The Shoreline Deformation in Convex Beach due to Sea Level Rise

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Abstract. Sea level rise (SLR) is become more serious on a global scale and has become one of the main reasons causes shoreline changes, and erosion, even on an extreme scale can cause the sinking of coastal areas and islands. It was recorded that many big cities were damaged by SLR. The Bruun rule is the most widely used method for predicting the horizontal translation of the shoreline associated with a given rise in sea level. In this study, however, the change in the average shoreline at the convex beach, which is more vulnerable to erosion due to sea level rise, is investigated. The increase in water depth by sea level rise causes a change in the wave crestline, ultimately leading to a linearization of the shoreline. In general, it is assumed that the annual average shoreline is parallel to the annual mean wave crestline. Moreover, assuming that the equilibrium depth contour is formed according to the crestline, the retreat of the shoreline is predicted. The shoreline change is indirectly predicted through the wave crestline deformation obtained from a wave model and this method is applied to the convex beach. Our result showed that for a convex beach with a length of 1 km has open ends with free littoral drift at both ends, the sea level rise of 1 m cause the erosion of 10 m in the protruding area, and the sea level rise of 2 m causes erosion of 23 m. However, if the convex beach is blocked at both ends, sea level rise of 1 m causes the erosion of 6.3 m in the convex area, but the shoreline advance of 3.8 m at both ends, and if the sea level rise of 2 m occurs, the erosion of 14.3 m can occur in the convex area and shoreline advance of 8.6 m can occur at both ends.

1. Introduction
The most common causes of erosion are waves and currents. In addition, another factor that also causes erosion on the coast is sea level rise (SLR). For coastal communities and ecosystems, sea level rise is a hazard and is closely related to various coastal hazards such as coastal erosion, storm surges, and low-land inundation [1]. The International Panel on Climate Change (IPCC) fifth assessment report shows that the rate of SLR since the mid-nineteenth century has been greater than average levels over the previous two millennia, and the global average SLR was 1.7 mm/year (1.5 to 1.9) between 1901 and 2010 and 3.2 mm/year (2.8 to 3.6) between 1993 and 2010. Global mean SLR will continue to increase and will not be uniform across regions during the twenty-first century, most likely at 52-98 and 28-61 cm by the year 2010 for both high and low emission scenarios correspondingly [2]. Potential responses to these SLR scenarios depend on the landforms occurring in a region and include an increased probability of erosion and shoreline retreat for all coastal types [3]. Regional and local factors (e.g.,
changes in ground elevation) will influence future relative SLR for specific shorelines around the world [4]. Also, increased sea levels allow waves and surges to act at higher levels landward in the beach profile, increasing erosion rates [5].

The most commonly applied relationship between sea level rise and shoreline recession follows the concepts of equilibrium profile geometry and sediment conservation and most often applied to low-lying coasts [6]. However, since the above study is for sandy beaches only, another research investigated the basis of a modeled relationship which suggests (with a number of caveats) that the equilibrium soft-rock cliff recession rate can be estimated by the square root of the relative change in sea level rise rate [7]. The above studies mostly used the Bruun rule method, where this method investigated shoreline changes due to sea level rise from axial view.

The submerged rock effect influences the formation of the convex beach, due to the refraction. So that it will catch sediment on the beach behind and will be eroded if the sea level rise effect is added which causes the shoreline to retreat. There is a study that determines the mechanism of shoreline change from coastal response to multifunctional submerged coastal structures through data collection on a highly dynamic coastal system with V-shaped submerged natural rocky cliffs [8]. In addition, another important thing about the submerged rock effect in the convex beach is the shape of the convex itself. There is a concavity effect on the foreshore profile for a given positive net sediment flux, the shoreline advance slows down as the shoreline morphology becomes gentle (i.e. a decrease in the concavity profile), the higher the net sediment flux is, the greater the influence of shoreline changes on shoreface morphology [9]. Furthermore, there were effects of shoal size on wave amplification along the shoreline. It was found that as the shoal size increased, the maximum wave amplification and its variation along the shoreline increased significantly due to wave refraction. These studies showed that the existence of submerged rocky causes changes in shorelines and affects socio-economics if not handled properly [10].

Most of the convex-shape beaches are beaches that were developed for tourism, so many kinds of facilities were built around, for example, Marllorca (Balearic Island) is a typical tourism-oriented beach in urban environments of the Mediterranean region, so their reduction or disappearance would be detrimental for the local economy [11]. Another example is the sandy beaches of the Grand Strand in Northeastern South Carolina which is also a type of convex-shaped beach. Tourism revenues produced along the Grand Strand account for more than 30 percent of the annual statewide total (2000–2004); this revenue represents an economic for the region as well as an important source of income for the State. With ongoing sea level rise, beach erosion is expected to continue or possibly worsen, endanger the future of the Grand Strand as a premier seaside resort [12]. Another researcher analyzed the rates of relative sea level rise (RSLR) and the variations in shoreline position over more than a century on pocket-beaches in Provence and on open beaches of the Camargue (France), thus, sea level rise will have important socio-economic impacts on the pocket-beaches of Provence. From some of the studies above, it can be concluded that sea level rise is very influential on coastal communities, especially beach areas which mostly affect the economy, tourism, so that if the coast declines the impact will be enormous if not handled properly [13].

However, several studies investigated shoreline changes due to sea level rise from an axial side view. Instead, this paper investigates shoreline changes due to sea level rise from a lateral view using a wave ray model. Increased sea levels allow waves and surges to act at higher levels landward in the beach profile, increasing erosion rates [5]. In addition, we investigate whether beaches that have special bathymetry such as siltation due to submerged elliptic rock, or coral reefs will experience more severe shoreline changes than beaches without siltation. Furthermore, in this study, rather than approaching shoreline retreat from sediment transport or morphological point of view, it indirectly examines the deformation of the wave crestline through the wave model.

2. Beach Erosion due to Sea Level Rise

2.1 Sea level rise over the world and Indonesia

According to the global mean sea level (GMSL), sea level is rising (with a 99 to 10% probability) and accelerating (high confidence)[14]. The tide gauges and altimetry observations analysis showed an increase from 1.4 mm/year over the period 1901-1990 to 2.1 mm/year over the period 970-1025, to 3.2 mm/year over the period 1993-2015, and to 3.3 mm/year over the period 2002-2015 [15]. A rising sea level does not occur in a uniform spatial pattern but shows a complex pattern, as indicated by the available observations [16]. Regional and global averages of sea level rise are the aftermath of global
warming. Changes in sea level show strong regional patterns (in space and time), which may deviate significantly from global averages [17]. Some regions experience local sea level rise faster and higher than the global average, whereas some local sea level rises that are far below or even negative from the global average may also occur in other regions [14].

In Indonesia, the centers of economic activity are mostly located in coastal cities, such as Jakarta, Surabaya, Makassar, etc. Indonesia is expected to be severely impacted by global sea level rise as well as subsidence [18]. The dominant impact will be perceived by people living in coastal environments, especially in big cities mentioned above and other cities along the northern coast of Java, which is populated by more than 40% of the total population of Indonesia [19]. The use of satellite altimetry to predict the trends of sea level rises in Indonesia reveals that Indonesia’s average rate is higher than the global average [18]. Through data from TOPEX/POSEIDON and Jason 1–3 altimetry satellites [2], it is estimated that Indonesia has a sea level rise up to 3.9±0.4 mm/year between 1992 and 2020 (Figure 1).

![Figure 1](image)

**Figure 1** The trend of sea level rise in Indonesia in 1992–2020 is estimated to be 3.9±0.4 mm/year, based on NOAA (2020)

2.2 *Shoreline retreat due to Sea Level Rise*

Sea level rise represents a most significant hazard for beaches, forcing their retreat/erosion a sea level rise will result in a shoreline retreat due to erosion of the beach face, the sediments of which are transported/deposited offshore, with the extent/rates of the cross-shore retreat controlled (amongst others) by bed slope, the texture and supply of beach sediments, and the hydrodynamic conditions [20]. Several studies related shoreline retreat due to sea level rise in the Mediterranean coastal cities [21,22]. These coastal cities are characterized by filled populations, industries, heavy transportation and communication networks as well as extensive coast-based tourist resorts. A rise in sea level will disrupt existing ecological problems through increased rates of coastal erosion, more persistent flooding, loss of wetlands, increased salinization of groundwater and soil, and greater influx of various pollutants [23]. In addition, flood-prone cities such as Ho Chi Minh City, Manila, Jakarta, Bangkok are vulnerable to future sea level rise and increased rates of coastal erosion due to extreme weather events [24].

3. **Beach behind a Submerged Elliptic Rock (SER)**

Two main variables with regard to wave refraction are focusing and defocusing [25]. Between them, focusing, or convexing refraction happens when a swell hits a kind of submerged circular rock sticking out of the shore with shallow. In the present study, the seabed model for convexing refraction is considered as composed of sand beach face and a rock shoal area.
3.1 Beach face

The equilibrium beach section is used as the beach face profile. The interpretation of sand beach response in nature is approached as a dynamic concept because the incident wavelength and water level are constantly changing. However, the beach profile averaged over a long period of time is defined as the equilibrium beach profile [26]. The equation (1) below is the equilibrium beach profile [26] applied to the beach face and is expressed in terms of $A$, the beach scale factor. The maximum depth is assumed to be 4 m without sea level rise because the SER represents the coral reef, where the reef crest zone (highest point of the reef) is in the depth of about 0 – 5 m [27].

$$h(y) = Ay^{2/3}$$  \hspace{1cm} (1)

Where $h$ is the water depth [m] at a distance $y$ from the shoreline [m] ($y = 0$ at the shoreline) and $A$ is the beach scale factor (a coefficient depending on the sediment fall velocity $\omega$ [m/s]).

3.2 Shoal Area

To simulate the formation of a convex coastline due to the influence of underwater topography, a rather elongated oval underwater reef was applied along the beach as shown in the equation below [28].

$$h_s(x, y) = 1 + \frac{3}{250^2} \left[0.25(x - x_o)^2 + 2(y - y_o)^2\right]$$  \hspace{1cm} (2)

Where $h_s$ is the shoal area, $x_o$ and $y_o$ are located in 500m and 200m, respectively, which are the center of the computational domain as shown below.

Figure 2 is a top view of bathymetry, where the blue ellipse is the shoal area while the red line represents the slope. Simulation of beach face model is using the equilibrium beach profile in equation 1, and the shoal area is using equation 2. By comparing the beach face and SER water depths. The illustrated figure 3 corresponds to the current water depth when no sea level rise has occurred. The sea level rise scenario in this model is a rise of 0.5 m, 1.0 m, 1.5 m, and 2.0 meters while the input wave is the same for all scenarios, using a wavelength of 0.5 m and a period of 5 s. When simulating the effect of sea level rise in each scenario, we increase the water depth according to the increase in sea level rise in the scenario model.

![Figure 2](image_url)

**Figure. 2** Beach face zone and boundary of submerged elliptic rock.
Figure. 3 An ideal rock shoal for the numerical experiment; a) 3D view b) Side view c) Depth contours

4. Wave crestline change due to SLR

4.1 Wave deformation model

The dispersive character of propagating waves (longer waves travel faster than shorter waves) is contained in the dispersion relation. This basic relation from linear wave theory provides a relation between (radian) wave frequency $\omega$ and wave number $k$ for given depth $h$. Wave deformations such as refraction due to changes in seabed depth are analyzed through numerical models. The linear governing
equation of the wave numerical model is a mild-slope equation, and the representative nonlinear governing equation is the Boussinesq equation. In this study, a numerical model called Wave Deformation Model (WADEM), which uses the mild slope equation of hyperbolic type as the governing equation, is applied.

The mild-slope equation can be derived by the use of several methods. For monochromatic waves according to linear theory with the free surface elevation given as $\zeta(x,y,t) = R \{ \eta(x,y)e^{-i\omega t} \}$ and the waves propagating on a fluid layer of mean water depth $h(x,y)$ the mild-slope equation [29] is

$$\nabla \cdot \left( c_p c_g \nabla \eta \right) + k^2 c_p c_g \eta = 0, \text{ with } \omega^2 = g k \tanh (kh)$$  \hspace{1cm} (3)

Where $\eta(x,y)$ is the complex-valued amplitude of the free-surface elevation $\zeta(x,y,t)$ in the horizontal position, $\nabla$ is the divergence operator, $\nabla$ the horizontal gradient operator, and $c_p$ and $c_g$ respectively are the local phase and group velocities.

4.2 Model results and discussion

The results obtained by applying the WADEM are shown in Figure 4. The applied incident wave condition was applied with a wave height of 0.5 m and a period of 5 sec, which is considered to be the normal wave height. Previously, in Figure 3, bathymetry has been shown as the input of this model. In the picture is the initial condition or without the effect of sea level rise. We include the effect of sea level rise by reducing the depth of the bathymetry according to the added sea level rise value. So basically, this model is run with the same wave parameters, but different bathymetric depths. That is, in the initial condition, the depth is 4 m, for the effect of SLR 0.5 m the depth is 3.5 m, SLR 1.0 m the depth is 3 m, SLR 1.5 m the depth is 2.5 m, and SLR 2.0 m the depth is 2 m. So there are a total of 5 bathymetric scenarios including initial conditions as a basis for comparison.

Figure 4 is the output of WADEM in which several indicators need to be understood, including the red oval line is the shoaling effect of bathymetry, the white line is the creaseline and the solid white is the beach width. The crestlines forming the breaking wave concerning the current normal wave at both ends where the crestline is not affected by the SER are marked with white lines. The white line represents the wave crestline, as we have explained in the research object, rather than approaching shoreline retreat from sediment transport or morphological point of view, it indirectly examines the deformation of the crestline through the wave model. From each increase in sea level rise in the wave model, we get the output in the form of crestline, and result in the shoreline deformation. Also, as the SLR increases, how the crestline changes are shown in Figure 5.

With respect to the current sea level, the coastline provides the result of a protrusion of 42 m. If the sea level rises by 1.0 m, it is reduced to 32 m, and if the sea level rises to a height of 2 m, the protrusion length is reduced to 19 m. Therefore, for a convex beach with a length of 1 km has open ends with free littoral drift at both ends, the sea level rise of 1 m in the future would cause the erosion of 10 m in the protruding area, and the sea level rise of 2 m causes erosion of 23 m. The calculation of the figures above is by subtracting the wave crestline from the initial depth (initial bathymetry) with the wave crestline of each scenario (addition of SLR) taking into account the scale.

![SLR=0.0m](image)
**Figure 4** Changes in wave crestlines due to sea level rise; Solid white lines indicate projected shoreline changes (fixed at both endpoints).
In Figure 5 several components need to be understood, the red line is the beach face of the equilibrium profile, the circle dash is the shoaling effect, and the blue arrow is the direction of shoreline retreat as the sea level rise effect increases, while some convex lines are the white line extraction from each of the previous scenarios in Figure 4. We can see more clearly the change in the crestline at each additional of the SLR. The top line is the initial condition where there is no effect SLR, the next line is clarified with blue arrows, sequentially the effect of SLR 0.5 m, 1.0 m, 1.5 m, 2.0 m. We can also see that the higher the SLR, the more flat the convex shoreline indicates a shoreline retreat.

If the convex beach with a length of 1 km is blocked at both ends and the movement of coastal sediment is restricted, the sand on the protrusion will be moved and deposited on the surrounding shore due to coastal sedimentation caused by the change of the wave environment. In this case, assuming that the beach surface area is preserved, less erosion occurs than in the case of the open end. That is, the sea level rise of 1 m causes the erosion of 6.3 m in the convex area, but the shoreline advance of 3.8 m at both ends, and if the sea level rise of 2 m occurs, the erosion of 14.3 m can occur in the convex area and shoreline advance of 8.6 m can occur at both ends. However, since this result does not include shoreline retreat due to beach response [6], it is possible to overlap this result by adding it to Per Bruun’s result.

**Figure. 5** Linearization of Convex shoreline due to sea level rise.

5. Conclusions
The results of the wave model examining the change of crestline according to sea level rise show that as the sea level rises, the refraction of the main wave is alleviated and the coastline can become flatter. In the scenario without any additional sea level rise effect, the convex line is still convex, along with the increasing effect of the sea level rise the convex line becomes flatter. Convex beaches are formed from the accumulation of sediment due to silting which can be caused by SER or coral reefs. If initially there was a buildup of sediment to form a convex beach, then there is an SLR effect which causes less refraction on this beach, the increasing SLR will flatten the beach, where erosion occurs. In addition, from the model results, if the boundary conditions on a 1 km long convex beach have an open end with free littoral drift at both ends, erosion is more severe than that of a convex beach that is blocked at both ends where the movement of coastal sediment is restricted.

In the end, in addition to the shoreline retreat due to the change in the cross-section of Per Bruun, it can be seen that the convex topography is a more vulnerable area for future beach erosion. As such, in the current beach that is convex by topographical influences such as coral reef and rock below the water surface, it is necessary to examine the rate of shoreline retreat at this type of shore in advance before serious erosion damage occurs in the future.

However, the result of this model is an early study on the erosion vulnerability of the convex coast, examines the deformation of the wave crestline through the wave model, and in order to derive more reliable results, it is required to directly numerically analyze the effect by combining the wave model and the coastline or isocenter model combined with the wave model.
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