

Effect of New Structures at Headland of Crenulate-Shaped Bays on the Equilibrium Shape of Bays in Mokran Coasts

Mohammad Arian¹, Hassan Akbari^{2*}, Seyed Mojtaba Hoseini Chavoshi³

¹ MSc in coastal engineering, Tarbiat Modares University; mehrshad_aryan@modares.ac.ir

^{2*} Assistant Professor, Tarbiat Modares; akbari.h@modares.ac.ir

³ MSc in coastal engineering, University of Qom; sm.hoseini@stu.qom.ac.ir

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ABSTRACT

Construction of a new coastal structure changes the stable shape of the shoreline. This issue generally leads to sedimentation and erosion around adjacent structures due to changes in Littoral Sediment Transport (LST). This mechanism is considerably more complicated in crenulate-shaped bays than in straight shorelines. Therefore, special theories have been introduced for these bays. In addition to the above-mentioned difficulties, using two-dimensional long-term morphological models with considerable run times is not practical in most real cases. Instability and numerical errors may also be occurred due to the complicated forms of shorelines. The aim of this research is to introduce a proper morphological model for South-Eastern shorelines of Iran. Long term morphological simulation has been done for three important bays in the Mokran coasts using numerical and empirical models. The results show that these models are appropriate for understanding the behavior of crenulate-shaped bays. Their responses to natural changes like climate changes as well as human interventions can also be simulated properly.

1. Introduction

One of the particular types of bays formed by swell waves attacking from a particular direction is Crenulate-shaped bays. They are formed naturally and/ or due to the construction of coastal structures. These bays have different shapes, but all of them usually have three parts including a curved zone, a gentle transmission zone (from the curved to straight) and a straight tangent segment.

After analyzing these bays, [Silvester and Hsu, 1997] divided them into three categories, static equilibrium, dynamic equilibrium, and unstable or natural reshaping bays. The static equilibrium occurs in a region with prevailing angle perpendicular to the coastline or in a region with small littoral drift. There is no external sediment source in these areas and the shape of coastlines will not change considerably. Coasts in the dynamic equilibrium also have a stable form while the littoral drift is not zero in this condition. In these kinds of bays, if net sediment discharge changes, the coastlines will change. In unstable bays, the equilibrium condition has been ruined due to river activities or construction of new structures. In such situation, the beach rebuilds and adjusts itself to a new equilibrium condition.

Although, these bays are different in size, shape, and hydrodynamic condition, engineers and geologists suggested mathematical equations which can be used for prediction the stable shape of these bays. As the first efforts, [Krumbein, 1944] predicts the stable shape of California coasts using logarithmic spiral equations and [Yasso, 1965] used the same equation for prediction the stable shape of four bays in west and east of American beaches. He concluded that the center of spiral curve is not coincided with diffraction point and the effect of wave characteristics, especially the wave angle is not considered in the above-mentioned equation. Later, [Walton, 1977] concluded that the logarithmic equations did not necessarily present an equilibrium condition. due to the weaknesses of this equation, [Hsu et al., 1989], introduced an equation named parabolic equation based on curve fitting to 27 stable bays including 14 laboratory models and 13 real bays. Their equation can be used to determine the stable shape of the bay. After that, various attempts have been made for introducing a simple and accurate equation. [Moreno, 1999] suggested using hyperbolic models. He evaluated it by investigating 46 bays in Spain and North America. However, the wave diffraction was not considered in their equation. Regarding the existing ambiguities in choosing the wave diffraction

point, [Gonzalez, 2001] determined the point of down-drift control through the results of wave energy flux. Later, [Martino, 2003] found the wave diffraction point by trial and error.

Among different proposed equations, the parabolic equations can determine the static shape but they cannot simulate the dynamic behavior of bays. They cannot also consider the effect of wave height and period as well as cross-shore profile and sediment size on final shape of bays. Instead, numerical models can be used for understanding the dynamic behavior of bays. Two dimensional numerical models are good instruments for short time simulations in order of some days; however, they are not appropriate for long-term morphological simulations. [Daly, 2014, 2015] simulated an imaginary bay between two structures with 150m distance from each other for 3 years using Delft3D software, but the simulation time was very long even by applying the speed-up factor. He found that the evolution of a coastline to a stable shape can be predicted well by an exponential function. An alternative to complicated 2D models is One-line model with simplified assumptions about cross shore profile. These models have been used for long time simulation of coastlines [Weesakul et al., 2010; Barkwith et al., 2014a, 2014b]. However, original One-line models with rectangular computational cells can be applied only to the straight parts of a coastline [Pelnaud-Considerere, 1956] and it is not appropriate for modeling curved coastlines. To address this issue, different modifications have been suggested. [Le Blond, 1972] proposed using the local coordinates so that the coastline can progress in all the directions. later, [Rea and Komar, 1975] introduced a coordinate system based on two independent perpendicular one-line models in which the coastline can progress along both of them. Yet, the mass was not conserved in these models because of the generated gaps between rectangular elements around convex or concave curves. [Kaergaard and Fredsoe, 2013] used polygonal elements to solve this problem. But this method also needed a trial and error which caused inaccuracy of results. In recent years, [Hurst, 2015] proposed a one-line model for simulation of a special kind of bays named crenulate-shaped bays. He showed that the Crenulate-shaped bays can be modeled with reasonable accuracy using the proposed method.

The Crenulate-shaped bays exist in different scales in Mokran coasts of Iran. Any change at the head of these bays can deform their stable shapes. A sample change is construction of a new structure at the heads. In this study, the response of Chabahar and Pozm bays to new constructions is investigated using an empirical model based on parabolic equation (MEPBAY) and a one-line numerical model (COVE). New strategies for decreasing of sedimentation

problems and instability of the coastline are also proposed.

2. Numerical and empirical models for morphological simulation of crenulate-shaped bays.

To calculate the long-term coastlines morphological changes, different numerical and empirical models have been presented. Some of them are especially for Crenulate-shape coastlines and some others are useful in any region. Two-dimensional long-term morphological simulations need more execution time and special computers because of the complicated calculations. Therefore, using one dimensional model or simplified equations are more common. One of the most important empirical equations which are still used is parabolic bay shape equation introduced by [Hsu et al., 1989] as:

$$R_n / R_\beta = C_0 + C_1(\beta / \theta_n) + C_2(\beta / \theta_n)^2 \quad (1)$$

Where, β is the angle between wave crests in diffractions point and the control line R_β . R_n is the distance between the control point and coast line along a line with angle θ_n with the wave crest. The control line is a line which connects the wave diffraction point to an optional point in down-drift part. The coefficients C were suggested initially through the curve fitting for 27 cases.

The MEPBAY software can determine the stable static shape of coastline based on the above-mentioned equation in Crenulate-shaped bays. To determine the equilibrium shape of a Crenulate-shaped bay, it is necessary to choose diffraction point and down-drift point correctly in straight part of coastline. Definition of wave diffraction point is easy in MEPBAY. For ease of implementation, MEPBAY is a good instrument for initial assessment of length, location, and layout of a new structure. However, such empirical equations cannot predict the dynamic behavior of bays. In addition, choosing a rough control point and not including some important parameters such as bed slope and wave specifications in empirical methods are some other drawbacks. A solution is using numerical tools for simulations.

LITPACK is a numerical one-line model which is one of the subsets of MIKE software, the product of DHI Company. This software is very flexible to influence all the parameters such as waves and tidal currents and sediment grading specifications. But, it is weak in modeling too curved coastlines. Furthermore, because of using single straight base line and rectangular elements, if a part of coastline has two different values of y-coordination (same as the situation shown in Figure 1), this software cannot be used for predicting the deformation of this coastline. Since the aim of this research is the simulation of crenulate bays with too much curvature, this problem limits using LITPACK.

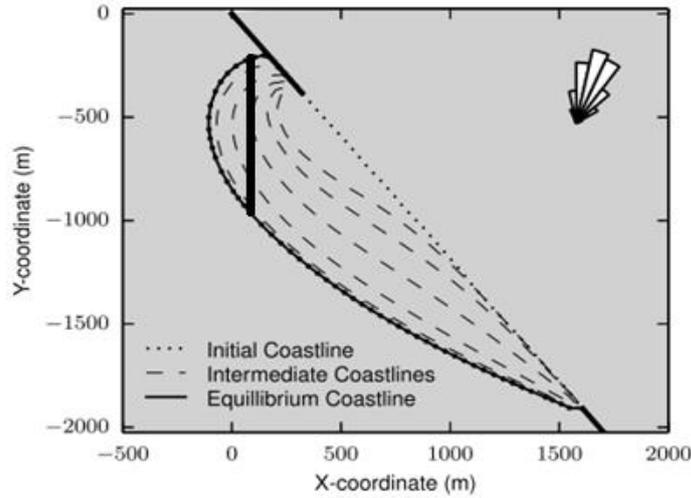


Figure 1: Shortage of the single line models with rectangular elements

Coastal Vector Evolution model (COVE), is another one-line model suitable for simulation of coasts with too much curvature. This model uses the local coordinate system and the form of elements in each area can be triangles, rectangular and trapezoidal based on the coastline curvature. For each element, the lateral boundaries are formed in a way to be perpendicular to the line which connects two adjacent coastal nodes. Coastal elements are formed in trapezoidal shapes in convex parts of the shoreline due to the divergence of boundaries. In concave parts, because of the convergence of boundaries, triangle elements are formed. In this way, the error decreases considerably. The mesh generation procedure used in COVE is shown in Figure 2. To solve the mass conservation equation and to calculate the progress rate of a coastline, equations (2) and (3) are solved in COVE for trapezoidal elements and Triangles/Polygon elements, respectively.

$$\Delta V = a_1 d\eta^2 + b_1 d\eta$$

$$a_1 = \frac{D_{sf}}{2} \cdot \tan(\epsilon_1 + \epsilon_2) \quad (2)$$

$$b_1 = w_0 D_{sf} + \frac{D_{sf}^2}{2 \tan \beta} (\tan \epsilon_1 + \tan \epsilon_2)$$

$$\Delta V = a_2 d\eta^3 + b_2 d\eta^2 + c_2 d\eta$$

$$a_2 = -\frac{1}{6} \tan \beta (\tan \epsilon_1 + \tan \epsilon_2) \quad (3)$$

$$b_2 = \frac{1}{2} w_0 \tan \beta$$

$$c_2 = A \tan \beta$$

where, w_0 is the width of coastal elements, β is bed slope in front of the coastline, A is the area of the elements and D_{sf} is closure depth. ϵ_1 and ϵ_2 are also used to measure the angle between elements as shown in Figure 2.

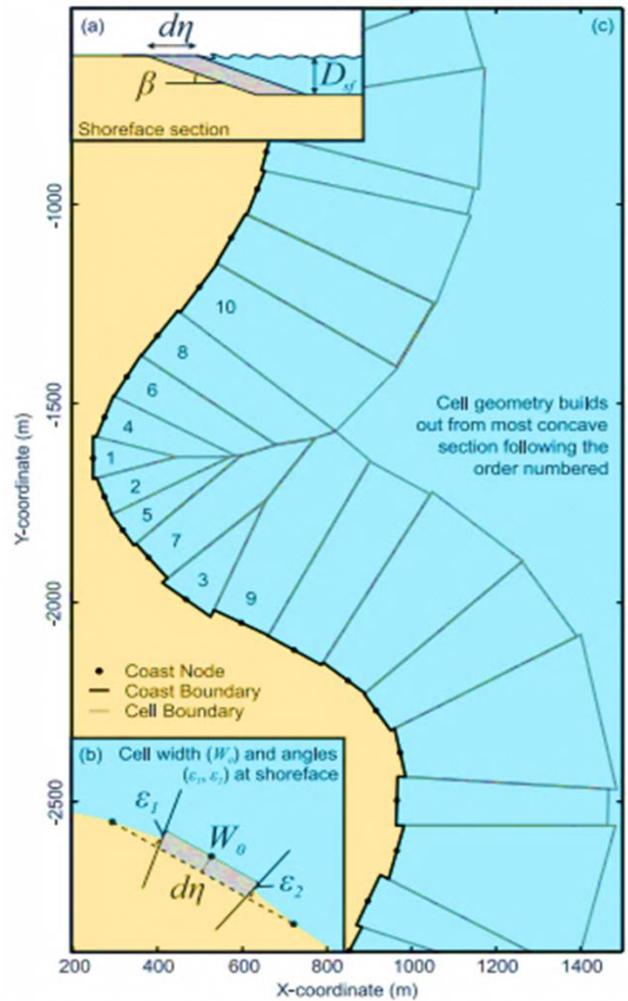


Figure 2: The way of making elements and using parameters in numerical modeling

In this numerical model, an equilibrium condition is calculated supposing that no sediment from the lateral boundaries influence the modeling area. The equilibrium condition happens when the rate of sediment transport parallel to coast is zero in all parts. In other words, the coastline will be stable if waves cannot generate any erosion. If there is a sediment source in the area or sediment exchange through the model boundaries, the equilibrium condition and

consequently the equilibrium shape of the bay will be changed. The original version of COVE, is able to predict only the static equilibrium and it is unable to present the dynamic equilibrium condition. The tidal currents cannot be simulated by this model too. But these shortages can be resolved in this open source software. Since the stable shapes of bays are studied in this research, there is no need to such improvements. In table 1, the mentioned models are presented and compared according to their priority and suitability for this research. In this table, number 1 means the most priority and number 3 means the least priority.

Table 1: Evaluation of the presented Modelling

	MEPBAY	COVE	LITPACK
Speed	1	2	3
Accuracy (too much curved coasts)	2	1	3
Stability of Solution	-	1	2
Influencing the entrance parameters (wave, bed and general currents specifications)	3	2	1

Finally, two models of MEPBAY and COVE are investigated in this research. The former is based on empirical equations and the latter one is based on one-line numerical models.

3. Sensitivity of the Numerical Results to Wave Parameters

To determine the effective parameters in the equilibrium shape of bays, a sample case is selected based on the parameters of Chabahar bay with the default input values presented in Table 2. Then, the

parameters are changed to investigate their importance. The final shapes of the bay obtained from numerical model are shown in Figure 3.

Table 2: Base values for sensitivity analysis

Parameters	Values
Shore-face Slope	0.0025
Node Spacing	40m
Closure Depth	10m
End time	100 year
Wave Parameters	$H_m=1.15$, $H_{std}=0.35$, $T_m=6s$, $T_{std}=3s$, $MWD_m=28$, $MWD_{std}=10$

As expected and presented in this figure, the prevailing wave angle is the most important factor in determining the stable shape of the coastline. In other words, coastline should conform to the wave direction and therefore, the stable shape of coastline is necessarily a function of dominant wave direction. On the other hand, by increasing the wave height, higher diffracted waves will reach to the shadow area at the back of the bay head. Consequently, the amounts of coastline erosion will be increased at this area and the stable shape of the coastline will be changed. Based on the outcomes, both the wave period and the bed slope can only affect the required time for generation an equilibrium coastline but these parameters do not considerably influence the final stable shape. Therefore, choosing the representative wave height and direction is more important than other parameters. To simulate the long-term behavior of a shoreline, a representative wave should be considered. Frequency of waves is an important parameter in this regard while waves with permanent specifications govern

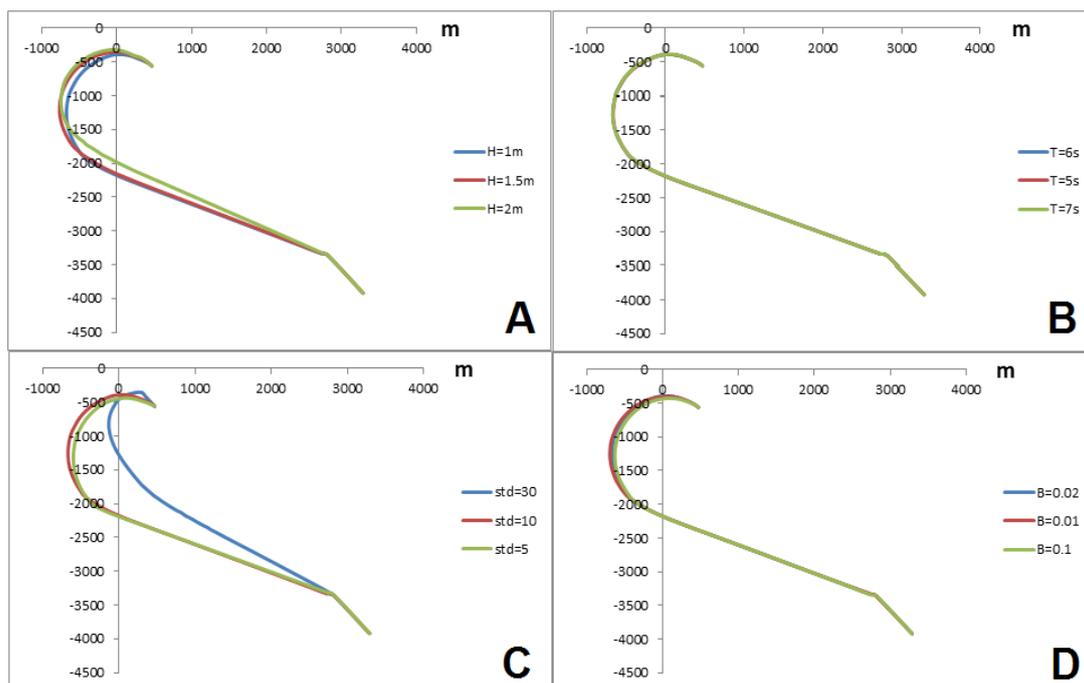


Figure 3: Effect of different parameters on the simulated morphological changes. (A): Wave height, (B): Wave Period, (C): Wave angle, (D): Bed Slope

the bay curved shape. Another factor is the wave potential in sediment transport. The criterion for choosing the representative wave is the well-known analytical sediment equation, CERC. Therefore, the height and direction of the representative wave are calculated as:

$$H_{rep} = \frac{\sum H_i^{2.5} * f_i}{\sum f_i}$$

$$\alpha_{rep} = \frac{\sum \sin(2\alpha_i) * f_i}{\sum f_i} \quad (4)$$

4. Model Verification

The numerical model COVE is not evaluated properly in modeling of Iran's bays. Therefore, it is necessary to test it on several real cases. Two cases are selected in this study as Shahid Beheshti port at the eastern part of Chabahar Bay and Pozm Port in Mokran coasts. These locations are shown with bold lines in Figure 4.

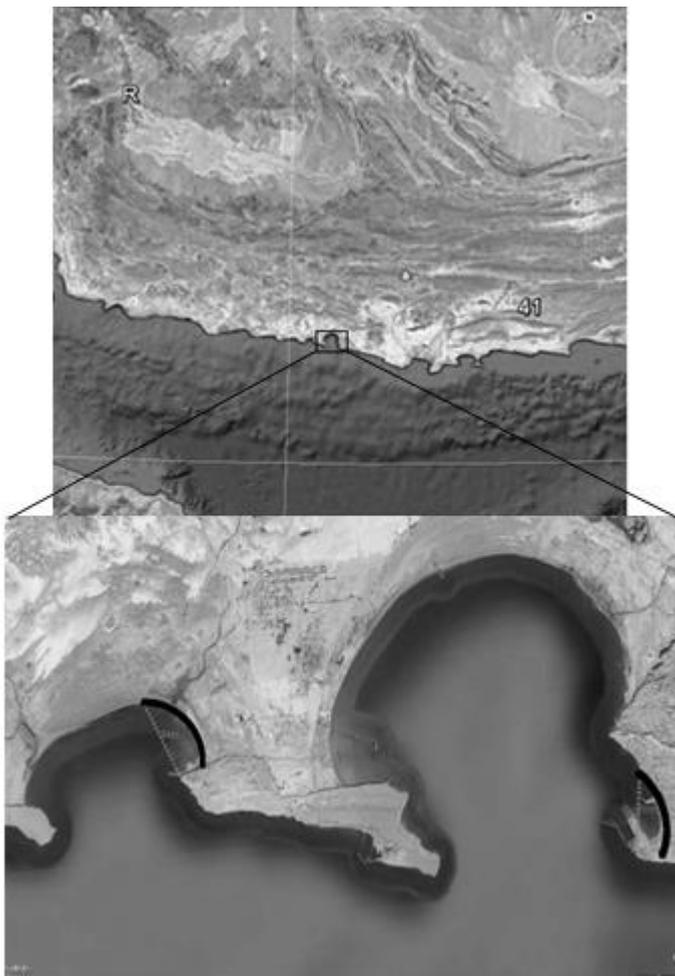


Figure 4- The applicability of COVE in the studied area (Bold lines show the areas which are modeled by COVE).

Since a long duration is required to reach a stable bay, it is assumed that the present shapes of the bays are compatible with the original position of headlands (assuming no new structure at the headlands). On the other hand, the stable shapes of these bays are obtained via both numerical and empirical models assuming no breakwater at the headlands. The results are shown in Figure 5 for Chabahar bay. The circle marks in the figures present the control points at upstream and downstream locations. Although the interior coast of the bay in Figure 5 is nearly consistent with the numerically predicted stable shape, both empirical and numerical models cannot predict well the coastlines close to the headland. However, it seems that the numerical model is generally more accurate for estimating the coastline shape.

To quantify and evaluate the results more accurately, the normal distance between the existing and the modeled coastline is measured and then its averaged value is calculated along the entire coastline to evaluate the amount of errors. Based on these calculations, the errors of the numerical and empirical methods are 11% and 18%, respectively.

The same methodology is performed for the eastern and the western areas of the Pozm bay and the results are presented in Figure 6. Again, the new constructed breakwaters are not considered in predicting the present form of the bay. Therefore, the control points are located by assuming no breakwater at the headlands. As it is observed, two numerical and empirical models have suitable ability in estimating the coastline shape. The errors of numerical and empirical models are 9% and 6.5% for the eastern part and 5% and 4% for the western part of the Pozm bay, respectively. These errors are clearly lower than the calculated values for Chabahar bay. The results also show that the coastlines in the eastern and western parts of the Pozm bay are in a static equilibrium condition.

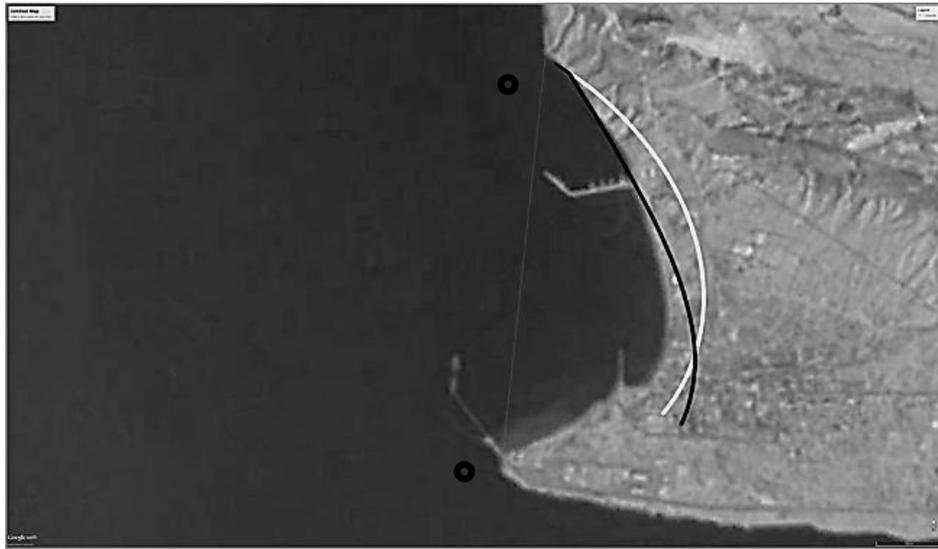


Figure 5- Dynamic equilibrium shape of Shahid Beheshti Port. (White curved line): empirical modelling MEPBAY, (black curved line): numerical model COVE

It can be understood from the results that the two mentioned models can be applied to estimate the stable shape of these bays with a relatively good accuracy. Generally, the numerical model is more accurate than the empirical model; however this is not

completely true in the Pozm area where the river can deteriorate the numerical assumptions. Therefore, it is better to use COVE numerical model for investigating the pure crenulate-shaped bays without any significant sediment transportation due to existence of rivers, etc.

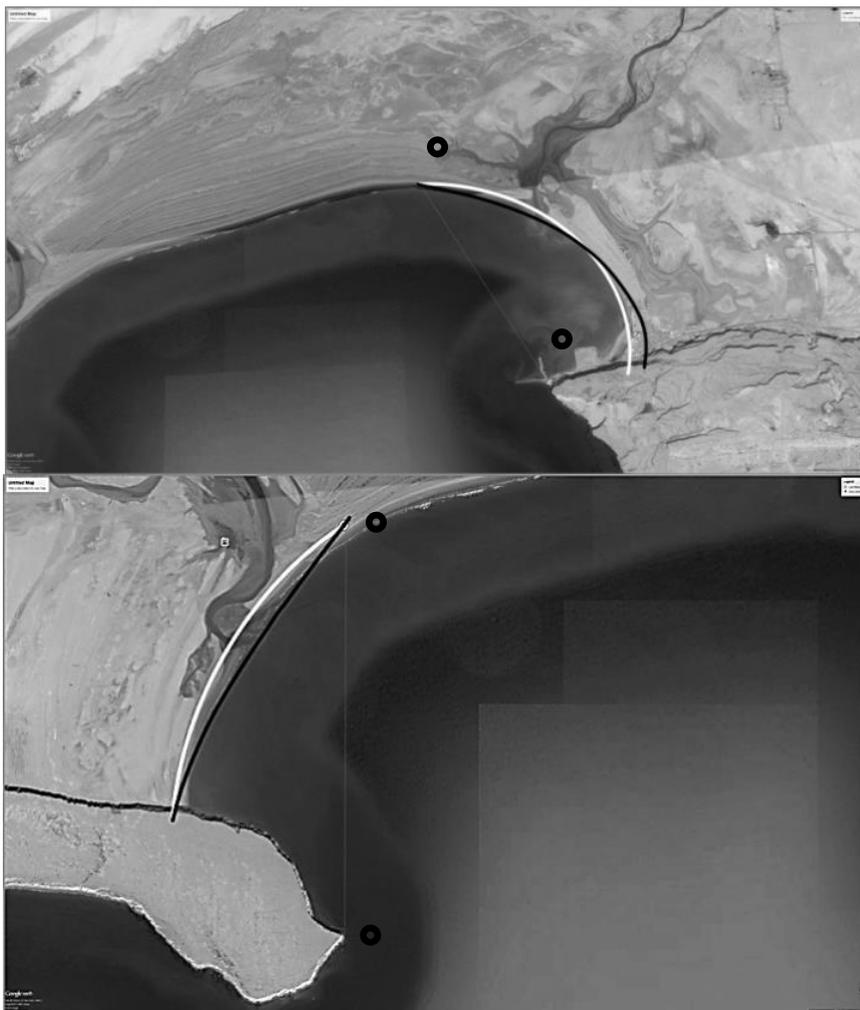


Figure 6- Static equilibrium of Pozm bay. (Up): eastern part, (Down): western part. White curved line shows empirical model results (MEPBAY) and black curved line shows numerical model results (COVE).



Figure 7- Construction of breakwater at eastern part of Chabahar bay. (Left): first construction, (Right): harbor extension.

5. Stable Coastlines around Shahid Beheshti Port

The headland at the eastern part of Chabahar Bay has been changed in two phases as presented in Figure 7. At the first phase, the static equilibrium shape of the coastline has been changed due to the construction of Shahid Beheshti breakwater. In the recent years, this breakwater has been extended during a port development plan. In this research, coastline evolution due to the breakwater extension has been investigated. Construction and extension of the breakwater at the eastern head of Chabahar bay has changed the location of control points. As a result, the stable shape of the bay has been changed. The numerical model is used for investigating this problem. It should be mentioned that the numerical model considers the influence of the hydrodynamic condition. In addition, the required time to reach a new equilibrium condition can be calculated by this model. Since the wave height and direction are the most effective parameters for estimating the stable coastline shape (as discussed in previous sections), the wave rose of the area (based on ISWM studies) as shown in Figure 8, is used to extract the height and direction of the representative wave.

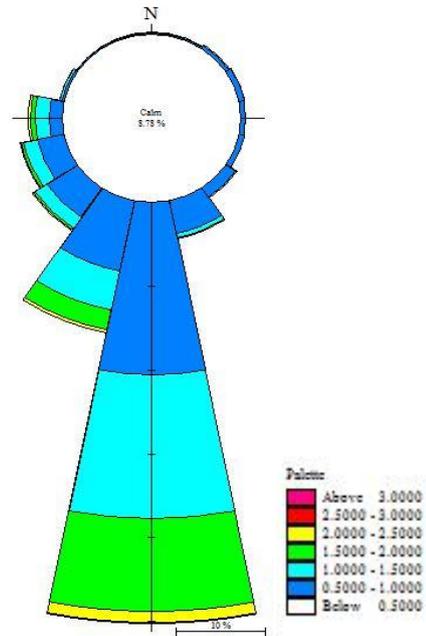


Figure 8- Rose wave ISWM Chabahar area

In the first phase, the position of the eastern headland has been changed to the breakwater head as presented in Figure 9. The new equilibrium condition is shown in figure too.



Figure 9- Coastline changes because of primitive construction breakwater



Figure 10- Changes of stable coastline because of port development

Based on the numerical results, the required time to reach this equilibrium condition is predicted about 120 years. In other words, it is anticipated that the coastline reached to its stable shape shown in Figure 9 after 120 years if no dredging performs in the port and no climate change occurs. However, the periodical dredging is an effective factor in the mentioned procedure.

In the recent years, extension of the breakwater has caused some changes in the wave and current circuits around the bay head and consequently, the sediment transport rate has been changed. This creates a new equilibrium conditions as presented in Figure 10 which is estimated to reach this condition in 100 years. New defined control points are clearly presented in this figure.

Based on the results, the stable time has been decreased after port development (from 120 to 100 years). Therefore, it can be concluded that this time is related to the interior distance between the bay heads. This conclusion is completely in agreement with the results reported by Hurst (2015). He studied the coastlines changes in several bays and concluded that the required time for making a stable bay is directly related to the square distance between two headlands. However, it should be mentioned that the wave condition and its diffraction pattern differs after

breakwater extension in the development phase of Shahid Beheshti port. This item can also change the required time to reach an equilibrium condition.

It should be emphasized that coastal changes never reached to an exact zero value in the simulations, however, after a long time; the changes become so few that can be neglected. For instance, in Figure 11, the results of coastline changes versus different years have been presented for the port development phase. To protect the clearness of picture, the curved line of the coastline changes are just shown and the background of the port is omitted. As shown in the figure, after 100 years, the coastline is involved in few changes that can be ignored.

The above-mentioned results show that if the basin is not dredged, the coastline tends to develop and reach the calculated stable shape. Meanwhile, this evolution depends on other parameters such as sediment sources and possible erosion of coastal materials. In addition, presence of reclaimed area inside the port basin as well as ship traffic will affect these outcomes.

6. Stable Coastlines Around Pozm Bay

In this part, the stability of the eastern part of the Pozm bay is investigated and the static stable

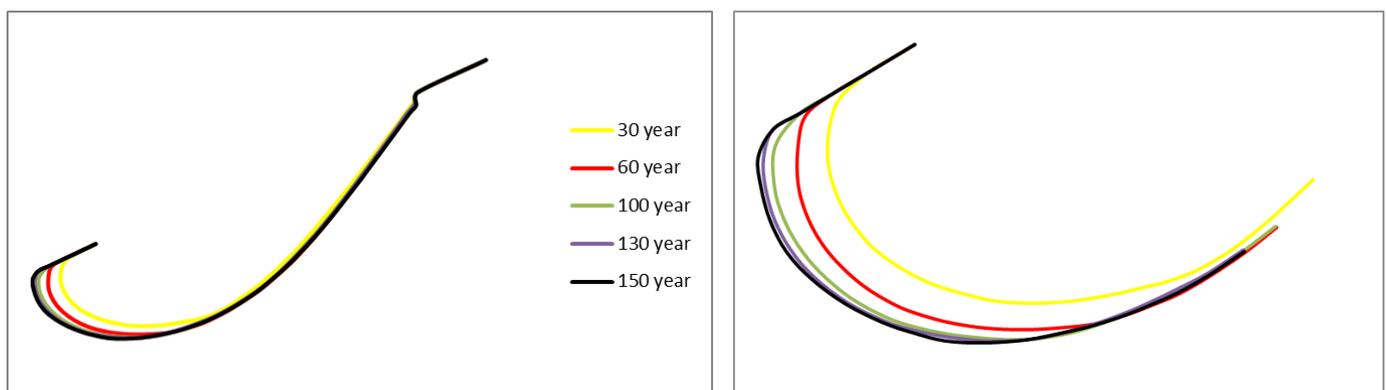


Figure 11- Coastline Evolution for the development phase of Shahid Beheshti port by the time

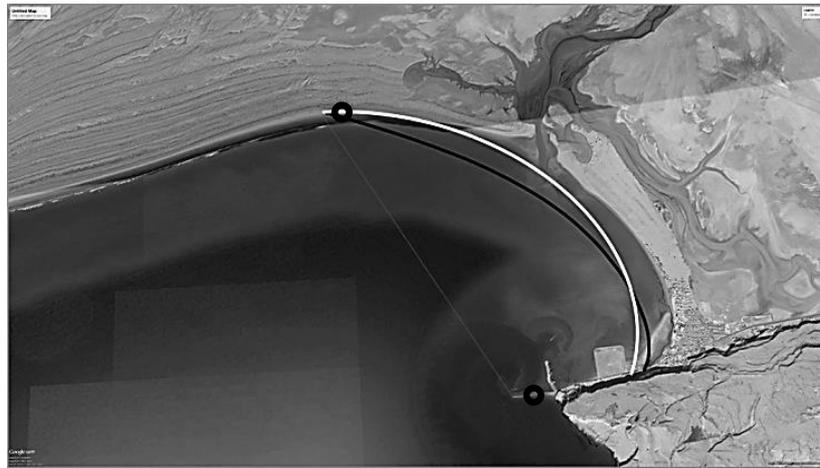


Figure 12- Changes of stable coastline because of breakwater construction along east-west (white curved line): empirical model MEPBAY, (black curved line): numerical model COVE

coastline is calculated by means of both numerical and empirical tools. As discussed in previous sections, the coastline was in an equilibrium condition before port construction (see Figure 4). The location of this headland has been changed in two steps. At first, an east-west breakwater is constructed and then, due to sedimentation problems, a north-south breakwater is designed. After breakwater construction along east-west, a new equilibrium condition as shown in Figure 12 has been created. Through breakwater construction along north-south, the diffraction wave points have been changed again. Meanwhile, as depicted in Figure 13, the new equilibrium condition in this condition is in better conformity with the present coastline.

From the above-mentioned results, it can be concluded that with the new breakwater, the stable coastline in Pozm bay is very close to the current condition and it is anticipated that no intense sediment problem threaten the port.

7. Conclusion

In this research, the stability of two crenulate-shaped bays of Mokran coasts in south-west of Iran is studied.

For this purpose, the empirical tool MEPBAY and the numerical model COVE are selected and after verification of these models, they have been applied to study the coastlines of two Chabahar and Pozm bays. These bays are selected since the location of their heads has been changed after breakwater construction. The results of sensitivity analysis show that the wave height and wave angle are the main effective parameters in coastline changes; while the contribution of other parameters such as wave and bed slope is less sensible in the final stable shape. According to the results, any construction at the headlands affects the stable shapes of the bays and it is advised to design a compatible layout with the present form of the bay to minimize unwanted effects. Based on the results, both methods can be applied suitably to predict the equilibrium shape of bays. However, the numerical model because of considering different parameters such as wave height, period, direction and also estimation of the required time to reach a static equilibrium, can be more practical. Its results are also more accurate than empirical outcomes where no additional sediment source exists.

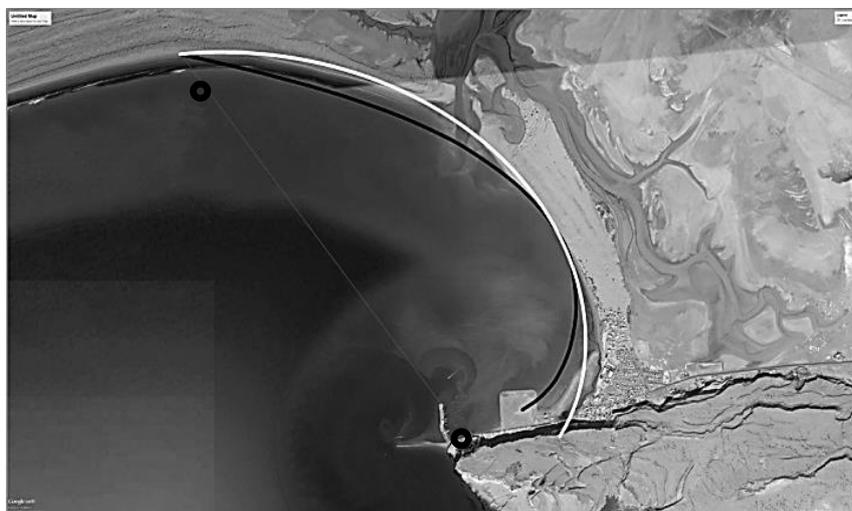


Figure 13- Coastline changes because of breakwater construction along north-south. (white curved line): empirical model MEPBAY, (black curved line): numerical model COVE

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