some certain material bodies have to move at a slight distance in direction perpendicular to the coastline plane (axis Oy). Then, depending on correlation between components of acting forces, the relative process is complete setting out of simultaneous motion of these individual big pieces either down or up in direction coinciding with the coastline plane (axis Ox), these are the behaviours of either collapse or hurl further to the land of the big pieces, respectively. Concerning motion time such processes can be understood as an extremely short-term and powerful coastal destruction. In the case of coastal crack the equation (7) has been able to take in further consideration, from there it follows:

$$a_y = \frac{1}{M}\left(\omega P \sin\beta - W \cos\beta\right) \qquad (8)$$

where β is the angle forming by inclined coastline plane and the horizontal (see the Fig. 1); $a_y \geq 0$. This expression is useful for determining the value of acceleration vector a_y of cracking process. From (8) it follows that in initial stage when $a_y = 0$ we'll have the critical situation of coastal crack, because with such just moment a coastal material body is not moving yet and in a moment after that only ($t > 0$), i.e. as soon as some wave blows have intensified sufficiently, the cracking process begins its existence. In this critical occasion we get:

$$W_{cr} = \frac{\omega P}{ctg\beta} \qquad (9)$$

where W_{cr} is the critical weight of wet material big piece at just touched situation. Because the material body is situated in underwater position as well as stands rightly under wave blows, its immersed weight W presents itself as a difference of two distinctive numbers: the pure material weight W_s and the weight of sea water W_w having the same volume as the pure material body, i.e. $W = W_s - W_w$. Hence, after simple mathematical operations, it follows:

$$W_{s.cr} = \frac{\omega P}{\left(1 - \frac{\rho_w}{\rho_s}\right) ctg\beta} \qquad (10)$$

where ρ_w and ρ_s are the densities of seawater and coastal material respectively.

It should be immediately emphasized that the expression (10) acquires specific meaning only after the acting force P as well as the angle β are established, that is, their dependence on the involved quantities is known. And here, the expression (2) gives the acting force modifying in dependence on height and period of waves which (as well as β) can be obtained through measurements. The dynamics of surface wave showed that in breaking zone of shallow waters the group velocity c_g can be written by:

$$c_g = \sqrt{gH_b} = 1.13\sqrt{gh_b} \qquad (11)$$

where H_b – the depth at breaking zone; h_b – the wave height at the same position. As this formula has been able to be used also in the case of direct wave attack on the coastline so, finally, substituting the forms of c_g and relative factors E, P into (10) we have found:

$$W_{s.cr} = 0.14 \frac{\rho_s g^{\frac{3}{2}} T_b h_b^{\frac{5}{2}} \omega}{\left(\frac{\rho_s}{\rho_w} - 1\right) ctg\beta} \qquad (12)$$

This is one of the fundamental equations of dynamics of coastal destruction in the case of storms, it is also the fundamental equation for technical calculation in the problems of coastal protection. From (12) it follows that, at one side the stronger storms (the higher wave heights and periods) as well as the steeper coastline plane the bigger weights (volumes) of cracking individual pieces. At the other side, depending on qualitative characteristics of coastal structures and intensity of wave actions, it is possibly the real occasion when material big pieces have limited their physical ability by certain values W_l smaller than W_{cr} (i.e. $W_l \leq W_{cr}$) the stronger storms the more variability and complicacy of coastal destruction forms. That is, for example, may be these individual material pieces either fall down (coastal collapse) or fly farther in the wave acting direction (material hurl) [4, 5]. As for $W_l > W_{cr}$, a crack usually might not be able to happen.

The analytical expression (12) bears resemblance to the empirical Hudson's formula of collapsing weight of armor unit (W_H) [1, 3]:

$$W_H = \frac{\rho_s g h_b^3}{k_D \left(\frac{\rho_s}{\rho_w} - 1 \right)^3 ctg\beta} \qquad (13)$$

which is generally accepted in practice design of shore-protection problems. In this formula the K_D is a stable coefficient that depends on the shapes of armor unit, the roughness of the structure's surface and the degree of interlocking obtained in placing the units. Therefore, this coefficient k_D has full of significance more or less like the above mentioned identical coefficient ω (in the equation (7)). In present, a weak point of our problem is an absence of any abilities for conducting relative hydrodynamical experiments in order to make the table of ω, it's desirable that such experiments would be carried out in future. However, if it is necessary in some occasions of rocky coasts, by a provisional compromise we have been able to make full use of the table of k_D introduced in the Shore Protection Manuel, Vol. 1, Tables 7 – 8 [1] together with relative transformation. Assume that $W_{s.cr}$ and W_H are equivalent, by that we can find the following equality:

$$\omega = \frac{k}{k_D} \sqrt{\frac{h_b}{g T_b^2}} \qquad (14)$$

where $k = 7.14 \left(\frac{\rho_s}{\rho_W} - 1 \right)^{-2}$.

3. Analytical model of coastal destruction behaviours

In connection with the cracking process there are happened simultaneous impressive events including in either fastest collapse or impetuous hurl of the above mentioned individual material pieces. The behaviours of those events and their existence along the coasts of Vietnam had been introduced in [4, 5], and quantitative characteristics of these pieces had been also determined in previous paragraph. But now, when our interest has turned toward considering a motion of these big pieces at the direction parallel to the coastline plane (i.e. at the axis Ox), the equation (6) must be taken for further investigation, from there it follows:

$$a_x = \frac{1}{M} \left(-P\cos\beta + W\sin\beta + F_x \right) \qquad (15)$$

Taking into account $M = W/g$ and $F_x = \mu(R_{ob}+P_{ry}) = \mu P\sin\beta$ the acceleration component at the Ox direction has been settled at the following form:

$$a_x = -\frac{g}{W} \left[P(\cos\beta - \mu\sin\beta) - W\sin\beta \right] \qquad (16)$$

Coefficient μ standing in front of $\sin\beta$ has been able to be understood as non-dimensional coefficient of friction which is created by sliding of material body on inclining plane of the coastline (sliding friction) together by empty space between structure particles of that body (internal friction). As in the above described case of a_y, this expression of a_x is useful for determining the value of the vector a_x in the time of coastal destroying, and both of them lead up to general numerical vector of acceleration of individual material big piece at beginning stage ($t > 0$) of destruction processes, as follows:

$$a = \sqrt{a_x^2 + a_y^2} \quad ; \quad \alpha = arc\cos\frac{a_x}{a} \qquad (17)$$

where α is the angle forming by the acceleration vector and inclined coastline plane. From there the sum (α + β) should be the angle restricting between the vector and horizontal. At the direction Ox if $a_x > 0$, the individual material body slides fast down into coastline part (behaviour of coastal collapse) and, on the contrary, if $a_x < 0$, it has been hurled farther to the land (behaviour of material hurl). From that, with the observance of the condition $a_y \geq 0$, the second critical criterion of coastal destruction processes is taken place (i.e. the condition of disappearance of acceleration at the axes Ox) and it has been formulated as follows (the first criterion is $W_{s.cr}$,(12)):

$$W_{s.cr2} = 0.14\frac{\rho_s g^{\frac{3}{2}} T_b h_b^{\frac{5}{2}}}{\left(\frac{\rho_s}{\rho_w} - 1\right)}(ctg\beta - \mu) \qquad (18)$$

Limiting condition for existence of $W_{s.cr2}$ is following:

$$ctg\beta \succ \mu \qquad (19)$$

In references we often find the value of internal coefficient being equal to 0.6 (tangent of the static friction angle for material particles) [2]. Here the coefficient μ can be slightly more than this value, but if we take, for example, μ = 0.7 so limiting condition must be as $0^o < \beta < 55^o$. Inside this restriction, if the real certain W_l is smaller than W_{cr2}, the behaviour of material hurl has taken place and, on the contrary, if $W_{cr2} < W_l < W_{cr}$ so the behaviour of coastal collapse has appeared relatively. As for outside this restriction there have no W_{cr2} and the acceleration of material body a_x acquires only positive sign, that is the motion is quite directed downward along an inclined coastline part (collapse). For that very arguments the formula (18) is one of the fundamental equations of dynamics of coastal destruction under influence of storm waves and relative technical calculation.

4. Analytical expression of coastal sustaining

It's very interesting to note that in real conditions it is possibly the occasion when the $W_{s.cr}$ and $W_{s.cr2}$ have one and the same numerical value simultaneously to $a_y = 0$ and $a_x = 0$, i.e. the occasion of simultaneous disappearance of all over the capacities of coastal destruction. It is also the most suitable condition for creating a stability of the coast under any external influences. In this case we can write:

$$ctg^2\beta_{sus} - \mu\, ctg\beta_{sus} - \omega = 0 \qquad (20)$$

from there:

$$\beta_{sus} = arc\ ctg\left(\frac{\mu}{2} + \sqrt{\left(\frac{\mu}{2}\right)^2 + \omega}\right) \qquad (21)$$

in which β_{sus} is the criterion of angle β satisfying the just mentioned critical conditions. The conclusion drawing from the equation (21) is like that the angle of stable slope of coastline plane under any wave influence depends on repercussion power degree and friction of coastal material body.

If we accept the above mentioned value as μ = 0.7 and ω = 1 (ω = 1 is the occasion of absolute force reflection of waves from the coast), we'll obtain the following condition of the coastline slope for its stability: $\beta_{sus} = 35^o21'$. But this equality is one of the thresholds, the other one is $\beta_{sus} = 55^o00'$ when ω = 0, between these limitations the smaller ω the larger angle of stable slope of coastline plane. It means that, theoretically, with $\mu = 0.7$ the suitable stability of coastal slope is restricted oneself as follows:

$$\sim 35^{o} < \beta_{sus} < \sim 55^{o} \qquad (22)$$

Outside this restriction (i.e. $\beta < 35^{o}$ and $\beta > 55^{o}$) the coastline is compelled to stand under permanent threat of changing under wave blows. It's necessary to recall that when $\beta < 35^{o}$ it is easy to happen the occasion of material hurl further in wave acting direction – one of the forms of coastal destruction [4, 5]. As for when $\beta > 55^{o}$ the coastline always stands in front of collapsed event.

The lower part of just introduced numerical restriction very well agrees with experimental (small-scale model testing and verification) conclusion of CERC (Coastal Engineering Research Center, USA) for technical design of shore-protection projects [1]. Technical recommendation in Shore Protection Manual had affirmed that the stable slope is placed at the threshold 1.5(hor.): 1(vert.), i.e. $\beta_{sus} = 33^{o}41'$. In addition, CERC's recommendation is formulated as the riprap subject to breaking waves be placed at slopes of 35^{o} or less [3], that is correctly another words for lower limitation of inequality (22). Such agreement is the second ground asserted a certain accordance between the above presented analytical problem and corresponding experimental method, and both of them are directed to solve the same scientific-technical problem of coastal destruction and shore-protection.

5. Numerical example

Along the sand coasts of Thuan An – Hoa Duan (Thua Thien - Hue province), in the case of storms we have the following data of measurements: $h_b = 2$ m; $T_b = 6$ s; $\rho_s = 2.6$ t/m^3 and $\beta = 70^{o}$ [5]. Find the critical weight of individual material body of possible coastal crack. Depending on qualitative structure characteristics of the coast let give some values of a real weight W_l of the body which are smaller than critical one and find the trajectories of their movement during wave action.

The large angle β makes the coastline stand under collapsed situation only. If we use the expression (14) with the $k_D = 1$, we'll get $\omega = 0.21$, that is only 21% of wave blowing force has been in reflection and this percentage has given destroying force $P_{ry} = 3.0$ T. Then using the equation (12) with respective real data we can get: $W_{s.cr} = 15$ T, that is equivalent to 7.5 m^3; $W_{cr} = 9$ T.

Assuming that $W_l = 8$ T (i.e. $< W_{cr}$) the relative vector of acceleration is as follows: $a = 5.93$ cm/s^2; $\alpha = 3^{o}04'13$. If W_l is assumed equal to 4 T so it'll give: $a = 21.44$ m/s^2; $\alpha = 10^{o}48'14$. The corresponding trajectories of collapse of those individual material bodies have been demonstrated in the Fig. 2. In the first case of assumption ($W_l = 8$ T) the material body has collapsed right in the toe of coastline plane, X = 1.4 m, trajectory (I). As for the second case ($W_l = 4$ T) the collapsed body has flew some more farther to the beach, X = 2.2 m, trajectory (II). Prolongation of each collapsed occasion is $t_1 = 0.42$ sec. and $t_2 = 0.18$ sec. respectively, i.e. momentary collapse of the coast but the larger weight of material body the slower collapse.

Similar calculations by using the above recommended models could be applied in technical problems of shore-protection and relative investigation.

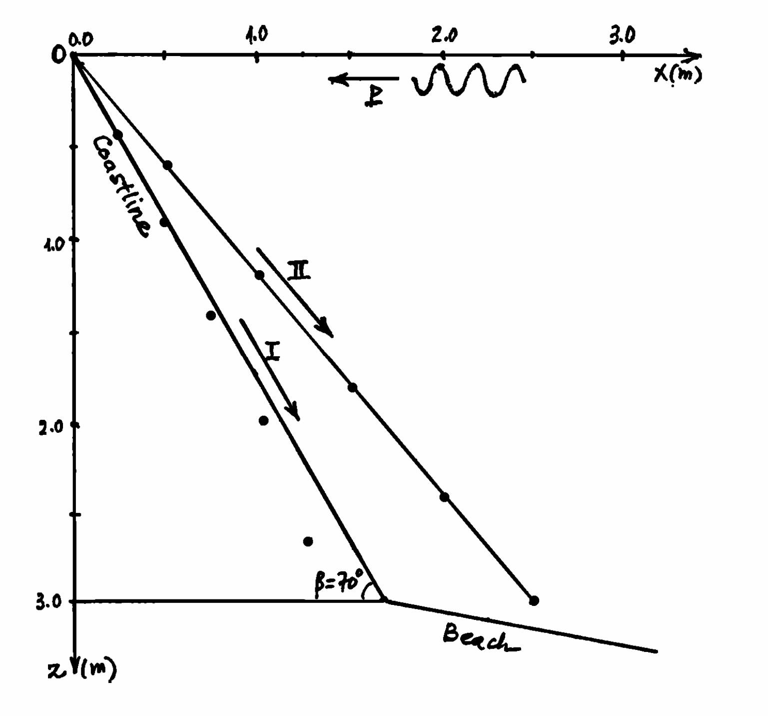

Fig. 2: Trajectories of collapsed individual big pieces (see example)

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