Development of a Predictive Closure Depth Equation Using Field Data and Wave Refraction Modelling

MS Ab Razak and AR Khan

Department of Civil Engineering, Faculty of Engineering, Universiti Putra Malaysia 43400 Serdang Malaysia

Abstract. In any beach nourishment project, the estimate of the closure depth is the most important aspect and it can be obtained from periodical beach profile survey data and an analytical approach. In this paper, beach profile survey data of four years 2003 (before nourishment), 2005-2007 (after nourishment) and 11 beach profile chainages were analyzed to measure the closure depth using the Fixed Depth Change (FDC) method for the case study at Teluk Cempedak, Kuantan. The results from the measured closure depth were then compared to that calculated from the Hallermieier equations. The $H_{s0.137\%}$ wave height was determined by a wave refraction model that was developed and analyzed against offshore wave heights to predict the onshore wave heights at a depth of 10 m using Delft3D model. In comparison, the predictive equation showed an underestimate of the average closure depth of approximately 5%. This underprediction could be due to the inclusion of closure depths that are captured at the mid-zone for the chainage profiles that are located near the southern headland. Neglecting these chainage profiles lead to an over-prediction of the closure depth. This is consistent with the concept of Hallermieiers that the predictive equation determines an upper limit value of the closure depth. The new closure depth for the studied area was established and can be equated to 0.8 times $H_{s0.137\%}$.

1. Introduction

According to the study carried out by Department of Irrigation and Drainage, Malaysia from November 1984 to January 1986, out of the country's coastline of 4,809 km, about 29% or 1,380 km was eroded. In 2006, a new shoreline study was carried out and the output from the study showed that the eroded coastline has increased by two to three percent. It continuous to prescribe prompt coastal erosion assurance on the critical coastline along Malaysia coastlines and prompted the advancement of the Coastal Erosion Control Program (CECP) under the Department of Irrigation and Drainage (DID), Malaysia. Since the rise of the tourism industry as a prevailing division of the Malaysian economy, the necessitate to safeguard the aesthetics and quality of shorelines has turned into a crucial incentive for the CECP. As a result, the comprehension of the development of nourishment coastlines must be upgraded to enhance prospect development and design work.

Several engineering approaches have been applied to counteract the effect of erosion, either by stabilizing or restoring the beach. Beach nourishment is one of the preferred shore protection measures because it is often the least expensive alternative, augments existing shore protection structures with great flexibility, and provides a natural and enjoyable coastal environment. Most coastal engineers consider beach nourishment, a viable engineering alternative for coastal protection when it is properly designed and placed in the proper location. Beach nourishment requires an improved understanding of
beach location, shoreline processes, cost-benefit, sand placement and distribution prediction design and monitoring.

The closure depth is an important aspect of beach nourishment. It is widely used within coastal engineering to describe the seaward limit of an appreciable depth change [1]. The closure depth is a theoretical depth along a beach profile, where sediment transport is very small or non-existent, dependent on wave height and period, and occasionally, sediment grain size. More specifically, the closure depth is defined as depth of closure for a given or characteristic time interval is the most landward depth seaward of which there is no significant change in bottom elevation and no significant net sediment transport between the near-shore and the offshore [2]. Often the closure depth is used in coastal engineering design for projects such as beach and nearshore berm nourishments, and jetty and navigation channel designs.

It is a common practice that the closure depth is determined by a predictive formula as introduced by [3], in case where periodical survey data is lacking. Recent developments on predictive formula to determine closure depth include the application of Galerkin formulation of the finite element method [18], determination of closure point based on sediment size [17] and cross-shore sediment transport by the calculation of the Net Cross-shore Sediment Transport Parameter [16]. Beach monitoring periodical monitoring survey is carried out after the completion of a beach nourishment project to determine the changes of beach profiles. This offers a prospect for further analyses and studies of the closure depth with intend of refining the beach nourishment design of sand-fill for local conditions. Periodical beach survey monitoring after the nourishment is essential to assess the performance of beach nourishment. There is very little knowledge or work that has been done to determine the actual time span for nourishment required. Due to lack of continuous beach profile data, it is hard to calculate the beach equilibrium profile that gives better understanding of the time span for nourishment required. In most cases, the determination of closure depth is carried out based on experiences from the past projects or based on the application of the predictive equation as proposed by [3] which has proven to over predict the closure depth. Nevertheless, the predictive equation is still valid, however proper judgement should be made before it can be applied.

This study, therefore, is done to help better understanding of beach nourishment project by combining data gathered from ground observation and wave modelling outputs. The research aims, first to determine the closure depth from beach profile data, second to determine onshore wave condition to be used in predicting the equation for closure depth, and third to compare both closure depths from measurement and prediction and thus formulate a local predictive equation for the study area.

2. Literature Review
Beaches are common features of the coast. There is continually sand being detached and sand being introduced to the beach. Regularly, beaches alter extensively throughout the year, depending upon the regularity of storms. In the long run, a beach erodes because the delivery of sand to the beach cannot keep up with the loss of sand to the sea. Most sand is carried from inland via rivers and streams. Sand can also be transported from beach to beach along a shoreline, but this is mostly just a redistribution of sand that is already on the coast. Natural factors such as shoreline geology, sand supply, wind, waves, tides, storms, current, change in sea level, bathymetry and quality, and sand movement among the dunes, offshore bars and beach can contribute to sand loss on the beach [4, 5]. Man-made activities including shoreline development, construction of seawalls, groins, harbours and jetty, damming of rivers, beach nourishment and dredging of tidal inlets can also cause the shortage of sediments [6, 7].

To locate the toe of nourished sand, closure depth point is required. There are several definitions for closure depth, including depth of active sediment movement, profile pinch-off depth, depth of active profile, critical depth, and beach erosion for maximum depth, the seaward boundary of nearshore eroding wave condition and seaward limit of effective wave action. The following sections describe the importance of closure depth estimation either based on profile surveying method and analytical calculation to beach nourishment.
2.1 Beach nourishment
When eroding coastline requires protection, the most preferred engineering solution is a beach or shore nourishment [8, 9]. It is important to have a detailed understanding when designing a beach nourishment project that how the local hydrodynamic or morphodynamic regime will respond to the nourished coast. Even if the hydrodynamic condition of the coast does not change still it will be useful to understand whether the local morphodynamic regime will be affected by the placement of fill material. In recent years’ closure depth, which is one of the fundamental aspects of the morphodynamic regime has received great attention [3, 10].

Beach nourishment projects are mostly done on the open coast, in a near-shore location dominated by the wave. However, it is important for engineers to know that there are other processes involved, which may determine the closure depth, depending on the conditions. To determine the actual location of the closure depth is a matter of the depth change criterion with the set of measurement used to define closure depth. Deeper changes are ignored when the criterions are greater, and the closure depth estimate will also be shallower. In practical, closure depth is mostly defined using the measurement precision. Models are limited to predicting closure depth. [3] was the pioneer researcher that developed the analytical method used to measure the annual closure depth for a sandy beach.

2.2 Closure Depth Estimation from the Profile Surveying Methods
Valuable data characterizing the morphology and key beach feature including nearshore, beach and sand bars can be obtained from the beach profile survey. The volume of sand that is gained or lost over a particular time interval can be calculated by comparing past data to present data. This helps to understand when to nourish beach, how much sand is required and where to place it. Through a chain of profile survey conducted over a period of time, the observed closure depth can be derived empirically. Depth coincides with a pinch-out depth under which depth variations become limited [11]. The analysis of profile to estimate the closure depth is largely influenced by the accuracy of the field survey. Hydrographical and topographical surveys are the most used methods of collecting beach profile data. For example, the hydrographic survey tool such as Coastal Research Amphibious Buggy (CRAB) was used at Duck for detail profile survey, which has surveyed accuracy standard deviation of up to ±2.5 cm [11, 12]. Sea-sled is another recommended method by [2] for beach nourishment design which has an accuracy of 2.54 cm.

Two popular approaches to estimate the closure depth by comparing different beach profile data include Fixed Depth Change (FDC) method and Standard Deviation Depth Change (SDDC) method [10]. The FDC defines closure depth as the point at which the depth variation between two profiles from the same location and taken at different moments of time is less than or equal to a pre-established value. The SDDC defines closure depth as the point at which the standard deviation reaches a minimum or a constant value different to zero that commonly coincides with the measurement error coming from the beach profile surveys. In this case, variation of the standard deviation is obtained for all the available profiles for the same alongshore location. The recent approach to determine closure depth is by the Net Cross-shore Sediment Transport Parameter (NCSTP) [16]. While the FDC and SDDC only consider the bottom elevation change, the NCSTP method works by quantifying the cross-shore sediment transport parameter, an important factor to be considered to observe the evolution of beach profiles. In this study, only the FDC method is applied.

2.3 Closure Depth Estimation from the Analytical Calculation
An analytical approximation, using linear theory for shoaling waves, to predict an annual value of closure depth, on natural beaches was developed [12]. This can be generalized to a time-dependent form [13]:

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[1] refers to the reference number in the text.
\[
h_{in} = 2.28H_s - 68.5\left(\frac{H_s^2}{gT^2}\right)
\]  
(1)

where \(H_s\) is the effective wave height just seaward of the breaker zone that is exceeded for 12 hours per year, i.e. the significant wave height with a probability of yearly exceedance of 0.137\%, \(T\) is the wave period associated with \(H_s\) and \(g\) is the acceleration of gravity.

Birkemeier presented that Hallermeier proposed a functional relationship that appeared reasonable, but the observed closure depth is over predicted about 25\% by Equation (1). Equation (1) was then modified by [14] and yields

\[
h_{in} = 1.75H_s - 57.9\left(\frac{H_s^2}{gT^2}\right).
\]  
(2)

The Hallermeier’s equation can be further simplified as [14, 15].

\[
h_c = 1.57\ H_{0.137}.
\]  
(3)

\(h_c\) is predictive closure depth and \(H_{0.137}\) is near shore wave height exceeded 12 hours in a year. Equation (3) has the advantage as it uses only one parameter to calculate closure depth without the need to find wave period that exceeded 12 hours in a given time interval, but this equation cannot be used to estimate closure depth for a particular storm event.

### 3. Methodology

#### 3.1 Study Area

The study area located on the east coast of Peninsular Malaysia is a popular beach amongst the local and international tourists. The beach is characterized as a pocket bay beach, bounded by two headlands Tanjung Tembeling dan Bukit Pelindung Tengah as shown in Figure 1. The beach length is 1000m with an average dry beach width of 120 m. The beach is exposed to South China Sea that brings higher waves during the northeast monsoon. The sediment grain sizes range from fine to coarse sand where the coarse particles are found near the headlands while finer sand particles commonly found in the middle part of the beach. Above the mean level, the beach sizes range from 1.4833mm to 0.969mm while below the mean sea level, sand particles range from 0.948mm to 0.842mm. The beach slope is relatively steep, indicating a reflective type of beach. The beach had undergone sand nourishment in 2004 and a series of beach monitoring survey was conducted in 2003 before the nourishment and lasted for three years i.e. 2004-2007 after the nourishment was completed.
3.2 Beach Profile Surveys
Eleven profile surveys were conducted covering the whole dry beach area and extending down to approximately 10-12 m depths of water. The profile depth is measured at every 10 m cross-shore at an interval of 100 m alongshore starting from Chainage 400 and ending at Chainage 1400. The northern, middle, and southern profile surveys are indicated in Figure 2. In this study, profile surveys of 2003 before nourishment, 2005, 2006 and 2007 after nourishment were used. Comparing profile surveys before the nourishment and profile surveys after the nourishment for three consecutive years, the beach profiles have evolved over the years and this is expected due to the natural action of waves and currents derived from the monsoonal system. The movement of sand is evident as the nourished profiles migrate shoreward and landward consecutively over the years and seem to reach its equilibrium state three years after the nourishment was done.
Figure 2. Measured beach profiles before nourishment and three years after nourishment for selected chainages. Chainage 400, Chainage 800 and Chainage 1400 represent northern, middle, and southern profile, respectively. Profile 2007 is overlapped with profile 2005. Inset represents the full cross-shore profile extending down to 12 m depth.

3.3 Fixed Depth Change (FDC) Method
To determine the closure depth, the fixed depth change method is adopted. For this study, a criterion line of 0.25 m was used as a reference to indicate the inner, middle or outer closure points as shown in Figure 3. The inner closure depth point is indicated when the down-crossing line is nearer to the 0-m shoreline. The outer closure depth point is marked when the down-crossing line is far away from the shoreline. The middle closure depth point is indicated between the inner and outer points.

Figure 3. FDC criteria line of 0.25 m applied in this study for data accuracy. The example shows the FDC method results in inner closure depth point located 140 m from the shoreline.
3.4 Wave Refraction Modelling

Delft3D model was used to model the propagated waves from offshore to nearshore. Non-equidistant grids were generated where the coarser grids were at the offshore boundary and finer grid cells were created near the shoreline. A linear interpolation method was adopted for bathymetry from the deepest depth of 25m at the offshore boundary and 0-m depth at the shoreline. The model area was extended few kilometres northward and southward of the study area to allow refraction and diffraction of waves near the intervening headlands. Figure 4 shows the model grid and bathymetry generated by the DEFGRID and QUICKIN modules.

![Model Grid and Bathymetry](image)

**Figure 4.** Model Grid and Bathymetry. Left panel represents model grid and right panel represents contour depth bathymetry. Positive values indicate depths above 0-meter water line and negative values indicate depths 0-m below water line.

To fulfill the requirement of the Hallermeier equation that requires the significant wave height that exceeds 12 hours per year i.e. $H_{S0.135\%}$, the historical offshore waves of five years i.e. 2003-2007 were analyzed. These data are obtained from National Oceanic Atmospheric Administration (NOAA) for the Kuantan coast, comprise of wave heights, wave periods, and wave directions as shown in Figure 5 (left).

An exceedance probability analysis was further conducted to determine the represented offshore wave height and associated wave period to be used as an input for the wave refraction model. Nearshore waves were then captured at 10 m contour depth. The nearshore wave height was used as an input to Hallermeier equation to determine the predictive closure depth. The Hallermeier predictive closure depth was then compared to the measured closure depth. The cumulative percentage curve is plotted to determine the represented offshore wave height as shown in Figure 5 (right). The effective wave height $H_{S0.137\%}$ from the graph can be noted as 3.3 m and its corresponding wave period as 11 sec and was used as an offshore boundary in the model.
Figure 5. Offshore waves. Left panel represents the offshore wave rose of wave heights and predominant direction and right panel represents the cumulative percentage of exceedance of wave heights.

4. Results and Discussion

4.1 Closure Depths Estimate from Fixed Depth Change Method

The beach nourishment was done between CH400 to CH1400. A criteria line of 0.25 m was established which correlate to the adequacy of the hydrographic survey using FDC method to estimate the closure depth. The results for this discussion are given starting from the north at chainage CH400 and ending at the southernmost chainage at CH 1400. The analysis of the closure depth for the year 2003, 2005, 2006 and 2007 revealed that some chainages have more than one closure depth i.e. inner-shore, middle-shore and outer-shore. The example of changes that consist of two closure depth points is given in Figure 6.

Figure 6. Selected chainage profiles that consist of two closure points.
At CH1200 the FDC method shows a closure depth of -3.285 m LSD and closure depth of -6.61 m LSD at 240 m and 630 m, respectively. The bar is located at -6 m water depth. There are significant bed elevation changes at the start of inshore which is due to the nourishment and at the mid-shore indicating beach is unstable. The FDC closure depth of CH 1200 is determined to be -3.29 m LSD located at 240 m from shoreline. No major changes in the shoreline occur due to the location of the middle bar.

Table 1 shows the measured closure depths for all chainages and their distances from the baseline. Generally, the closure depths from all data indicate that it lies in shallower water depth at an average range of depth -3.1 m to -4.6 m LSD, located approximately between 253 m to 418 m from shoreline. The 2005-2006 measured closure depths indicate that the closure depth tends to be deeper and located further offshore. This phenomenon reveals that the sediment has begun to move seaward and the beach profile is close to attaining equilibrium state. After three years (2007) of nourishment, the beach profile is more even and no major changes in bed height were noticed. In general, the closure depth tends to be deeper and the closure point is further seaward.

Table 1. Closure depths from measured beach profiling surveys

| CH  | 2003-2005 | 2005-2006 | 2006-2007 |
|-----|-----------|-----------|-----------|
|     | Measured Hc (m) | Distance from shoreline (m) | Measured Hc (m) | Distance from shoreline (m) | Measured Hc (m) | Distance from shoreline (m) |
| 400 | -1.86     | 140       | -3.14     | 290       | -2.29     | 160       |
| 500 | -2.49     | 160       | -5.04     | 570       | -1.79     | 140       |
| 600 | -2.61     | 170       | -4.00     | 410       | -2.19     | 160       |
| 700 | -2.71     | 170       | -3.26     | 230       | -2.46     | 170       |
| 800 | -3.04     | 190       | -4.90     | 500       | -2.16     | 160       |
| 900 | -2.81     | 190       | -3.66     | 270       | -1.01     | 130       |
| 1000| -2.96     | 200       | -4.64     | 440       | -1.89     | 180       |
| 1100| -2.84     | 210       | -4.66     | 410       | -1.19     | 160       |
| 1200| -3.29     | 240       | -3.69     | 270       | -6.49     | 600       |
| 1300| -5.49     | 470       | -6.29     | 570       | -6.51     | 600       |
| 1400| -7.26     | 640       | -7.24     | 640       | -7.26     | 640       |
| Average | -3.39     | 253       | -4.59     | 418       | -3.13     | 282       |
4.2 Closure Depths Estimate from the Analytical Equation

[10] presented the predicted closure depth as to represent its relationship to the chosen time period of analysis. Delft-3D model was used to transform offshore wave height that exceeds 12-hous to their nearshore equivalents. The output of model was then used to fit the predictive equations for both original and simplified versions.

4.2.1. Wave Refraction Modelling Output. To create nearshore wave condition, National Oceanic and Atmospheric Administration (NOAA) offshore wave data for a period of 2004-2007 has been used to extract on-shore wave heights from the eleven chainage locations within the model at a depth of 10 m, based on the exact location of the profile line used in the study. The wave height and period extracted from the model are needed to calculate the annual closure depth using Hallermeier predictive equation. The outcome of the wave modelling is shown in Table 2. The transformed wave height at nearshore was observed to be lesser than the offshore wave. This is due to refraction process. As the wave approaching the shore, wave losses its energy due the breaking effect with the bed of the shore. Figure 7 shows the pattern of wave refraction for two different scenarios of incoming wave directions.

![Figure 7](image)

**Figure 7.** The patterns of wave refraction using the offshore wave height of $H_{0.137^\circ}$ in the model for wave direction of $90^\circ$ (left panel) and $120^\circ$ (right panel) from the north. The transformed wave height at nearshore was observed to be lesser than the offshore wave as indicated by the coloured bar.

The details of mean and max wave height are tabulated in Table 2. The maximum wave height at 10 m depth is almost 35% less than the offshore height and the wave period is reduced by 20 %. This is expected as the wave loses its energy when it propagates from deep water to shallow water. Wave processes such as shoaling and refraction have taken in place, diminishing the wave energy as wave approaching the shore.
Table 2. Wave heights at 10 m depth based on offshore wave of $H_{S_{0.137}} = 3.3$ m and $T_p = 11$ sec

|       | CH 400 | CH 500 | CH 600 | CH 700 | CH 800 | CH 900 | CH 1000 | CH 1100 | CH 1200 | CH 1300 | CH 1400 |
|-------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| N30   | Hs (m) | 0.74   | 0.63   | 0.80   | 0.84   | 0.77   | 0.58   | 0.57   | 0.54   | 0.47   | 0.46   | 0.36   |
|       | Tp (s) | 8.77   | 9.27   | 9.54   | 9.70   | 9.59   | 9.20   | 9.33   | 9.48   | 9.51   | 9.43   | 9.10   |
|       | MWD (deg) | 83.69 | 76.15 | 76.72 | 82.14 | 83.65 | 77.45 | 71.43 | 75.76 | 73.34 | 76.96 | 81.50 |
| N60   | Hs (m) | 1.50   | 1.55   | 1.69   | 1.87   | 1.72   | 1.62   | 1.75   | 1.83   | 1.87   | 1.98   | 2.16   |
|       | Tp (s) | 8.60   | 8.52   | 8.68   | 8.85   | 8.75   | 8.65   | 8.83   | 8.89   | 8.99   | 9.05   | 9.16   |
|       | MWD (deg) | 76.95 | 71.21 | 63.01 | 63.78 | 64.73 | 65.71 | 62.33 | 62.69 | 62.46 | 68.11 | 65.94 |
| N90   | Hs (m) | 1.70   | 1.66   | 1.86   | 2.02   | 1.82   | 1.64   | 1.76   | 1.79   | 1.75   | 1.90   | 1.88   |
|       | Tp (s) | 8.69   | 8.79   | 8.97   | 9.09   | 8.97   | 8.78   | 8.95   | 8.99   | 9.07   | 9.10   | 9.11   |
|       | MWD (deg) | 80.33 | 74.80 | 67.98 | 69.96 | 72.05 | 71.06 | 66.56 | 69.49 | 69.57 | 74.60 | 73.57 |
| N120  | Hs (m) | 1.37   | 1.25   | 1.46   | 1.56   | 1.42   | 1.19   | 1.25   | 1.22   | 1.15   | 1.22   | 1.09   |
|       | Tp (s) | 8.67   | 8.93   | 9.17   | 9.29   | 9.16   | 8.85   | 9.01   | 9.07   | 9.13   | 9.10   | 8.96   |
|       | MWD (deg) | 82.70 | 76.56 | 72.50 | 75.97 | 78.38 | 75.41 | 69.73 | 74.03 | 73.94 | 78.57 | 80.44 |
| N150  | Hs (m) | 0.74   | 0.63   | 0.80   | 0.84   | 0.77   | 0.58   | 0.57   | 0.54   | 0.47   | 0.46   | 0.36   |
|       | Tp (s) | 8.77   | 9.27   | 9.54   | 9.70   | 9.59   | 9.20   | 9.33   | 9.48   | 9.51   | 9.43   | 9.10   |
|       | MWD (deg) | 83.69 | 76.15 | 76.72 | 82.14 | 83.65 | 77.45 | 71.43 | 75.76 | 73.34 | 76.96 | 81.50 |
| Mean Wave Height | 1.21   | 1.14   | 1.32   | 1.42   | 1.30   | 1.12   | 1.18   | 1.19   | 1.14   | 1.20   | 1.17   |
| Mean Wave Period | 8.70   | 8.96   | 9.18   | 9.33   | 9.21   | 8.94   | 9.09   | 9.18   | 9.24   | 9.22   | 9.08   |
| Max Hs | 1.70   | 1.66   | 1.86   | 2.02   | 1.82   | 1.64   | 1.76   | 1.83   | 1.87   | 1.98   | 2.16   |
| Corresponding Tp | 8.77   | 9.27   | 9.54   | 9.70   | 9.59   | 9.20   | 9.33   | 9.48   | 9.51   | 9.43   | 9.16   |

$H_s =$ significant wave height, $T_p =$ wave period, MWD = mean wave direction.

4.2.2. Prediction of closure depths from the original Hallemeier equation. Using local nearshore wave condition, Hallemeier equation has been applied to predict the annual closure depth. The results have shown that unlike most cases, Hallemeier equation under-predicts the closure depth by an average of 5%. If we ignore chainages CH1200, CH1300 and CH1400 as they are located close to Tanjung Tembeling headland, and the measured closure depths are affected by too much change in depth of profile line, the Hallemeiers equation remains valid and over-predicts the closure depth by 8%, still within the acceptable percentage as proposed by [3]. Table 3 shows the distribution of predictive closure depth along the coastline. These results indicate a tendency of higher accuracy with an increase in the data of profile surveys and time used to determine the exact location of closure depth.
The results show that the measured closure depth values are generally close to the predicted values. Table 3 presents the measured and predicted Hallermeier closure depth values, and Table 4 shows the measured and simplified predictive Hallermeier closure depth values.

**Table 3. Measured and predictive Hallermeier closure depth**

| CH | 2003-2005 | 2005-2006 | 2006-2007 | Predicted hc | % Diff. 1-yr |
|----|-----------|-----------|-----------|--------------|-------------|
|    | Measured hc (m) | Distance from shoreline (m) | Measured hc (m) | Distance from shoreline (m) | Measured hc (m) | Distance from shoreline (m) |            |            |
| 400 | -1.86 | 140 | -3.14 | 290 | -1.86 | 140 | 2.6 | 40.90 |
| 500 | -2.49 | 160 | -5.04 | 570 | -2.49 | 160 | 2.6 | 5.30 |
| 600 | -2.61 | 170 | -4.00 | 410 | -2.61 | 170 | 3.0 | 13.50 |
| 700 | -3.04 | 170 | -3.26 | 230 | -2.71 | 170 | 3.2 | 18.30 |
| 800 | -3.04 | 190 | -4.90 | 500 | -3.04 | 190 | 2.9 | -3.1 |
| 900 | -2.81 | 190 | -3.66 | 270 | -2.81 | 190 | 2.7 | -5.3 |
| 1000 | -2.96 | 200 | -4.64 | 440 | -2.96 | 200 | 2.8 | -6.3 |
| 1100 | -2.84 | 210 | -4.66 | 410 | -2.84 | 210 | 2.8 | 0.1 |
| 1200 | -3.29 | 240 | -3.69 | 270 | -3.29 | 240 | 2.8 | -14.8 |
| 1300 | -5.49 | 470 | -6.29 | 570 | -5.49 | 470 | 2.9 | -46.4 |
| 1400 | -7.26 | 640 | -7.24 | 640 | -7.26 | 640 | 2.9 | -54.8 |
| Average | -3.39 | 253 | -4.59 | 418 | -3.13 | 282 | 2.8 | 5.2 |

**4.2.3. Prediction of closure depths from the Simplified Hallermeier.** The simplified form of the Hallermeier equation does not depend on the wave period and therefore it can be used for a quick calculation of the closure depth. Applying the Equation (3), results show an under prediction of the closure depth value by an average of 4.5 % when compared against all the measured closure depth as tabulated in Table 4.

**Table 4. Measured and simplified predictive Hallermeier closure depth**

| CH | 2003-2005 | 2005-2006 | 2006-2007 | Predicted hc | % Diff. 1-yr |
|----|-----------|-----------|-----------|--------------|-------------|
|    | Measured hc (m) | Distance from shoreline (m) | Measured hc (m) | Distance from shoreline (m) | Measured hc (m) | Distance from shoreline (m) |            |            |
| 400 | -1.86 | 140 | -3.14 | 290 | -1.86 | 140 | 2.7 | 43.5 |
| 500 | -2.49 | 160 | -5.04 | 570 | -2.49 | 160 | 2.9 | 11.9 |
| 600 | -2.61 | 170 | -4.00 | 410 | -2.61 | 170 | 3.2 | 17.0 |
| 700 | -2.71 | 170 | -3.26 | 230 | -3.04 | 190 | 2.9 | -3.8 |
| 800 | -3.04 | 190 | -4.90 | 500 | -3.04 | 190 | 2.9 | -3.8 |
| 900 | -2.81 | 190 | -3.66 | 270 | -2.81 | 190 | 2.9 | -8.4 |
| 1000 | -2.96 | 200 | -4.64 | 440 | -2.96 | 200 | 2.8 | -8.4 |
| 1100 | -2.84 | 210 | -4.66 | 410 | -2.84 | 210 | 2.9 | 1.3 |
| 1200 | -3.29 | 240 | -3.69 | 270 | -3.29 | 240 | 2.9 | -9.3 |
| 1300 | -5.49 | 470 | -6.29 | 570 | -5.49 | 470 | 3.0 | -44.8 |
| 1400 | -7.26 | 640 | -7.24 | 640 | -7.26 | 640 | 3.3 | -53.9 |
| Average | -3.39 | 253 | -4.59 | 418 | -3.13 | 282 | 2.9 | -4.5 |

The lowest measured closure depth as shown in Table 3 and 4 is 2.6m LSD , measured at CH600. A simplified relation can be determined between offshore wave, $H_{50,137}$% and the predicted hc as shown below.
\[ \frac{h_c}{H_{S0.137\%}} = \frac{2.6}{3.3} = 0.80 \tag{4} \]

Therefore, equating the above to \( h_c \), yield

\[ h_c = 0.8 H_{S0.137\%} \tag{5} \]

This relation can be used to predict the closure depth at any location on the east coastline of the Peninsular Malaysia for a beach restoration project, considered that similar wave climate condition is obtained.

5. Conclusion
A series of overlapping survey data were used and analyzed to establish the positions and depths of closure depth. The shoreline of Teluk Cempedak Beach, Kuantan was selected to estimate the closure depth using beach profile survey data of four years. The Fixed Depth Change (FDC) method was used with the criterion line set at 0.25m. Hallermeier equation was applied to calculate the closure depth and was then compared against the measured closure depth. The findings show that, Hallermeier equation under-predicted the closure depth by 5% and this is due to the presence of the Tanjung Tembeling headland located at the most southern chainages. Profiles close to headland are steeper than other profiles, extending the location of the closure depth to be in the mid-shore region. A simple relationship was developed and presented for the study area as the closure depth can be equated to 0.8 times \( H_{S0.137\%} \). Based on this formulation, the closure depth can be predicted from this relation for any coastline along the east coast of Peninsular Malaysia that is considered for beach nourishment project.

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