Supermoon Drives Beach Morphological Changes in the Swash Zone

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Abstract
The effect of the supermoon, which appears much larger than a normal full moon, on the morphological changes of a sandy beach was investigated by analyzing a 25-year daily observation data set of beach morphology in the swash zone. The beach morphology fluctuated in two cycles related to the supermoon: the semisyndodic month cycle (from full moon to new moon, and vice versa) and the anomalistic month cycle (from perigee to perigee). The supermoon makes the erosion of the upper swash zone more likely by generating a larger tidal range. The high-water-level contour positions observed during supermoons retreated significantly, although there were no trends in the change for all the observations. Erosion due to high waves coincident with a supermoon can be expected to be more severe in the upper swash zone; including the supermoon effect in beach morphodynamic models can improve coastal management.

Plain Language Summary
A “supermoon” is a full moon that appears much larger than a normal full moon. It causes an unusually high tide known as a “king tide,” and it increases the risk of coastal inundation. However, beach morphological changes induced by supermoons have not been investigated despite the effect of such changes on the vulnerability of coastal regions to inundation. Here, we show the correlation between the morphological changes (erosion and accretion) across the beach and the moon cycles using long-term beach observation data. Our results indicate that the supermoon increases the risk of more severe beach erosion near the shoreline. The erosion is caused by a larger tidal range resulting from a stronger lunar gravitational force. The findings emphasize the importance of understanding the extreme erosion and inundation caused by the supermoon effects, particularly when combined with high waves and storm surges.

1. Introduction
The Moon phases affect various Earth systems (Balling & Cerveny, 1995; Pertsev & Dalin, 2010); in some cases, this occurs through the action of tides (Carpenter et al., 1972; Cochran et al., 2004). The Moon orbiting the Earth aligns with the Sun and the Earth (full moon or new moon) in a 14.77-day cycle (semisyndodic month); this cycle reinforces the tidal force, resulting in the spring tides. The orbit of the Moon is an ellipse with the Earth at one focus. The distance between the Moon and the Earth changes with a period of 27.55 days (anomalistic month). The distance to the Moon from Earth’s center changes from 406,000 km at the apogee to about 357,000 km at the perigee. When the Moon and the Earth are closest (perigee), the tidal force caused by the Moon increases. A “supermoon” occurs when the full moon is synchronized with the perigee (in a broad sense, the new moon at a perigee is also a supermoon). The supermoon appears larger than the normal full moon. The full moon on 8 April 2020, which is an example of a recent supermoon, was 14% larger in apparent diameter than the smallest full moon, or “micro–full moon,” on 31 October 2020 (NAOJ, 2020). Scientists suggest that the supermoon can also affect some natural phenomena (e.g., Portugal et al., 2019). It has greater gravitational force than the normal full or new moon and produces a larger tidal range, in particular the high tide known as the “king tide” (Flick, 2016; NOAA, 2019). A king tide, which is an unusually high tide at the perigee spring tides with a supermoon, is a predictable cyclic astronomical tide, unlike tide fluctuations caused by weather factors such as storm surges. A king tide is more likely to cause coastal disasters including inundation (Román-Rivera & Ellis, 2018) when it occurs simultaneously with storm surges and high waves (Gallien et al., 2013).

Such large tidal ranges due to the supermoon may also affect the morphological change of the beach, which is related to the coastal vulnerability to inundation. Beach morphological changes are caused mainly by waves but also affected by water-level anomalies (Barnard et al., 2015, 2017; Gratiot et al., 2008). However, most
morpodynamic models do not account for the effects of tidal range on the morphological changes. Studies suggest that spring tides may have an impact on beach morphological changes. They show that the beach elevation a few meters above the mean water level was minimal a few days after the spring tide and was maximum a few days after the neap tide (Aubrey et al., 1976; Clarke et al., 1984; LaFond, 1939). The observations in these studies were limited, focusing on individual events, and the discussions did not provide a full explanation of the beach process in response to tidal fluctuations. Moreover, morphological changes related to the supermoon cycle were not reported.

The accuracy of existing numerical models without taking into account the effects of the cyclic tidal ranges is not sufficient to predict the short-term morphological change with “the supermoon effect.” The long-term reproducibility of beach morphology obtained by long-term integration of the short-term changes is also reduced. Understanding the effects can improve the model accuracies. This study investigated the effect of the supermoon on the beach morphological changes in the swash zone using a unique data set of daily morphological changes of a sandy beach observed since 1986. To determine the supermoon effect, we analyzed the data using spectral analysis and statistical methods.

2. Data and Methods

2.1. Data Description

The data used for the analysis in this study were obtained at the Hasaki coast, a microtidal sandy beach facing the Pacific Ocean in Japan (Figure 1a), from 12 March 1986 to 31 December 2010. The beach is a long-shore uniform beach (Figure 1b), and the impact of longshore sediment transport on the beach profiles is relatively small (Kuriyama, 2002). The median sediment size of the foreshore sand is about 0.18 mm, and the porosity is about 39.5% (Katoh & Yanagishima, 1995).

The beach profile measurements were conducted along a 400-m-long pier (HORS; Figure S1 in the supporting information; 35° 50’ 27”N, 140° 45’ 41”E) situated on the Hasaki coast; the measurements were made at cross-shore intervals of 5 m every weekday for 25 years. The total length of the observation line was 500 m, consisting of 115 m along the land and 385 m along the pier (underwater). The beach profiles were measured with a 3- or 5-kg lead line released from the pier on the seaside and with a level and staff on the shoreside.

We used a contour defined by the cross-shore position with a specific elevation in the measured profile as a proxy for the beach morphology (Figure 2a). The diurnal changes of 61 reference-level contour positions measured for 25 years were used for the analysis. The reference levels of the 61 contours are every 0.05 m from −1.0 to +2.0 m of elevation, which corresponds to the swash zone. The level of the elevations is based on the datum level at Hasaki, and the high, mean, and low water levels (H.W.L., M.W.L., and L.W.L.) are 1.25, 0.65, and −0.20 m, respectively. The contour positions are based on a cross-shore coordinate system, in which an offshore direction is positive relative to the origin of the pier’s base. Thus, a positive value of the contour change indicates seaward movement resulting from accretion, while a negative value indicates landward movement resulting from erosion.

The seawater level was recorded every hour by a float-type tide gauge inside the Kashima Port (Figure 1a). Waves were observed every 20 min to 2 hr (2 hr from 1986 to 2007; 1 hr from 2007 to 2009; and 20 min since 2010) at a water depth of 24 m offshore of the pier (Figure 1a) using an ultrasonic wave gauge.

Considering that the beach profile measurements were taken mostly around 8 a.m., the daily data were based on the time from 8:00 a.m. to 7:00 a.m. the next day. The tidal range was the difference between the maximum and minimum of the observed seawater level during one day. The water level was defined as the daily mean of the observed water level. The offshore wave energy flux $E_g = \frac{\rho g H_s^2 c_{g,s}^2}{16}$ was averaged daily; here, $H_s$ is the significant wave height, $\rho$ is the seawater density, $g$ is the gravitational acceleration, and $c_{g,s}$ is the group velocity corresponding to the significant wave period $T_g$. The subscript 0 denotes the deepwater value. For the spectral analysis, all the missing data were adjusted to the daily interval data $(n = 9,060)$ by simple linear interpolation using the nearest available data values. For the stochastic analysis, the data without the interpolation were used; thus, the number of data points varied depending on the combination used.
2.2. Spectral Analysis

To investigate the cyclic changes in the beach morphology, the power spectra of the contour changes were calculated using the fast Fourier transform (FFT). For the FFT analysis the original time series data set of 9,060 points was expanded to 16,384 data points by adding 7,324 zero padding points. The reduced power was corrected to the original power level. The power spectrum was smoothed five times by a triangular filter.

FFT power spectra often fluctuate around the statistically expected values and miss small spectral peaks. Therefore, we also calculated the power spectra using a parametric method—the multivariate autoregressive (MAR) model because MAR spectra tend to be more stable than FFT spectra. The power spectra of the contour changes were estimated by the model, expressed as Equation 1.

\[
x_i(t) = \sum_{j=1}^{k} \sum_{m=1}^{M} a_{ij}(m)x_j(t - m) + e_i(t),
\]

where \(x_i(t)\) is the time series data, \(a_{ij}(m)\) is the coefficient of the \(j\)th data point for the \(i\)th variable, \(e_i(t)\) is the white noise, \(t\) is the time, and \(m\) is the time lag. The change rate of the contour position, the contour position, the offshore wave energy flux, the water level, and the tidal range were used as variables \((k = 5)\), and the model parameters \(a_{ij}\) and \(M\) were estimated at each reference level of the contour position. The regression coefficients \(a_{ij}\) were determined by solving the Yule-Walker equation using the Levinson-Durbin algorithm. The best order \(M\) was determined by minimizing the Akaike information criterion (AIC; Akaike, 1973). The
effect of the lower order of $M$ is similar to the smoothing effect in the FFT method. The power spectrum densities were obtained by using the coefficient of the MAR model (Gangopadhyay et al., 1989):

$$ p_{ii}(f) = \sum_{j=1}^{k} |A(f)^{-1}ij|^2 \sigma_j^2 $$

(2)

$$ a_{ij}(f) = \sum_{m=0}^{M} a_{ij}(m)e^{-2\pi jm}, $$

(3)

where $p_{ii}(f)$ is the power spectrum of $x_i(t)$, $A(f)$ is the matrix having the element $a_{ij}(f)$, and $\sigma_j^2$ is the variance of the innovation. $a_{ij}$ is obtained by FFT.

The peak rate was calculated from the power spectrum density of the frequency component normalized by the overall average power at the reference-level contour change. The statistical significance of the peak was tested using the $\chi^2$ distribution with equivalent degrees of freedom, considering the effects of the zero padding and smoothing filter in the frequency domain (Koopmans, 1974; Priestley, 1981; Von Storch & Zwiers, 2001). The null hypothesis—that the peak of the spectrum was generated randomly from white noise—was rejected at a 5% significance level.

The amplitude is expressed by Equation 4 as the absolute value used in the power spectrum density of the frequency component.

$$ \text{Ampl.} = 2|X(f)| \cdot df, $$

(4)

where $X(f)$ is the spectral component at frequency $f$ and $df$ is the frequency resolution.

The phase differences of the contour changes with tidal range were calculated from the cross spectra by the FFT method. Additionally, the cross-spectral cospectrum and quad spectrum were smoothed five times by a triangular filter.

### 2.3. Statistical Analysis

We evaluated the anomalies of the tidal range and the contour changes due to supermoons and full or new moons. A supermoon was defined as a full moon or a new moon within 24 hr of the time when the Moon is at perigee. The beach morphological changes that occurred during the time of the corresponding supermoon and full or new moon were used for the analysis. Note that the spring tide on the coast occurs between 0 and 2 days after the full or new moon; however, this lag is negligible because the beach morphological change precedes the tidal range by a similar lag, which is shown in the spectral analysis later.

We compared the mean values of the tidal range and the contour changes during those events with the mean of all the observations. The assumption of the statistical $t$ test was that the mean value is the same as the null hypothesis; this was rejected with a $p$ value of 0.05. To check the change in the histograms of the H.W.L. contour change and the offshore wave energy flux.

### 3. Results and Discussion

#### 3.1. Two Supermoon-Related Cycles of Beach Morphological Change

The power spectra of the contour changes show peaks in the annual and semiannual cycles (Figure 2b). The annual and semiannual cycles are caused mainly by seasonal wave fluctuations (Eichentopf et al., 2020). The
wave energy fluxes have no significant peaks apart from the cyclic ones (Figure S2); thus, the spectral analysis can confirm that the wave components do not affect the supermoon cycles.

In the power spectrum of the H.W.L. contour change, the highest narrow peak corresponds to the 14.77-day semisynodic month cycle (Figure 2b). This indicates that the morphological change in the semisynodic month cycle is the most dominant process in the H.W.L. contour change. The narrow peak of the semisynodic month cycle is centered around the H.W.L. and extends ±0.5 m (hereinafter, the upper swash zone), then the power decreases as the contour level recedes from the H.W.L. (Figure 3a). Similarly, the other narrow peak is obtained below the bottom limit of the upper swash zone (hereinafter, the zone above L.W.L. is referred to as the lower swash zone; Figure 3a). In other words, the morphological change with strong periodicity of the semisynodic month cycle occurs characteristically at two ranges in the swash zone.

The amplitudes of the cyclic contour changes in the upper swash zone are similar to those in the lower swash zone (Figure 3b); however, the phase of the contour change shifts to approximate opposite phase (by about 0.8π) at the boundary between the upper and lower swash zones (Figure 3c). The phase differences between the contour changes and the tidal range show that the maximum retreat of the contours in the upper swash zone (i.e., erosion) occurs about 1.5 days before the maximum tidal range (i.e., spring tide), resulting in contour advancement of the same volume in the lower swash zone (i.e., accretion) due to the sand moving to the lower swash zone. These results clearly show the semisynodic-month-cycle erosion in the upper swash zone and accretion in the lower swash zone as the tidal range increases. The maximum erosion in the upper swash zone and the maximum tidal range do not coincide completely in the semisynodic month period. The 1.5-day lag may be due to the influences of other factors, for example, the antecedent beach morphology before the change (Eichentopf et al., 2020) and the water level (Barnard et al., 2015). The phase difference
of the contour movement between the upper and lower swash zones is also not completely in antiphase. This may be due to the interaction with the beach morphology on the offshore side of the swash zone.

The power spectra of the contour changes obtained using the MAR model show significant narrow peaks corresponding to the 27.55-day anomalous month period, particularly in the upper swash zone (α = 0.05) (Figures 2c, 3a, and S4), although it is not detected by the FFT method (Figures 2b and S3). The region showing the significant spectrum peak in the anomalous month period approximately coincides with the upper swash zone, while it is not clear in the lower swash zone (Figure 3a). The H.W.L. power in the anomalous month cycle is 11% of that in the semisynodic month cycle, but it is 2.6 times larger than the average power and the second largest peak among all the frequencies (Figures 2c and 3b). The contours in the upper swash zone are more likely to retreat as the Moon approaches the perigee and the tidal range increases in the anomalous month cycle as well as in the semisynodic month cycle. The H.W.L. contour is most likely to retreat about 0.8 days before the maximum tidal range (Figure 3c).

### 3.2. Beach Erosion Anomaly During Supermoon Events

The spectral analysis shows that the erosion in the upper swash zone is more likely to occur when the tidal range increases in a supermoon event (i.e., the periagean spring tide). The mean tidal range observed on the Hasaki coast during the past supermoons was 1.43 m (n = 91), which is 13 cm larger than the mean value of 1.30 m (n = 613) for all full and new moon tides. The mean value of all the observations was 1.04 m (n = 9,060). The supermoon significantly increases the tidal range (α = 0.05). The mean values of the contour changes in the upper swash zone were negative during the larger tidal ranges, although the values for all the observations were around 0 (Figure 4a). The mean value and standard deviation of the H.W.L. contour change (n = 4,905) was 0.0 ± 1.71 m/day (mean ± S.D.) for all the observations due to the long-term stability of the contour position, whereas the H.W.L. contour during the full and new moons (n = 325) and supermoons (n = 42) changed at −0.37 ± 1.75 m/day and −0.47 ± 1.93 m/day (mean ± S.D.), respectively, and at −0.35 and −0.18 m/day on the median, respectively (Figures 4b and 4c). There was no significant difference between the mean wave heights during those events (α = 0.05); the mean wave heights of all the observations, full and new moon events, and supermoon events, were 1.34, 1.37, and 1.43 m, respectively.

The linear regression shows an erosion trend as the wave energy increases (Figure 4d). The coefficients of the linear regression between the offshore wave energy flux and the H.W.L. contour change (Figure 4d) for all the data were an intercept of +0.39 m/day and a slope of −0.040 (m s)/(kN day). For the supermoon events, the intercept decreased to +0.27 m/day and the slope was −0.059 (m s)/(kN day), which was 1.49 times higher than that for all the data (Figure 4d). The results indicate that supermoons will lead to smaller accretion of the H.W.L. contour during low waves and larger retreat of the contour during high waves. The retreat during supermoons was estimated to be more than 49% larger than normal for the same wave regime, although the null hypothesis was rejected at 18.2% significance level. The low statistical significance probably arises because the beach response to waves does not follow a simple linear relationship. The response may be influenced by infragravity waves and prior beach morphological condition. The results imply that although the sensitivity of the H.W.L. contour response to waves may be affected by the influence of supermoons, further investigation is needed into the processes.

### 3.3. Interpretation of the Supermoon Effect

As mentioned above, the beach in the upper swash zone is more likely to be eroded when the tidal range is large; moreover, it is more likely to be accreted when the tidal range is small. This difference may be related to the response of the groundwater level to the tide-induced sea level fluctuation. Studies suggest that infiltration and exfiltration of water on the beach face influence the sediment transport (Clarke & Eliot, 1987; Coco et al., 2004; Duncan, 1964; Masselink & Li, 2001). During flood tide, the wave run-up is higher than the groundwater level, so the water from the wave run-up percolates into the beach. As a result of weakened backwash, more sediment is deposited in the upper swash zone. Conversely, during ebb tide the groundwater level fall is slower than the sea level fall, and the effluent groundwater is added to the backwash. Then, more sediment in the upper swash zone is likely to move to the lower swash zone due to the stronger backwash. These studies only account for the processes during flood tides and ebb tides. The amount of accretion and erosion during a single tidal cycle is influenced by the tidal range. During ebb tide when groundwater is discharged into the sea, the groundwater table drops at a slower rate than the
seawater level (Emery & Foster, 1948); therefore, a larger tidal range will increase the difference between the seawater level and groundwater level. Hence, when the tidal range is large, the erosion of the upper swash zone due to the ebb tide will become more significant. However, during flood tide the groundwater level rises rapidly with the rising sea level due to rapid percolation of the wave run-up (Turner et al., 1997); therefore, the accretion in the upper swash zone due to the flood tide will not change significantly regardless of the magnitude of the tidal range. As a result, when the tidal range is large, the erosion due to the ebb tide would be dominant, and when the tidal range is smaller, the accretion due to the flood tide would be dominant. This explains why the cyclic changes in beach morphology coincide with the semisynodic month and the anomalistic month periods. Because the sediment transport is enhanced and inhibited by altering the effective sediment weight and thickness of the boundary layer through infiltration and exfiltration (Butt et al., 2001), the efficiency would change depending on the local tidal range and the local sediment grain size related to the permeabilities (Kulkarni et al., 2004; Masselink & Li, 2001). The cause of this cyclic morphological change and its effect should be further investigated.

4. Conclusions
The spectral analysis and statistical analysis using a 25-year daily beach observation data set showed that the Moon’s phase and its distance from the Earth affect the beach morphological changes in the swash zone through fluctuations of the tidal ranges. The morphological changes have a semisynodic month cycle of 14.77 days and an anomalistic month cycle of 27.55 days. Supermoons with two synchronized cycles make
the erosion of the upper swash zone of a sandy beach more likely by generating a larger tidal range. It is therefore important to consider not only the risk of inundation but also the risk of erosion during king tides. Our study indicates that high waves that coincide with a supermoon are likely to cause severe erosion in the upper swash zone. Thus, advance attention is advised when extreme waves are forecast to occur during a supermoon. Understanding the beach erosion processes caused by predictable water-level fluctuations is important for predicting coastal disasters and for long-term coastal management such as beach-width maintenance. In addition to future sea level rises, future changes in wave characteristics (Hemer et al., 2013) are predicted to cause severe beach erosion and shoreline retreat (Vitousek et al., 2017). More advanced numerical models that include the supermoon effect presented in this study will be needed for more precise risk management.

Data Availability Statement

The data sets that support the findings of this study are publicly available in Zenodo: https://zenodo.org/record/4054577 (https://doi.org/10.5281/zenodo.4054577; Banno & Kuriyama, 2020).

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