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Coastline Response to Groins Analysis

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Abstract— This research investigates the morphological response of coastlines to the construction of groins, focusing on both single groins and paired groins. The evolution of the coastline is analyzed with the aim of identifying a new stable coastline geometry. The approach involves modeling the stable coastline using polynomial functions, where the polynomial coefficients are determined through the application of point-specific and line-specific characteristics, as well as the principle of mass conservation. The resulting stable coastline configuration typically forms a crenulate-shaped bay an equilibrium shoreline geometry occurring between two headlands. The derived geometry, whether partial or complete, exhibits features consistent with the known characteristics and dimensions of a crenulate-shaped bay.The modeled stable coastline can be calibrated against empirical crenulate bay profiles, confirming its validity as a representation of an actual stable coastal form.

I. INTRODUCTION

A groin is a substantial coastal structure constructed perpendicular to the shoreline, either as a single unit or as part of a groin system comprising two or more groins. The primary objective of this structure is to stabilize the coastline in the vicinity of the groin. In addition to traditional groins, similar effects can be produced by causeway large-scale constructions that connect the mainland to offshore piers thereby also altering littoral processes.

These structures impede the natural movement of littoral sediments, disrupting the sediment transport equilibrium and resulting in patterns of erosion and sedimentation. This disruption leads to instability in the coastal profile near the groin, prompting an evolutionary adjustment toward a new state of equilibrium characterized by a reconfigured shoreline geometry. As such, any groin construction must include predictive assessments of the potential extent of erosion and sedimentation.

Within a groin system, the coastal area between two groins undergoes progressive morphological changes due to sediment deposition and erosion, ultimately approaching a stable shoreline configuration. The degree of erosion is influenced by the spacing between groins: greater distances typically result in increased erosion, which may threaten existing coastal infrastructure. Furthermore, the extent of erosion directly correlates with sediment deposition. Excessive spacing between groins can lead to sediment accumulation beyond the groin terminus or facilitate sediment bypassing, thereby undermining the effectiveness of the groin system. Consequently, groin system design must incorporate a thorough analysis of erosion and sedimentation patterns to determine appropriate groin spacing and length.

The formation of a stable coastline around a single groin is similarly characterized by processes of erosion and sedimentation. Consequently, the planning and design of a single groin must also incorporate estimates of the potential erosion and sedimentation affecting the adjacent coastline.

The theoretical foundation for modeling coastline evolution was first introduced by Pelnard-Considère (1956), who developed the so-called One-Line Model. This model is derived from the sediment transport equation and is expressed as a partial differential equation in both space and time. Analytical solutions to this model were subsequently explored by Pelnard-Considère (1956), Larson, Hanson, and Kraus (1987), and later by the same authors in 1997. Building on the One-Line Model, several numerical models have been developed, notably GENESIS by Hanson and Kraus (1989), and the ONELINE model by Dabees and Kamphuis (1998). These models—both analytical and numerical are considered dynamic models, as they simulate shoreline evolution as a function of time.

Whereas, the present research proposes the development of a static model that describes the final, equilibrium configuration of a stable coastline resulting from the construction of a groin. Compared to dynamic models, static models are relatively rare. One notable example is the work of Hutahaean (2018), who developed a static model describing the stable shoreline between two groins.

A well-established static model exists for the stable coastline formed between two natural headlands, often referred to as a crenulate-shaped bay. This concept has been studied extensively by researchers such as Yasso (1965), Silvester and Hsu (1972), and Hsu and Evans (1989). Based on the crenulate bay theory, it is hypothesized in this research that a similar static model can be formulated to describe the equilibrium coastline geometry formed in the presence of a groin.

II. DEFINITIONS OF TECHNICAL TERMS

The wave angle can be defined in two distinct ways. The first definition considers the wave angle as the angle between the wave ray and the beach normal, where the beach normal is a line perpendicular to the shoreline (Fig 1). Given that a groin is typically constructed perpendicular to the coastline, the wave angle may also be interpreted as the angle between the wave ray and the groin structure. The second definition describes the wave angle as the angle between the wave front and the shoreline, where the wave front is a line perpendicular to the wave ray.

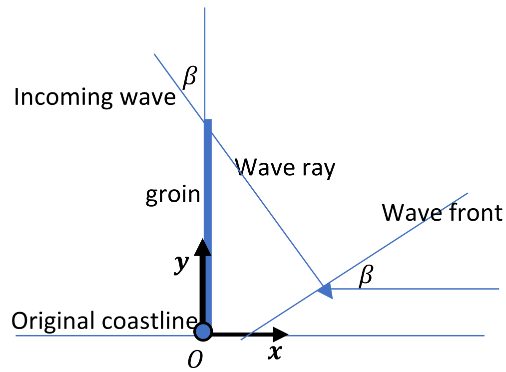

Fig (1). The definition of wave angel and axial system.

In this research, the horizontal-x axis coincides with the coastline while the vertical-y axis coincides with the groin.

III. Stable Coastline around Single Groin

In a single groin, the stable coastline on the upstream side differs from the stable coastline on the downstream side (Fig.(2)). The static equations of the stable coastlines on the two sides are also different.

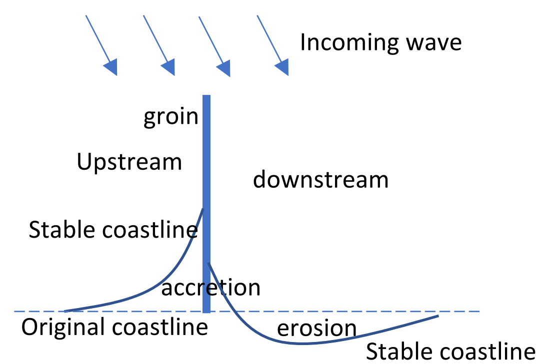

Fig.2: Stable coastline at single groin.

On the upstream, sedimentation and erosion are due to incoming waves, while on the downstream side diffraction waves can cause accretion in the groin, where erosion is caused by the incoming.

3.1. The stable coastline model on the downstream

a. Minimum Point

Within the single coastline–groin system, incoming wave angle is denoted by β (Fig. 3). On the downstream, the coastline will evolve due to sediment transport along L_{inf}, with an infinite length. The determination of L_{inf} is essential to understand the extent of coastline adjustment and sediment redistribution through trials and errors.

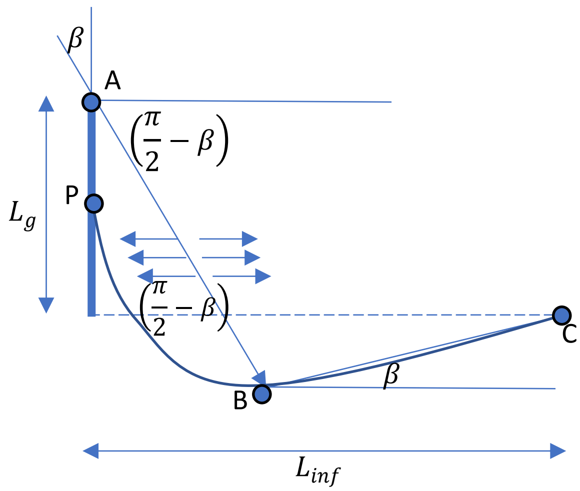

Fig.3: Stable coastline on the downstream.

Along the AB line, sediment transport occurs in two opposing directions. Due to wave diffraction, there is sediment transport directed toward the groin, while the incident (original) wave induces sediment transport away from the groin. This interaction results in the highest rate of erosion along the AB line, with the minimum point of the stable coastline located at the terminus of this line.

In reference to the theory of stable coastlines, the tangent to the equilibrium shoreline is perpendicular to the wave ray. Consequently, the AB line, which is influenced by the diffracted wave, must be perpendicular to the direction of the diffracted wave. This relationship can be expressed mathematically by the following equation:

$$y = -\tan\left(\frac{\pi}{2}-\beta\right)\, x + L_g \qquad \ldots(1)$$

Meanwhile, equation of line BC formed by the original incoming wave is expressed as:

$$y = \tan\beta\ x - L_{inf}\tan\beta \qquad \ldots(2)$$

The intersection of line BC with the diffracted wave line occurs at point $B(y_B, x_B)$ as follows

$$x_B = \frac{L_{inf}\tan\beta + L_g}{\tan\left(\frac{\pi}{2}-\beta\right) + \tan\beta} \qquad \ldots(3)$$

$$y_B = \tan\beta\ x_B - L_{inf}\tan\beta \qquad \ldots(4)$$

At Point $B\ (x_B, y_B)$, two critical conditions are known: first, the value of $x = x_B$, it is known that $y = y_B$. As the minimum point, there applies $\frac{dy}{dx} = 0$.

b. Stable Coastline Equation.

The stable coastline is modeled using a third-degree polynomial function of the form:

$$y(x) = a_0 + a_1 x + a_2 x^2 + a_3 x^3 \qquad \ldots(5)$$

$$\frac{dy}{dx} = a_1 + 2a_2 x + 3a_3 x^2 \qquad \ldots(6)$$

In this formulation, the coefficients a_0, a_1, a_2 and a_3 must be determined. To solve for these four unknowns, four independent equations are required. These equations are constructed based on the known geometric characteristics of specific points along the stable coastline (Fig 3), specifically points A, B, C, and D.

1. At $x = x_B$, it is known that $y = y_B$, hence

$$a_0 + a_1 x_B + a_2 x_B^2 + a_3 x_B^3 = y_B \qquad \ldots(7)$$

2. Point (x_B, y_B) represents a local minimum of the coastline profile. Therefore, the derivative at this point must equal zero: $\frac{dy}{dx} = 0$.

$$a_1 + 2a_2 x_B + 3a_3 x_B^2 = 0 \qquad \ldots(8)$$

3. The curve PB (Fig 3), formed by the diffraction of incoming waves, is orthogonal to the wave front, meaning that the tangent of PB is parallel to the incident wave ray.

$$\int_0^{x_B}\left(\frac{dy}{dx} - \left(-c_d\tan\left(\frac{\pi}{2}-\beta\right)\right)\right) dx = 0.$$

$$a_1 x_B + a_2 x_B^2 + a_3 x_B^3 = -c_d x_B \tan\left(\frac{\pi}{2}-\beta\right) \qquad \ldots(9)$$

c_d is the diffraction coefficient, with a range of $0.1 < c_d < 1.0$. Value c_d is obtained through calibration, by fitting the resulting stable coastline to the empirical shape of a crenulate bay.

4. At the terminal point of the stable coastline, where $x = L_{inf}$, $y = 0$, the coastline returns to its original position.

$$a_0 + a_1 L_{inf} + a_2 L_{inf}^2 + a_3 L_{inf}^3 = 0 \qquad \ldots(10)$$

There are four linear equations with four unknowns, namely equations (7), (8), (9), and (10). Using these four equations, the polynomial coefficients a_0, a_1, a_2 dan a_3, while L_{inf} is obtained through trial and error, until a condition is found that corresponds to the characteristics of a crenulate-shaped bay.

3.1.1. Crenulate Shape Bay Equation

There is a stable coastline between two headlands (Fig(4)) in the form of crenulate.

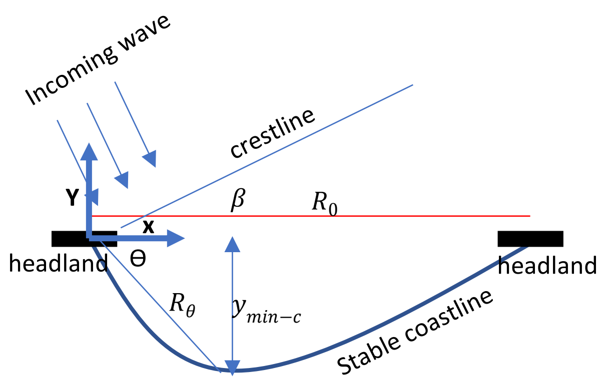

Fig.4: Crenulate shaped bay

Crenulate shaped bay equation proposed by Hsu & Evans (1989),

$$\frac{R_\Theta}{R_0} = C_0 + C_1\left(\frac{\beta}{\Theta}\right) + C_2\left(\frac{\beta}{\Theta}\right)^2 \qquad \dots(11)$$

$$C_0 = 0.0000000479\,\beta^4 - 0.00000087963\beta^3 + 0.0003521878\,\beta^2 + 0.0047891887\beta + 0.0715244255$$

$$C_1 = -0.0000001281625\,\beta^4 + 0.0000181988465\beta^3 - 0.0004865839195\beta^2 + 0.0077130700611\beta + 0.9551247533875$$

$$C_2 = 0.00000011262\,\beta^4 - 0.00001561035\beta^3 + 0.00055939061\beta^2 + 0.01497707408\beta + 0.0859531142$$

Seen from the definitions of R_0, R_θ, β and θ, both β and θ are expressed in radians. Using the relevant equation, the value of y_{min-c}, which represents the lowest point of the crenulate-shaped bay, can be determined.

In the stable coastline model, two critical parameters must be evaluated: the diffraction coefficient c_d (see Equation 9) and the length of the stable coastline L_{inf} (see Equation 10). Both c_d and L_{inf} are unknown variables and must be determined through a trial-and-error procedure. Further calculations are conducted in the segment exhibiting a crenulate-shaped bay geometry (as shown in Fig (5 and 6). Within this region, R_0 is computed, and subsequently, y_{min-c} is determined using (11). The model's accuracy is verified by comparing the computed minimum value y_{min} with y_{min-c}.

As an illustrative example, the model is applied to a coastline featuring a single groin with a length of $L_g = 100\ m$ and an incoming wave angle of 15^0. Through the trial-and-error procedure, the values $c_d = 0.35$ and $L_{inf} = 75\ m$ meters are obtained (see Fig.(5)).

There is a crenulate shape bay profile on the stable coastline, with the headland presented in Fig (6).

The headland is situated at an elevation $+1.590\ m$, with a distance between headlands $R_0 = 56.874$. The minimum point relative to the headland axis is $y_{min} = -13.646\ m$. Using (11), $y_{min-c} = -13.192\ m$ is obtained with relative difference $\varepsilon_R = \left|\frac{-13.646+13.192}{-13.192}\right| x100\% = 3.44\ \%$. This difference can be further minimized by adjusting the value of $L_{inf} = 73.0\ m$, to obtain $\varepsilon_R = 0.01\ \%$.

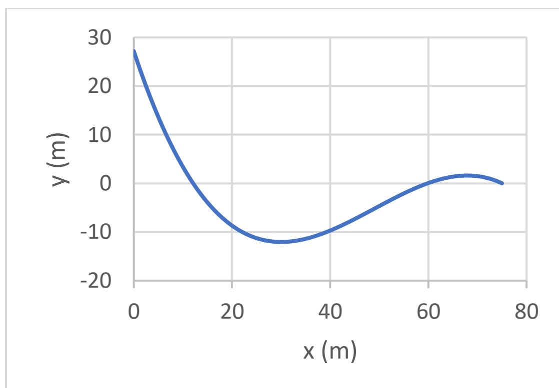

Fig.5: Stable coastline profile

From the review of stable coastline tangents, it is observed that the average tangent of line AB is $-\tan\left(\frac{\pi}{2} - \beta\right)$, perpendicular to the diffraction wave. Meanwhile, the tangent of line BC is $\tan\beta$, both of which meets the condition for a stable coastline being perpendicular to the wave direction that governs sediment transport. These findings confirm that the requirement for a stable coastline tangent to be perpendicular to the wave ray or parallel to the wave front does not imply that the resulting stable coastline must be a straight line. Rather, the stable coastline may take a curved or nonlinear form, as long as the local tangents align with the direction of the sediment-transporting wave.

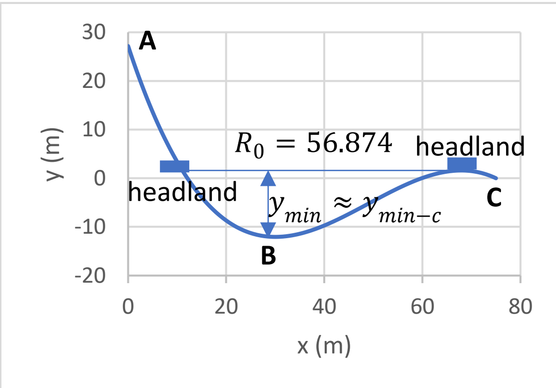

Fig.6: Headland analysis

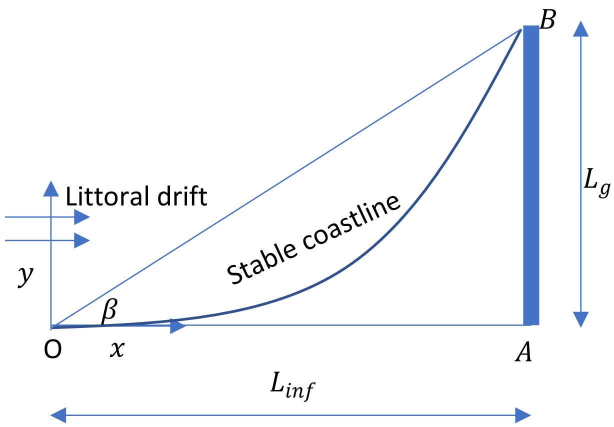

Fig.7: Stable coastline on upstream groin.

2.2. Model stable coastline on the upstream groin

The development of the stable coastline model on the upstream side of a groin is based on the assumption that there is an adequate supply of sediment from the updrift. Under this condition, over a sufficiently long time period, sedimentation will accumulate until it reaches the tip of the groin, as illustrated in Figure 7. In the event of sand bypassing, the stable coastline profile remains unaffected and continues to follow the same configuration as depicted in the figure. Accordingly, the first characteristic of a stable coastline is that at point A, where $x = L_{inf}, y_A = L_g$.

the second characteristic of the stable coastline is observed at point O, where $x = 0$, $y = 0$ and $\frac{dy}{dx} = 0$. The third characteristic is that the average slope of the stable coastline corresponds to $\tan\beta$. Therefore, the length of the groin's influence, or the extent of the stable coastline that forms, is expressed as:

$$L_{inf} = \frac{L_g}{\tan\beta} \quad \text{... (12)}$$

There are three characteristics of the stable that can be approximated by a quadratic polynomial with three unknown coefficients, represented as:

$$y = a_0 + a_1 x + a_2 x^2 \quad \text{... (13)}$$

To determine the coefficients of this polynomial, the following boundary conditions are applied,

1. At point $x = 0, y = 0$, hence
   $$a_0 = 0 \quad \text{... (14)}$$
2. At point $x = 0$, $\frac{dy}{dx} = 0$,
   $$a_1 = 0$$
3. Furthermore, the average slope of the curve from point OB is $\tan\beta$,
   $$\int_0^{L_{inf}} \left(\frac{dy}{dx} - \tan\beta\right) dx = 0.0$$

$$a_2 L_{inf}^2 = L_{inf} \tan\beta$$

Substituting (12),

$$a_2 = \frac{\tan^2\beta}{L_g} \quad \text{... (15)}$$

Accordingly, the stable coastline equation at the upstream groin can be expressed as:

$$y = \frac{tan^2\beta}{L_g} x^2 \quad \text{... (16)}$$

As an illustrative example, consider a groin with a length of $L_g = 50.0\ m$, incoming wave angel 15^0. Based on (12), the groin's influence area is calculated as $L_{inf} = 186.60\ m$, with stable coastline profile presented in Fig (8).

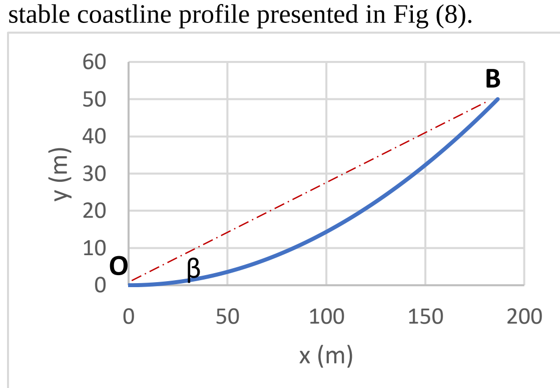

Fig.8: Stable coastline on the upstream groin.

As shown in Fig (8), the derived profile satisfies the conditions for a stable coastline, particularly the requirement that the average slope of the coastline corresponds to $\tan\beta$.

IV. STABLE COASTLINE BETWEEN TWO GROINS

On developing a stable coastline model between two groins, an important assumption is made: the distance between the groins is sufficiently short such that interaction occurs between them. The criterion for a "short" distance refers to the condition in which sediment deposition does not extend beyond the length of the groin. This distance is relative and largely influenced by the groin length itself the longer the groin, the greater the allowable spacing between groins while still being accommodated.

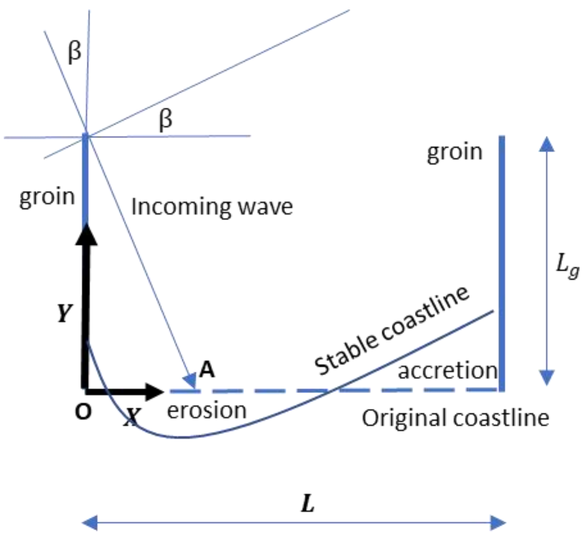

Fig.9: Stable coastline between two groins.

The stable coastline between two groins is approximated using a second-degree polynomial function:

$$y(x) = a_0 + a_1 x + a_2 x^2 \quad \dots (17)$$

To determine the values of the three unknown coefficients, three equations are required. These are obtained from a mass conservation principle and two boundary or characteristic conditions.

1. Conservation of Mass Equation

$$\int_0^L y\, dx = 0$$

$$a_0 L + \frac{1}{2} a_1 L^2 + \frac{1}{3} a_2 L^3 = 0 \quad \dots (18)$$

In this context, it is assumed that the eroded and deposited sediments possess the same porosity coefficient and are both in a saturated state.

2.At $x = 0$, a boundary condition analogous to that used for the downstream side of a single groin (as previously described in (4) and depicted in Fig. (3) is applied,

$$a_o = c_s x_A \tan\left(\frac{\pi}{2} - \beta\right) \quad \dots (19)$$

Where $x_A = L_g \tan\beta$.

c_s is a coefficient dependent on both the groin length L_g and the spacing between groins L, For a given pair of values (L_g, L), c_s is treated as a constant for a specified wave angle β.

3. The third condition asserts that the average tangent of the stable coastline between $x = x_A$ and $x = L$ is $\tan\beta$,

$$\int_{x_A}^{L} \left(\frac{dy}{dx} - \tan\beta\right) dx = 0$$

$$a_1 (L - x_A) + a_2 (L^2 - x_A^2) = (L - x_A) \tan\beta \quad \dots (20)$$

By simultaneously solving Equations (18), (19), and (20), the coefficients a_0, a_1 dan a_2 of the polynomial can be determined.

As an example, consider a model using a groin of length $L_g = 30\ m$, wave angel 10^0 and $L = 50\ m$. The resulting stable coastline profile is shown in Fig. (10). In this case, a value of $c_s = 0.153$, where $y_{min} = -3.538\ m$. Since the groin spacing is known, the only parameter adjusted through a trial-and-error process is the coefficient c_s.

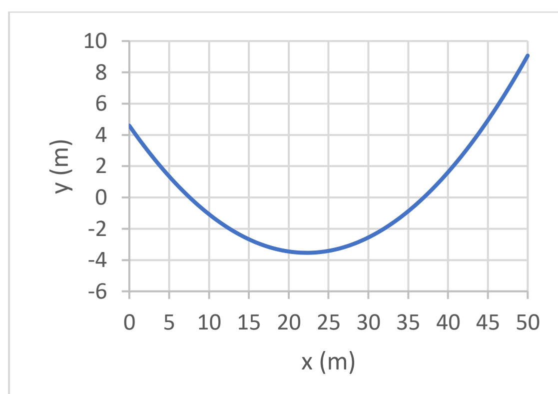

Fig.10: Stable coastline profile between two groins.

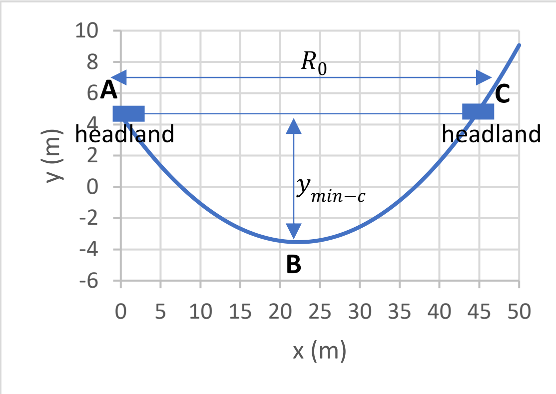

Fig.11: Verification of model results for a crenulate-shaped bay

The headland of the bay is situated at an elevation of $y = 4.590\ m$, with the left headland positioned at the groin location $x = 0$ (Fig (11)). The right headland is located at $x = 44.533\ m$, therefore $R_0 = 44.533\ m$. Using Equation (11), the minimum elevation of the crenulate-shaped bay is calculated as: $y_{min-c} = -8.137\ m$, yielding $(y_{min} - 4.590) = -3.538 - 4.590 = -8.128\ m$. Relative gap:$\varepsilon_R = \frac{-8.137-(-8.128)}{-8.137} x\ 100\% = 0.110\ \%$.

The slope of line AB is $-\tan\left(\frac{\pi}{2} - \beta\right)$ perpendicular to the diffracted wave direction Conversely, the slope of line BC is $\tan\beta$, parallel to the wave front.

V. CONCLUSIONS

Based on the analysis of the stable coastline's tangent, the polynomial approach adopted in this research yields a model that meets the criteria for a stable coastline. When evaluated against the established theory of stable coastlines in crenulate-shaped bays, the polynomial model also produces results consistent with observed patterns. Therefore, in general, the polynomial model developed in this research effectively represents the stable coastline configuration around a groin.

The coastal response to the presence of a groin involves both erosion and sedimentation processes. In eroded regions, the resulting stable coastline tends to form a crenulate-shaped bay. However, the interplay of erosion and sedimentation may also produce a crenulate geometry, as observed in the equilibrium shoreline between two groins. In the case of a single groin, erosion and sedimentation can occur on either the downstream or upstream side, allowing such structures to serve as effective protective measures against coastal erosion in their immediate vicinity.

In the design of groin systems for shoreline protection, the spacing between groins emerges as a critical parameter. Larger distances between groins tend to result in increased erosion, which may pose a threat to onshore infrastructure. Therefore, careful consideration must be given to the spacing in order to achieve optimal coastal stability.

In conclusion, while the principle of a stable coastline states that the tangent to the shoreline at equilibrium is parallel to the wave angle, this does not imply that the stable coastline is a straight line. Rather, the coastline may assume a curved form when the resultant tangent at any given point aligns with the tangent of the wave angle.

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