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Abstract. Shoreline evolution is a simple and common method to illustrate beach erosion or accretion in coastal engineering. Extracted waterlines on different satellite images are sometimes used for shoreline evolution. However, time-varying waterlines for tidal variation and wave runup are different from the shoreline at the mean water level. Waterline evolution may bring about misunderstanding of beach erosion or accretion. In a former study, the one-line shift method was proposed to determine the waterlines on a satellite image and to shift the waterlines to shorelines while only considering the tidal variation. The upward shift extension of the waterline due to wave runup and wave setup is considered. Some acceptable equations of wave runup were examined to correct the waterlines on three satellite images in one month when the foreshore beach slopes were specified. The suggested equation for wave runup includes both wave conditions and an average beachface slope at two points located shoreward and seaward away from mean water level by an equal distance of 62.5 m. When on-site shore bathymetrical measurement is sometimes unavailable, a method of minimizing the difference between the initially guessed and estimated foreshore beach slopes by the one-line shift method is proposed.
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1 Introduction

Beach evolution can be better represented visually in the form of shoreline changes than in the form of bathymetrical variation under the sea. The location of the shoreline and its historical rate of change can provide valuable information for the planning and design of coastal protection works and for the calibration and verification of numerical models.[1–2] One type of shoreline indicator is a waterline, defined as a wet/dry line on the beach, extracted from a satellite image, which is used to describe the land-water boundary at the instant of image capturing time.[3–7] For coastal engineering, the waterline at mean water level (MWL), considering tidal variation alone, is the commonly defined the shoreline and is used in this paper. Boak and Turner[8] proposed that the use of the instantaneous waterline seems misguided because it represents the position of the land-water interface at one instant in time rather than "normal" or "average" conditions. Ryu et al.[9] noted that the location of the waterline is also an important factor to consider; the discrepancy of waterline position is largest on the middle tidal flat. Pardo-Pascual et al.[10] indicated that the applicability of the waterline extraction method in areas with high-tidal ranges is an important issue in tidal flats. Zhu et al.[11] extracted the coastlines along the Bohai Sea by using multitemporal remote sensing data and noted that the effects of tides were one of the error sources in coastline analysis.

For a calm sea, ocean tides represent the rhythmic rise and fall of the sea level with time. These tides are manifested at a coastline by the periodic advancing and receding of the waters over the shore. Thus, the extracted waterlines from different satellite images taken over the same

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place over a short period can be in various positions depending on the different tidal elevations at the time of each satellite image capturing. Considering these tidal variations for different satellite images, Chen and Chang[12] proposed the one-line shift method, which shifts the extracted waterlines on three sequential satellite images to the corresponding shorelines at MWL, when the beachface beach slope is unknown.

When ocean waves approach a coast, the majority of wave energy is dissipated across the surf zone by wave breaking. However, a portion of that energy is converted to potential energy in the form of runup on the foreshore of the beach. A propagating wave on a tidal level can push water onshore for some distance and then run down. Even though the tides are the same at the capture times of the chosen satellite images, the extracted waterlines are different due to the wave runup. Setup, the super-elevation above MWL, is driven by the cross-shore gradient in radiation stress that results from wave breaking. The relationships between setup and environmental conditions, and the resulting expressions for setup at the shoreline, have been the topics of many research studies. Thus, understanding the magnitude of extreme runup and wave setup is critical for accurate prediction of the shorelines from satellite images for further application to shoreline evolution.

Both theory and laboratory measurements show that the maximum setup occurs at the shoreline so that it is called the shoreline setup, denoted by $\langle\eta\rangle$ in this paper. Bowen et al.[13] proposed a simple expression for a relative setup proportional to a constant fraction of the local water depth under normally and monochromatically incident waves. Longuet-Higgins and Stewart[14] theoretically derived the expression for wave setup under the concept of radiation stresses. Battjes[15] carried out the computation of setup and compared it with the experimental data. Goda[16] presented a design diagram of wave setup for unidirectional random waves as a function of wave steepness and beach slope by the random wave breaking model. Guza and Thornton[17] found $\langle\eta\rangle$ to be about $0.17\,H_0$, where H_0 is the significant deepwater wave height of irregular waves on deep water. Holman and Sallenger[18] indicated that shoreline setup varies during different stages of the tide. Hanslow and Nielsen[19] stated that the shoreline setup is proportional to $(H_0L_0)^{1/2}$, where $L_0 = gT^2/2\pi$ is the wave length on deep water for mild beaches and that surf-zone slope plays a leading role in the shoreline setup at low tide. Stockdon et al.[20] used diverse field experiments on natural beaches over a wide range of conditions and developed a dimensional form of shoreline setup expression that includes foreshore beach slope, offshore wave height, and deep-water wavelength. Goda[16] empirically derived an equation for estimating shoreline setup and examined the effects of spectral peakedness and directional spreading, surface roller, and turbulent eddy viscosity on shoreline setup based on numerical computation results.

Nielsen and Hanslow[21] suggested that the dimensional vertical scaling of runup distributions is independent of beach slope and proportional to $(H_0L_0)^{1/2}$ for beaches with low-beachface slope less than 0.1. Ruessink et al.[22] studied the behavior of swash on a highly dissipative beach and found that the swash signal was dominated by energy in the infragravity band (frequencies, $f < 0.05$ Hz) and scaled with H_0. Ruggiero et al.[23] indicated that the elevation for the 2% exceedance runup, $R_{2\%}$, scales best with H_0 for highly dissipative beaches. Holman[24] found a dependence of runup $R_{2\%}$ on the deep-water significant wave height and the offshore surf similarity parameter. Stockdon et al.[20] expanded upon the Holman[24] analysis with additional data covering a wider range of beach slopes, and developed a general expression for runup $R_{2\%}$ on all beaches and an empirical equation of runup on dissipative beaches. Stockdon et al.[20] named $R_{2\%}$, the extreme runup. With large-tank experiments, Denissenko et al.[25] showed that the distribution function of the extreme runup can be approximated by the Rayleigh curve in the wide range of wave amplitudes and spectra, even if an incident wave field is represented by a non-Gaussian process.

A method was proposed in this paper to correct the position of an extracted original waterline on a satellite image to the shoreline while considering wave and tide. The suitable expressions of the wave setup of a regular wave and the runup for irregular waves introduced in the previous works were examined to shift the waterline on each satellite image when the beachface slope of each beach profile is known. With the help of the one-line shift method, a procedure of shifting waterlines considering wave runup, setup, and tidal variation was proposed for a possible case of unavailable beachface slopes.

2 Methods

The materials and techniques used in this study are introduced in this section. The materials include satellite-derived data, oceanic conditions, and beach features. Parameterized expressions for wave runup and setup are chosen in this paper, and the procedure of waterline extraction on a satellite image when beachface slopes are known or unknown are demonstrated below.

2.1 *Materials*

About 40% of satellite images have cloud coverage over coastal zones of Taiwan.[26] Therefore, it is hard to choose several satellite images clearly showing waterlines during a short period of time. Only three satellite images for which the capture time was one month were available to avoid large shoreline change due to the impacts of waves over a long time. Summary of the satellite-derived data used in this study is shown in Table 1.

One of the three images is of SPOT4. Two super-mode images of SPOT5 with a high-spatial resolution of 2.5 m are used. The panchromatic image of SPOT4 with a high-spatial resolution is unobtainable. Thus, multispectral images with a low-spatial resolution of 20 m are used to produce a panchromatic image in a band ratio of normalized difference vegetation index (NDVI). NDVI is a simple graphical indicator that is commonly used to analyze remote sensing measurements. NDVI is defined by the ratio of individual measurements as follows:

$$\mathrm{NDVI} = \frac{\mathrm{NIR} - R}{\mathrm{NIR} + R}, \tag{1}$$

where R and NIR stand for the spectral reflectance measurements acquired in the visible red bands with a range of 0.61 to 0.68 μm and near-infrared spectral bands with a range of 0.79 to 0.89 μm, respectively.

The corresponding offshore wave conditions and tidal levels at the capture time were obtained by analyzing wave data and tides measured by the Institute of Harbor and Marine Technology (IHMT) of the Institute of Transportation, Ministry of Transportation and Communications, Taiwan. Wave data at a water depth of 20 m near the Taichung harbor were measured by the Nortek AWAC, which is a revolutionary instrument designed to measure both the current profile and the wave directional spectrum at a single point using proven acoustic Doppler technology. There were no typhoons or large waves during this period of one month. Thus, the bathymetry of the beach can be assumed to have slight variations due to the impact of monsoon waves during the period so that the shoreline seems unchanging.

The type of tide in the Taichung waters is semidiurnal. According to tidal data at the Taichung harbor observed by the IHMT, the mean tidal range is approximately 3.63 m, and the mean spring tidal range is approximately 4.85 m. Tidal elevations were observed each hour, but the satellite images were not taken hourly. Thus, the tidal elevation at the capture time was estimated by linear interpolation between two adjacent tidal observations. The computed tidal elevation at the capture time of the third image is 8 cm, which is close to the mean sea level. Thus, the extracted waterlines can be directly taken as shorelines at a datum of still sea level without any correction to the waterlines for tidal variation. Tidal levels of the other two satellite images are 98.0 and −135.6 cm, and they significantly and oppositely deviate from MWL. Wave heights

Table 1 Summary of the satellite-derived data used in this study and the corresponding measured offshore wave conditions and tidal levels.

Source	Time (GTM+0)	H_s (m)	T_s (s)	Tidal level (cm)
SPOT 4	2003/09/29 02:45	1.08	5.33	98.0
SPOT 5	2003/10/18 02:53	2.83	5.41	−135.6
SPOT 5	2003/10/29 02:41	2.29	5.76	8.0

exceeding 1 m during the time period can produce considerable wave runup and setup, making the waterline appear to be at a high position.

According to wave statistics on hourly data of wave measurements in a 20-m depth, the mean significant wave height in September 2003 is 1.54 and 2.17 m in October and the corresponding mean period of significant waves is 5.71 and 5.37 s, respectively. Waves in these two months have wave steepness on a range of 0.0067 to 0.0722. Wave heights and periods of offshore significant waves at the capture time of each image were also estimated by linear interpolation from two adjacent hourly wave data and were listed in Table 1. The corresponding wave steepness at the time of each image capturing is 0.0243, 0.0619, and 0.0442, respectively.

From several bathymetrical measurements made between 1996 and 2006, the beachface slopes were evaluated in a range of $1/98$ to $1/61$ with an average of $1/79.4$.

2.2 *Waterline Extraction on a Satellite Image*

The capture time of the single chosen image is in September 2003 and the other two are in October. The beach beyond the northern breakwater of the Taichung harbor, which is located on the western coast of central Taiwan, is investigated in the paper. The procedure of extracting the waterline on a satellite image follows three steps.

Step 1: the first step is to resample the grayscale image to the same size and manifest image contrast in bright histograms through different transformations of bright scales in each image. Histogram equalization is a useful and common method for efficiently enhancing the characteristics of some brighter or darker imagery. Image adjustment that emphasizes the bright range of the boundary zone is an important treatment prior to waterline extraction. Waterline extraction is a kind of edge extraction that enhances the most desired features of an image but neglects some unwanted information. Thus, the process can reduce the storage of a large number of data in an image.

Step 2: the Canny algorithm is a common method for detecting an edge that efficiently filters out white noise from an image by the Gaussian function. The key skills of the Canny edge detector include nonmaximum suppression, which means that given the presmoothing filters and edge points are defined as points where the gradient magnitude assumes a local maximum in the gradient direction. Atmospheric correction is an essential process of correcting the intensity of each band in image segmentation. The result of image segmentation is a set of segments that collectively covers the entire image, or a set of contours extracted from the image. Therefore, image segmentation can be commonly used for region analysis of edge detection. Atmospheric correction on a satellite image has little effect on the Canny edge detector. Atmospheric correction is not a possibility when using the Canny edge detector.

Step 3: finally, some unwanted features near the waterline, resulting from possible breaking whitecaps in the seas, were removed manually using an erasing function and skeletonized to omit residual parallax errors.

2.3 *Calculation of Shoreline Wave Setup*

The maximum shoreward extent of wave runup has particular significance to the erosion of features backing the beach and in the overtopping of revetments. The total runup consists of three primary components:[27] (1) the setup, which determines the mean shoreline position above which the swash of individual waves occurs; (2) fluctuations around the mean shoreline due to the swash of incident waves producing runup and rundown; and (3) a component in the swash oscillations having periods in excess of 20 s, which are infragravity periods beyond the usual range of incident wave periods. A sketch description of wave setup and runup on a planar beach with a sloping angle of β is shown in Fig. 1.

The wave setup balances the gradient in the cross-shore-directed radiation stress (i.e., the pressure gradient of the mean sloping water surface balances the gradient of the incoming momentum). For a detailed derivation of shoreline setup for a regular wave the reader can refer to Bowen et al.[13]

$$\langle\eta\rangle = \bar{\eta}_b + \frac{3\kappa^2}{8+3\kappa^2} h_b, \tag{2}$$

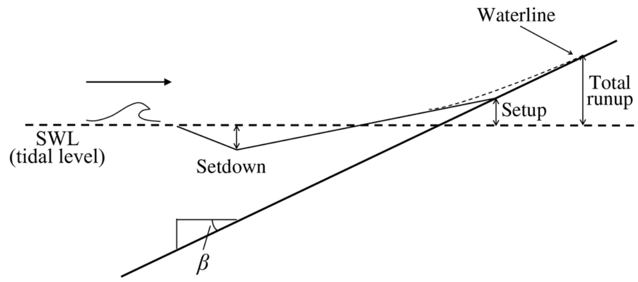

Fig. 1 Definition sketch of runup and setup indicates the corresponding rise in a waterline.

where $\bar{\eta}_b$ is the setdown at the breaking depth, h_b, and κ is the ratio of the wave height to the mean water depth in the surf zone. $\bar{\eta}_b$ is less than 5% of the breaking depth for $\kappa = 0.8$.

Measured setup values were found to be greater than those predicted by theory due to the asymptotic approach of the setup to the beach surface.[13] From field measurements or laboratory studies on the setup of irregular waves on uniformly sloping beaches, empirical parameterization was commonly used to express the shoreline setup in terms of wave steepness, H_0/L_0, or the surf similarity parameter, ξ_0, in several studies. The surf similarity parameter is also called the Iribarren number and is defined as

$$\xi_0 = \frac{\tan \beta}{\sqrt{H_0/L_0}}, \tag{3}$$

where $\tan \beta$ is the slope of a planar beach or the beachface slope of a natural beach.

For dissipative beaches with mild beachface slopes, the nondimensional shoreline setup is a function of H_0/L_0 alone and is independent of beachface slope. Stockdon et al.[20] obtained an expression for the shoreline setup as follows:

$$\frac{\langle \eta \rangle}{H_0} = 0.016 \left(\frac{H_0}{L_0} \right)^{-0.5}. \tag{4}$$

Katoh et al.[28] presented an empirical equation, Eq. (5), of the wave setup at Hazaki beach, which has a mean slope of $1/60$ when averaged over beach profiles with or without bars

$$\frac{\langle \eta \rangle}{H_0} = 0.052 \left(\frac{H_0}{L_0} \right)^{-0.2}. \tag{5}$$

Goda[16] used the random wave breaking model to compute the shoreline wave setup on planar beaches induced by directional spectral waves to examine the validity of Eq. (5) and showed that on a base of Goda's predictions, Eq. (5) tends to under-predict shoreline wave setup for waves of low steepness ($H_0/L_0 < 0.02$) and to over-predict for waves of high steepness ($H_0/L_0 > 0.02$). For reflective beaches with steep beachface slopes ($\tan \beta > 0.06$), the nondimensional shoreline setup was found to be proportional to the surf similarity parameter as follows:

$$\frac{\langle \eta \rangle}{H_0} = c\xi_0, \tag{6}$$

where the regression coefficient c is suggested to be 0.45 by Hanslow and Nielsen[19] and to be 0.35 by Stockdon et al.[20]

2.4 *Calculation of Wave Runup*

Aside from the mean water level due to wave setup, the onshore momentum of incident waves will push water particles up the beach face slope. The higher the particles ascend, the lower the velocities of the particles become through the conservation of energy. The highest possible distance of the particle advancing above MWL is called the wave runup. At the point of the highest potential with zero velocity, the flow will reverse and water particles rush down the beach face slope until the next wave comes. The furthest distance below the mean water level is called wave rundown. The beach is wet when water travels, making the interface between the dry and wet sand on the beach obvious. Figure 2 illustrates the positions of waterline and wave front of a photo at the capture time. The former is located higher than the latter. The statistical distributions of the swash oscillations measured on beaches were compared with the Gaussain model on the linear-random waves.[29] If the swash oscillation is Gaussian, the probability distribution of the time-varying shoreline elevation can be described by its mean and standard deviation (degree of the shoreline oscillation). Myrhaug[30] indicates that the mean values of $R_{2\%}$ are in the range 3 to 4 m with standard deviations in the range 0.3 to 0.5 m depending on the distribution and dataset considered. The relative standard deviation is about 0.1. At the condition of an instant tidal level and Gaussian-distributed irregular waves, the time-varying waterlines due to the grouping effect may compose the Gaussian distribution. The standard deviation of waterline distribution is small and close to that of runup distribution during a short period of time.

Determining a suitable expression of wave runup is the key for shifting an extracted waterline to the position of the shoreline. Irregular wave runup has also been found to be a function of the surf similarity parameter,[21,31] but differs from regular wave runup due to the interaction between individual runup bores. Uprush may be halted by a large backrush from the previous wave or uprush may be overtaken by a subsequent large bore.

Using laboratory data for irregular waves propagating over the gently sloping plane of an impermeable beach, Mase[31] proposed predictive equations for the maximum runup ($R_{\max}$), the runup exceeded by 2% of the runups ($R_{2\%}$), the average of the highest 1/10 of the runups ($R_{1/10}$), the average of the highest 1/3 of the runups ($R_{1/3}$), and the mean runup ($\bar{R}$). The expressions for these runups can be written as follows:

$$\frac{\mathrm{R}_{\%}}{H_0} = a\xi_0^b. \tag{7}$$

In early laboratory experiments of monochromatic waves on planar beaches, all quantities were well defined. For random waves, both wave period and wave height become statistical measures, often described by the wave height, H_s, and period, T_s, of significant waves. ξ_0 is calculated from the deepwater significant wave height and length. The appropriate slope for natural beaches is the slope of the beachface.[24,31] The effects of tide and wind setup must be independently calculated.

The coefficients a and b are dependent on the runup exceedance quartile are given by Mase[31] and are listed in Table 2. The behavior of swash under extremely dissipative conditions ($\xi_0 < 0.3$, $\tan\beta < 0.02$) is different from that for reflective and intermediate conditions. On low-sloping beaches, energy in the incident band is saturated and increases in H_0 contribute only to increases in the infragravity band.[18,22,32] A suggested expression for runup on all examined beaches by Stockdon et al.[20] is improved for extremely dissipative beaches as follows:

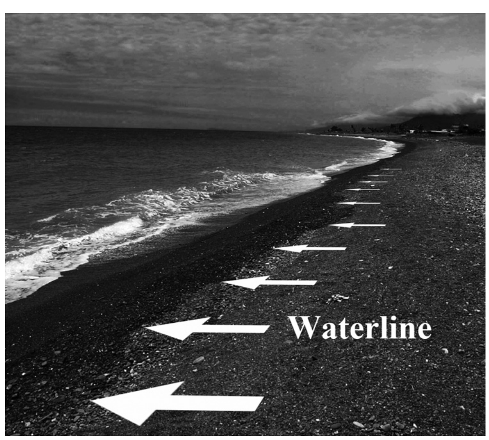

Fig. 2 Arrows point to the positions of a waterline on a photo defined as the interface between dry/wet sand of the beach.

Table 2 Coefficients *a* and *b* dependent on the runup exceedance quartile are suggested by Mase.[31]

a and *b*	R_{max}	$R_{2\%}$	$R_{1/10}$	$R_{1/3}$	$\bar{R}$
a	2.32	1.86	1.70	1.38	0.88
b	0.77	0.71	0.71	0.70	0.69

$$R_{2\%} = 0.043(H_0 L_0)^{1/2}. \tag{8}$$

2.5 *Estimation of Unknown Beachface Slope*

For coastal protection planning and management, bathymetric measurements are sometimes unavailable for the time of the selected satellite images. With an unknown beachface slope, the proposed method in Sec. 2.4 cannot be directly used to shift such an extracted waterline to the shoreline. The one-line shift method[12] is applied to determine the beachface slope from three sequential satellite images considering tidal variation. The method is briefly introduced below.

Generally, the tide level rises or falls in the range of beachface for the case of a small tidal range. Even the beach bottom in this zone possibly forms a sloping bottom with small variations. It is reasonable to assume that a beachface has a uniform slope. Three waterlines from three satellite images at different times are extracted. At time t_i, the waterline is located at x_i away from the origin of the transformed co-ordinates and the corresponding water depth is h_i above or below MWL. When the sea surface is at MWL, the MWL-datum-based shoreline is located at z_i away from the origin. The beachface slope, tan β_c, is defined by

$$\frac{h_i}{x_i - z_i} = \tan \beta_c \qquad (i = 1,2,3). \tag{9}$$

Both tan β_c and z_i are unknown. The beach is assumed to move in a steady velocity during a period of t_1 to t_3. The moving speed of the beach profile can be expressed as

$$V = \frac{z_j - z_i}{t_j - t_i} = \frac{\Delta z_{ji}}{\Delta t_{ji}} \qquad (i, j = 1,2,3), \tag{10}$$

where Δ is the difference in a physical quantity from time t_i to t_j. Two-time differences between t_1 and t_2 and between t_2 and t_3 are chosen. Equating the moving speeds during two-time differences and then inserting the result into Eq. (10), the beachface slope can be expressed as

$$\tan \beta_c = \frac{\Delta h_{32} - \frac{\Delta t_{32}}{\Delta t_{21}} \Delta h_{21}}{\Delta x_{32} - \frac{\Delta t_{32}}{\Delta t_{21}} \Delta x_{21}}. \tag{11}$$

Avoiding the effect of seasonal variation of beach profiles on the speed of shoreline changes, the capture of three images in the same season is advisable for satisfying the assumption of a constant moving speed of beach profiles.

3 Results

To evaluate the model accuracy of the proposed waterline-to-shoreline method for both cases of known beachface slopes and the unknown beachface slope in two parts, we compare the positions of shifted shorelines from extracted waterlines on three satellite images in one month. An example of comparing original waterlines with the corresponding shifted shorelines shows the necessary correction considering wave runup. An applicable expression of 2% exceedence value for runup and a suitable definition of beachface slope are examined.

3.1 *For the Case of Known Beachface Slopes*

Beachface slopes of 47 equidistant beach profiles for three wave conditions can be estimated from bathymetric measurement. The obtained beachface slopes together with the wave steepness of three significant waves produce the values of the surf similarity parameters. All values of the surf similarity parameters are estimated in a range of 0.031 to 0.1167 with a mean of 0.067 and a standard deviation of 0.019. The result indicates that the beach is a dissipative beach.

Based on the equation of runup of Mase[31] at different quartiles and Eq. (8) of Stockdon et al.[20] for some specified beachface slopes obtained from bathymetric observations in 2003, an examination of extracted waterlines was made. The beachface slope of a measured seabed profile is defined as the secant, which is the ratio of elevation differences at two points of a beach profile to the corresponding horizontal distance, ΔL. Nine possible choices of any two points of a measured topographical profile to determine the beachface slope were examined and are shown in Fig. 3.

Three extracted original waterlines on three satellite images are shown in Fig. 4. The large deviation of the three extracted waterlines shown in Fig. 4 falsely indicates that a large shoreline change happens during one month. The extracted waterlines which are regarded as shorelines in coastal engineering will indicate beach erosion or accretion, despite an almost invariant shoreline. This misrepresentation results from the extracted waterlines without the consideration of wave runup and tidal variation, as shown in Fig. 4.

The positions of the extracted original waterlines on three images of a profile and their corresponding shifted shorelines were shown in Fig. 5(a) and those are indicated in Fig 5(b) considering tidal variation alone and considering tidal variation along with runup $R_{2\%}$. Figure 5 is an example for showing the importance of corrections and accuracy evaluation. Estimated runup $R_{2\%}$ on the beach profile 40 is 0.34, 0.63, and 0.58 m, respectively, for three cases. Three original waterlines, denoted x_i ($i = 1, 2, 3$) in Fig. 5(a), are located apart. The furthest distance between x_1 and x_2 is 93.2 m. Three shifted shorelines are denoted z_i ($i = 1, 2, 3$) in Fig. 5(a) under the consideration of tidal variation alone. The furthest shifting from x_2 to z_2 among three waterlines is shown in Fig. 5(a) because of a large tidal deviation. These three shifted shorelines (z_1, z_2, z_3) are separated by a smaller distance than original waterlines (x_1, x_2, x_3). However, these shifted shorelines are located above MWL by a distance from 20 to 45 m. The seaward distances result from wave runup. Figure 5(b) illustrates that three shifted shorelines, also denoted z_1, z_2, z_3, are closer than those in Fig. 5(a) and are located around MWL.

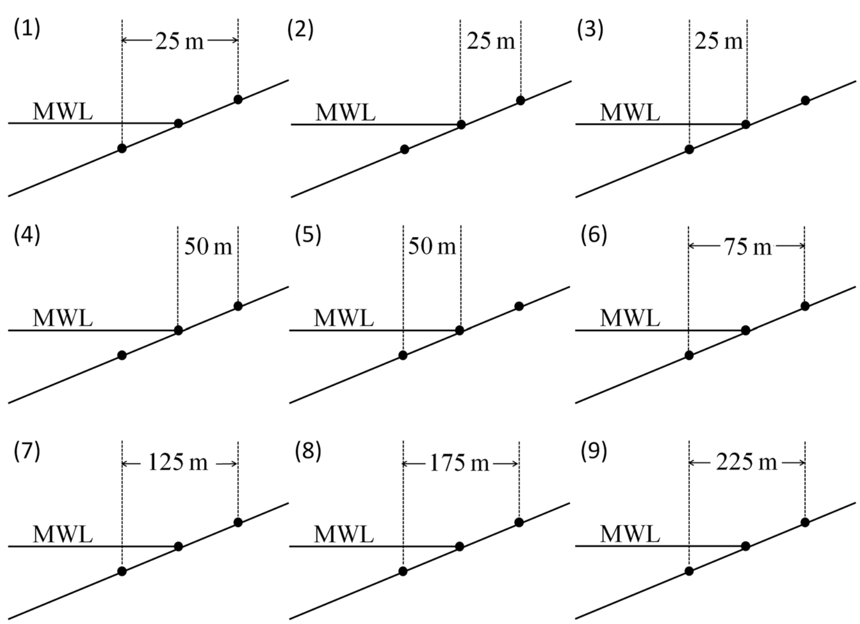

Fig. 3 Nine definitions of a beachface slope are examined as to suitability for the water-to-shoreline correction.

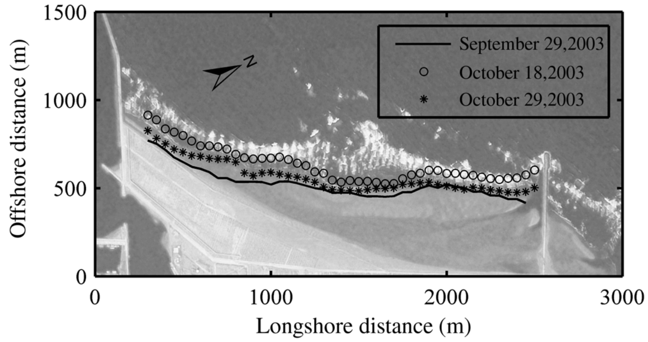

Fig. 4 Extracted original waterlines on three selected satellite images whose capture time difference is a month are located apart, falsely showing that a large shoreline change occurs during such a period.

The measured shoreline by field observation is unavailable during the capture time for the selected images. It is hard to evaluate the accuracy of three shifted shorelines based on a "true" shoreline by field measurement at the capture time of the selected images. Under an assumption of slight beach change in one month under monsoon wave impacts the shoreline varies insignificantly. That the mean of three shifted shorelines, $\bar{z}$, is regarded as a standard by field measurement is acceptable for this situation. Deviation of three shifted shorelines from the mean of three shorelines is thus taken as a criterion for evaluating the model accuracy. The original waterlines are separated by a standard deviation (SD) of 39.4 m. The shifted shorelines under the consideration of tidal variations alone in Fig. 5(a) have an SD of 15.6 m. However, the SD of the three shifted shorelines for Fig. 5(b) is 6.6 m. The reduction of SD demonstrates that extra shifting a waterline on a satellite image to the shoreline by runup is necessary, except for the primary correction by tidal variation.

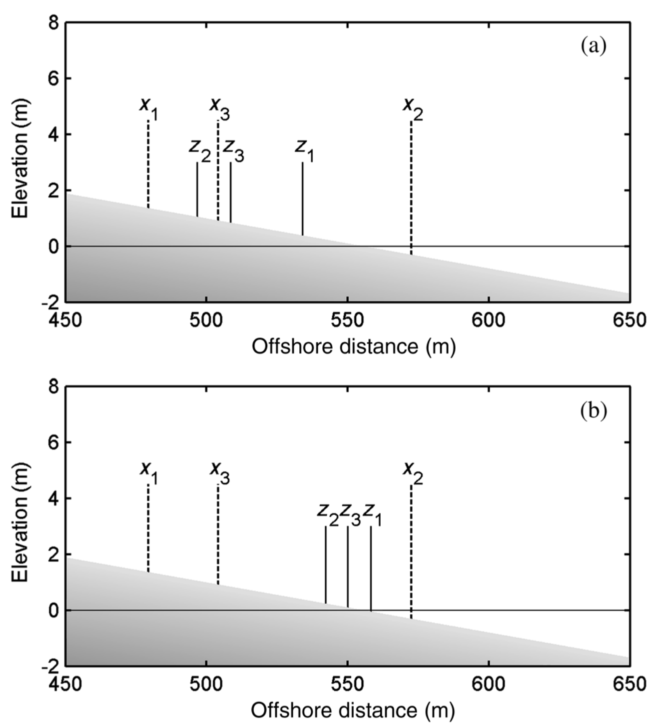

Fig. 5 The difference between three extracted original waterlines of the beach profile 40 and the corresponding shifted shorelines: (a) considering tides alone and (b) considering tides and runup together show that three shifted shorelines are located close at the mean water level in (b).

Table 3 Average values of SD at the whole 47 profiles considering a different definition of beachface slope and Mase's[31] expressions for the runup of different exceedance quartiles on gently sloping beaches and runup $R_{2\%}$ Stockdon et al.[20] for dissipative beaches.

Case	Mase					Stockdon et al.
	R_{max}	$R_{2\%}$	$R_{1/10}$	$R_{1/3}$	$\bar{R}$	$R_{2\%}$
1	26.3	26.3	26.8	27.7	29.3	28.0
2	26.6	26.6	27.2	28.2	30.1	28.9
3	40.5	40.5	41.1	42.1	44.1	42.1
4	32.1	32.0	32.6	33.7	35.7	34.2
5	40.9	40.8	41.3	42.2	43.9	41.9
6	23.8	23.8	24.4	25.5	27.5	26.5
7	**23.6**	**23.6**	24.2	25.3	27.3	26.3
8	26.0	26.0	26.6	27.7	29.7	28.7
9	32.2	32.1	32.7	33.7	35.6	34.4

Note: The bold values indicate the minimum of each column.

According to the definition of SD for the positions of shifted shorelines on three images of each beach profile, the smaller the SD the more applicable is the proposed correction. The average SD for the whole 47 beach profiles considering different definitions of beachface slope and Mase's (1989) expressions for the runup of different exceedance quartiles on gently sloping beaches and considering runup $R_{2\%}$ for dissipative beaches by Stockdon et al.[20] is shown in Table 3.

Columns 2 to 7 of Table 3 indicate the computed SD using Eq. (7) with the same exceedance quartile runup on different beachface slopes and using Eq. (8). The results of each column show that the smallest SD occurs for case 7. For the runup equation with different quantiles on a specified beachface slope, each row of Table 3 indicates that the mean SD for R_{max} is equal to that for $R_{2\%}$ and is the smallest among all options. The result shows that R_{max} or $R_{2\%}$ runup and the average beachface slope determined by two points located shoreward and seaward away from MWL by an equal distance of 62.5 m are acceptable for determining the shoreline

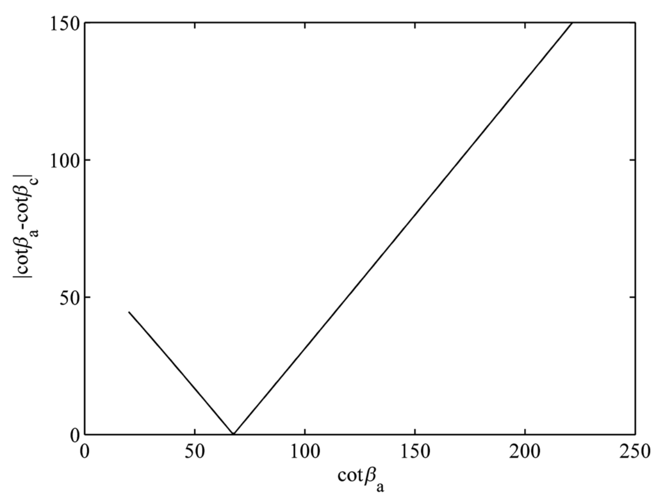

Fig. 6 Minimization of absolute errors of initially assumed beachface slopes and the calculated results against different cot β_a for the beach profile 40 determines the possible beachface slope for the case of the unknown slope.

from the extracted original waterline on a satellite image. The SD for this case is 23.6 m, indicating the accuracy of determining the shoreline from an extracted waterline on a satellite image considering both tidal variation and runup by the proposed method. When only tidal variations are considered, the mean SD for 47 beach profiles is 31.5 m.

3.2 *For the Case of Unknown Beachface Slopes*

A procedure is introduced to shift the extracted waterline to the shoreline at MWL for the case of an unknown beachface slope in Sec. 2. At first, each of the beachface slopes of the 47 examined profiles is estimated by an initial value, denoted by $\tan\beta_a$, in a range of $1/20$ to $1/250$. These values refer to those of previous bathymetric observations. The second step is to calculate the wave runup using the predicted beachface slope in Eq. (7) and the corresponding seaward distance. The offshore distances of the shifted shorelines are then determined. The third step is to estimate the beachface slope using Eq. (11) with the tidal differences, time differences, and shifted shorelines of the three satellite images and to compute the absolute error between $\tan\beta_a$ and $\tan\beta_c$. The smaller the absolute error is, the closer the assumed $\tan\beta_a$ is to the true beachface slope. The last step is to find the minimum absolute error of the beachface slope among all presumed values of $\tan\beta_a$. Figure 6 gives an example of the absolute error of the computed $\cot\beta$ and the estimate for the beach profile 40. A minimum absolute error of $\cot\beta$ very close to zero occurs at an assumption of $\cot\beta_a = 68$. The result indicates that the beachface slope of the beach profile 40 is determined by $1/68$. The beachface slope of each beach profile is individually assumed from $1/250$ to $1/20$ to decide the probable slope.

To evaluate the validity of the proposed method for the case of unknown beachface slopes, the computed beachface slope of each beach profile and the measured, denoted by stars and open circles, respectively, are shown in Fig. 7. The correlation coefficient between the estimated beachface slopes and the measured in Fig. 7 is 0.68, indicating that the computed beachface slopes agree with the measured. The proposed method is thus applicable for determining beachface slopes by considering wave runup and tidal variation when these slopes are unknown.

Using the estimated beachface slopes of all 47 beaches, the shifted shorelines for three images has a mean SD of 19.8 m, which is slightly smaller than that obtained when known beachface slopes are specified.

A perfect way for evaluating the accuracy of extracted shorelines from satellite images is to have onsite shoreline observation as a standard. However, it is very difficult to obtain onsite real waterline measurement at an instant as the capturing time of a satellite image. Based on the small deviation of $R_{2\%}$ caused by equivalent waves on a sloping beachface, it is reasonable to take the mean of corrected shorelines from extracted waterlines of three satellite images whose capture times are within one month as the "true" shoreline.

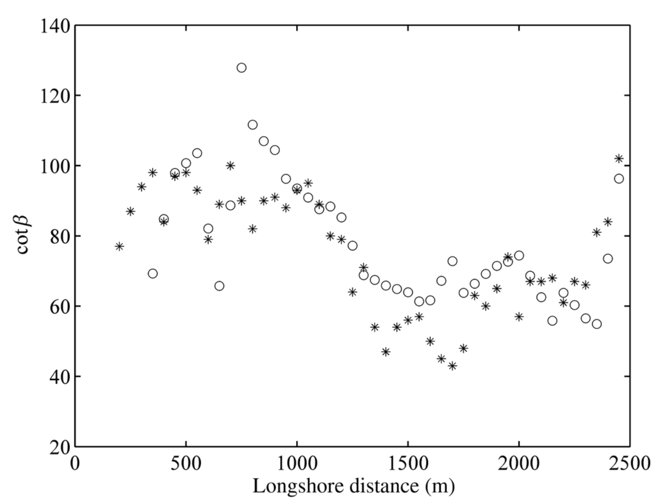

Fig. 7 A comparison between the computed beachface slopes (stars) and the measured beachface slopes (open circles) shows the applicability of the one-line shift method.

4 Discussion

From the results obtained above, we discuss the effects on the waterline-to-shoreline corrections in this section. The key factors are the determination of a beach face slope, different equations of runup for dissipative beaches, and application of shoreline setup correction.

4.1 *On Beachface Slope*

From mean SD of waterlines-to-shorelines corrections in Table 3, it is obvious that beachface slopes and runup of exceedance quartile are two key factors. Beachface slope is a dynamic feature that changes in wave conditions as well as the gain or loss of different sediment sizes on the beachface. Definition of a single beach slope becomes difficult on natural beaches with typically concave profiles and is further complicated by the common presence of offshore sandbars. A representative beachface slope of a natural beach is not well defined and widely accepted. In practice, the beachface of a concave beach profile almost linearly declines so that it is reasonable to represent the beachface slope by a straight line. However, which two points on beachface should be selected to compute the slope is a prime concern. Realizing the variability of beachface slope in terms of both definition and measurement, Stockdon et al.[20] defined the beachface slope as the average over a region of two times the standard deviation of continuous water level record. However, the definition is difficult to utilize. An alternative definition of surf-zone slope was also considered by Stockdon et al.[20] and was defined as the slope between the shoreline and the cross-shore location of wave breaking.

In the present study, beachface slope defined over the portion of a beach extending roughly 62.5-m landward and seaward from the shoreline is the most suitable only for a mild sloping beach with an average slope of around $1/80$. An estimated runup $R_{2\%}$ of about 0.6 m on a beach with a slope of $1/80$ can move horizontally about 50 m. The landward and seaward distances from the shoreline re approximate to the distance of the wave's climbing on the beach. A large SD for cases 3, 4, 5, and 9 in Table 3 indicates an improper definition of beachface slope. Two points on the beachface slope for cases 3, 4, and 5 are located at the shoreline and at either a landward or seaward distance alone. For case 9, two points are centered on the shoreline but are far away. The beachface slope defined over the portion of the swash zone extending landward and seaward from the shoreline by a suitable distance is recommended from the present study. Wave runup $R_{2\%}$ climbing on a beach for a seasonal mean significant wave is favorable for estimating the suitable distance.

4.2 *On Wave Runup*

The maximum runup and the runup $R_{2\%}$ are examined for the best correction for each beachface slope. The maximum and minimum of all obtained ξ_0 are 0.117 and 0.031, respectively. Inserting the maximum into Eq. (7) yields $R_{\max} = 0.445\,H_0$ and $R_{2\%} = 0.405\,H_0$. For the minimum, $R_{\max} = 0.160\,H_0$ and $R_{2\%} = 0.158\,H_0$ are obtained. The relative differences between estimated $R_{\max}$ and $R_{2\%}$ is 1.2% and 9.6%. The small difference between all estimated $R_{\max}$ and $R_{2\%}$ shows that both corrected shorelines are approaching. The subject of $R_{2\%}$, such as Stockdon et al.,[20] Nielson and Hanslow,[21] Mase,[31] Wassing,[33] Van der Meer and Stam,[34] and so on, is commonly investigated in some studies for coastal engineering applications. Based on the best correction in the present study and common engineering applications, the extreme runup used for shifting a waterline on an image to the corresponding shoreline is recommended.

The beach in the present study is extremely dissipative based on low values of the surf similarity parameter.[20,22] Stockdon et al.[20] showed that shoreline motions on dissipative beaches are dominated by energy in the infragravity band and extreme runup is significantly related to $(H_0 L_0)^{1/2}$ neglecting the beachface slope. When Eq. (8) proposed by Stockdon et al.[20] is used for case 7, it also has the smallest mean SD among the 9 cases in Table 3. However, the average for case 7 is 26.3 m which slightly exceeds that by Mase's equation.

Considering both Eqs. (7) and (8) at a wave steepness ranging from 0.01 to 0.08 when the wave height of 1.5 m and the mean beachface slope of $1/80$ are specified, the shifted distances of waterlines due to runup are computed and shown in Fig. 8(a). Both lines in Fig. 8(a) indicate that two shifted distances are close at a wave steepness of 0.01 and decrease with an increase in wave steepness. The results obtained by Eq. (8) are lower than those by Eq. (7). Equation (8) was obtained from best fitting to field data for dissipative beaches. At a fixed wave height, a low-wave steepness stands for a long wave and a high steepness for a short wave. A long wave has uniformly distributed horizontal velocity so that the wave has strong momentum to climb on a sloping beach. On the contrary, a short wave with an exponentially decayed velocity distribution has low momentum to climb on a sloping beach.

The difference between both results has a maximum of 6.1 m and a mean of 4.8 m. However, the difference is rather small against a large scatter of original field data that were best parameterized in a dimensional form of the Iribarren-based expression or in terms of the surf similarity parameter shown in the previous studies. A small difference exists between the mean SD in Table 3 discussed above and the shifted distances in Fig. 8(a) for Eqs. (7) and (8); both equations are applicable for making the water-to-shoreline correction due to wave runup on a very mild beach.

4.3 *On Setup Correction*

Although wave runup and tidal variation are considered in the proposed water-to-shoreline correction, the position of the shoreline setup is the intersection between the beach and the mean water surface at a fixed tidal level. The shoreline setup determines a mean waterline above a still water level and makes a horizontal distance between such a waterline and tidal level. Using Eqs. (4)–(6), the shifted distance of a waterline from a still water to shoreline setup level is computed and shown in Fig. 8(b) at the same computational conditions for Fig. 8(a). Both shifted distances estimated by Eqs. (4) and (5) are approximate and have an increasing difference as the wave gets steeper. The shifted distance estimated by Eq. (5) exceeds that by Eq. (4) for waves of high steepness (H_0/L_0>0.02) and is lower than that by Eq. (4) for waves of low steepness (H_0/L_0<0.02). The result shows that the shoreline setup computed by Eq. (4) agrees with the prediction by Goda's random wave breaking model. In Fig. 8(b), the shifted distance estimated by Eq. (6) with the regression coefficient of 0.45 is much lower than those by the other two equations. It is suggested that Eq. (4) is suitably used to determine the position of the shoreline setup from the still tidal level for a dissipative beach. The shifted distance due to the shoreline being up from the still tidal level is estimated by Eq. (4) in a range of 6.8 to 19.2 m with a mean of 10.2 m for the computational conditions.

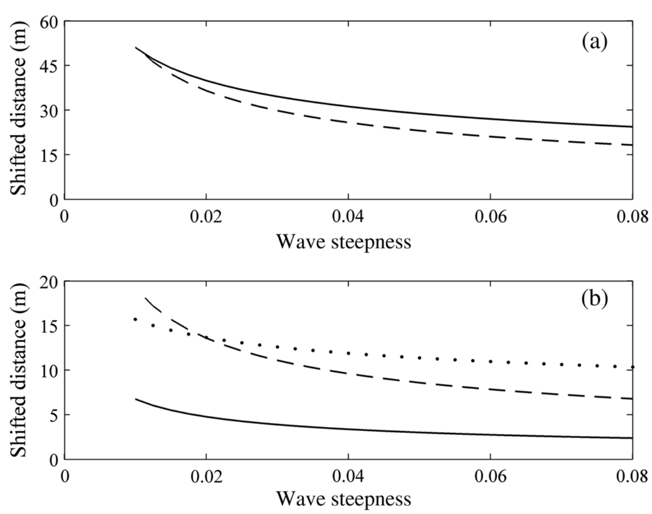

Fig. 8 The shifted distance of waterlines due to (a) runup and (b) shoreline setup is estimated considering a different equation. The solid line denotes the prediction by Eq. (7) and the dashed line by Eq. (8) in (a). The dotted line denotes the prediction by Eq. (5), the dashed line by Eq. (4), and solid line by Eq. (6) in (b). The result shows the shifted distance depending on wave steepness and the difference between shifted distances.

Wave runup on a natural beach in space and time are commonly complicated due to varied topography and irregular waves. According to the conclusions of Stockdon et al.[20] on infragravity-dominated dissipative beaches, the magnitudes of both setup and swash are dependent only on offshore wave height and wavelength. Statistics of predicted runup averaged over all sites indicate a relative bias of about 10% and a relative rms error of around 26% based on the mean observed runup elevation for all experiments. On intermediate and reflective beaches, the runup parameterized in an alongshore-averaged beach slope has a relative error equal to 51% of the fractional variability between the measured and the averaged slope. Therefore, it is hard to accurately determine shoreline setup and runup in terms of offshore wave conditions with or without beachface slope. The use of an alongshore-averaged beach slope in practical applications of the runup parameterization may result in an error of about 23.6 m using the proposed image-based waterline-to-shoreline correction. Because of the restriction of model accuracy, the proposed waterline-to-shoreline correction method is limited to the case of severe shoreline variations for studying shoreline evolution.

5 Conclusions

The location of the shoreline at MWL and its historical rate of change are applicable for examining beach changes. Shoreline evolution is visually and commonly used to explain the beach erosion or accretion. Accurate determination of the positions of historical shorelines is important in coastal engineering. A waterline on a satellite image is different from the shoreline at MWL due to wave runup and tidal variation. A method of shoreline determination by extracting waterlines on three chosen satellite images and shifting the waterlines to the shoreline at MWL considering wave runup and tidal variation was proposed and determined as valid in this paper. The shorelines corrected with the simple consideration of tidal variations were located at a higher shoreward position than those with the correction by wave runup and tide, indicating that joint consideration of wave setup and runup is necessary for accurately determining the shoreline position from the extracted waterline on a satellite image.

The expressions for the 2% exceedance runup of Mase[31] or the extreme runup of Stockdon et al.[20] for dissipative beaches with an average beachface slope at two points located shoreward and seaward away from MWL by an equal distance of 62.5 m were evaluated and are deemed acceptable. For the possible case of unavailable beachface slope measurements, the one-line shift model was applied to estimate the unknown slopes by minimizing the absolute error between the assumed and calculated slopes. Offshore wave height, period, and fore beachface slope are required to calculate wave runup. Therefore, the proposed correction by wave runup is not applicable for the case of offshore wave conditions being not available. Deviations of Gaussian-distributed time-varying waterlines result in the slight uncertainty of extracted shorelines by the proposed method. Statistical analysis on the waterline-to-shoreline correction will be considered in the future study.

Using only the application of parameterization to scattered original field data of wave shoreline setup and runup, empirical equations for shoreline setup and runup cannot distinguish the fractional variability between the measured and the averaged runup. Computation of the proposed image-based waterline-to-shoreline correction shows an error of about 23.6 m for all 47 examined beach profiles. The accuracy of the present method can be improved by using high-spatial resolution of more images and by comparing with the measured shoreline available at the capture time of images in the future.

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