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Analysis of Beach Area Response to Gradual Decrease in Sediment Supply

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Artificial developments such as dams and harbors can cause serious beach problems by blocking sediment drift from the river. These problems alter the sediment budget, which in turn can lead to long-term shoreline retreat. In this paper, we present the background erosion due to gradual decreases in sediment supply based on sediment mass conservation. The proposed methodology is validated using aerial maps of Korean beaches from the 1970s to the 2010s. Furthermore, we discuss the application of the proposed methodology to beach nourishment according to the time to converge to equilibrium beach area. It is expected that the methodology of this paper can be used to predict and respond to problems caused by changes in sediment budget.

1. Introduction

Rivers act as conveyors to transport large amounts of sediment from the land to the ocean.[1–4] These acts play an important role in geologic and geochemical cycles, as well as in coastal environments. However, man-made developments (e.g., dams and harbors) disrupt the continuity of river and coastal systems that transport sediment from rivers to coasts.[5] In the second half of the 20th century, approximately 45000 large dams and 800000 small dams were built worldwide, a nearly 10-fold increase from 1950.[6] It is estimated that more than 30% of the sediment flux is trapped upstream of dams owing to vast amounts of construction.[7] Subsequently, the global sediment cycle from the river to the coast has been significantly reduced.[8]

Littoral cells (i.e., beach compartments) provide the basic knowledge needed to understand the source, transport, sinking, and storage of sand along the nearshore coast. In a typical beach compartment, littoral transport begins at a rocky headland or artificial harbor where updrifts limit the supply of sand. Sediments enter the littoral cell primarily from coastal streams and cliff erosion, and are transported alongshore under the effects of prevailing wave conditions.[9] On the other hand, sand is lost from the system or cell either through a submarine canyon, a coastal dune field, or in some cases, by sand mining. The difference between the amount of sediment lost and gain in a single littoral cell is called the sediment budget.[10]

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Bowen and Inman[11] attempted to estimate sediment budgets for littoral cells along the central coast of California, which became a valuable reference for subsequent studies. However, owing to spatial and temporal variations, it is difficult to accurately quantify the sediment budget of littoral cells from coastal streams and cliff erosion.[12,13] Beaches maintain their shape by balancing the sediment budget in a littoral cell. This indicates that the beaches in the coastal cell respond by balancing sediment losses and gains, eventually reaching equilibrium.[14–16] However, if the sediment budget is altered, such as by beach sand extraction or the construction of dams/harbors, the shoreline will move backward to reach another equilibrium.[14–18]

Recently, Lee and Lee[14] have proposed an equation to estimate the long-term beach retreat due to a change in sediment budget through sand mass conservation. They derived the equation by assuming that the sediment gain and loss rates are constant because these parameters are difficult to accurately predict. However, after the construction of dams or harbors, the source of sediment is not immediately reduced, but gradually. Therefore, in this paper, we propose an equation for a sediment budget that reflects the gradual reduction of a sediment source due to man-made structures. We validate the proposed methodology by applying it to beach area changes obtained from aerial maps.

In this regard, optical remote sensors, particularly aerial photographs acquired by airborne optical cameras, play an indispensable role in the present study. Previous studies have demonstrated that historical aerial photographs and other time-series optical images can provide reliable shoreline-position records for assessing long-term coastal change, particularly in data-scarce environments.[19–22] These remotely sensed shoreline and beach-area datasets are also well suited for deriving shoreline-change statistics and for supporting the calibration and validation of predictive coastal-evolution models.[23–25] Therefore, the quantitative beach-area data extracted from such optical sensor records serve as the essential observational basis for the proposed predictive model, thereby linking historical shoreline tracking with the modern predictive modeling of coastal change.

2. Background Erosion According to Sediment Source Reduction Rate

2.1 Existing study on background erosion due to decrease/increase in sediment supply

Lee and Lee[14] proposed an equation for the change in the sediment volume of littoral cells due to the development of watershed/coast areas and the extraction of sea sediments from the law of mass conservation. According to the law of mass conservation, the amount of sediment on the beach satisfies the following equation:

$$\frac{dV}{dt} = Q_{in} - Q_{out}, \tag{1}$$

where V is the beach volume at time t, Q_{in} is the sediment gain rate into the littoral cell, and Q_{out} is the sediment loss rate from the littoral cell.

The sediment budget can be broadly divided into gain/loss caused by sources and wave incidence.[14,15] The sediment budget caused by sources refers to the amount of sediment gain and loss, for example, in rivers and ports, etc. On the other hand, the sediment budget caused by wave incidence refers to the difference between the sediment suspended by wave energy and the sediment inflow by continuous wave incidence. Suspended sediment is constant as long as the wave climate does not change; however, the sediment inflow by waves varies depending on the beach volume. Therefore, Lee and Lee[14] derived the following equation by assuming that the sediment loss rate due to waves is a constant:

$$\frac{dV}{dt} = \Delta Q_p - KV. \tag{2}$$

Here, ΔQ_p is the sediment budget caused by sources and K [y^{-1}] is the offshore sediment loss rate. Moreover, assuming that the vertical height of the littoral cell is constant as the shoreline changes owing to the sediment budget deficit, Eq. (2) can be expressed as

$$\frac{dA}{dt} = \frac{1}{D_s}\Delta Q_p - KA, \tag{3}$$

where A is the beach area at time t and D_s is the vertical height of the littoral cell, which is the sum of berm height and closure depth. If the beach area does not change owing to reaching equilibrium, the following equation is satisfied:

$$\Delta Q_p = KA_iD_s, \tag{4}$$

where A_i is the initial beach area before the construction of dam/harbor structures. However, when dams or harbors are built in the littoral cell, the equilibrium beach area changes because the sediment budget caused by sources decreases. If the construction of a dam/harbor results in the sediment discharge being α percent less than before, the following relationship is satisfied:[14]

$$\frac{dA}{dt} = K\left(\alpha A_i - A\right). \tag{5}$$

Here, α is the sediment reduction rate from rivers. Lee and Lee[14] assumed that the sediment reduction rate is constant. By solving Eq. (5), the governing equation is obtained as

$$A(t) = (1-\alpha)A_i + \alpha A_i \exp(-Kt). \tag{6}$$

According to the above equation, the beach area converges to the new equilibrium depending on the sediment reduction rate. Figure 1 shows the temporal changes in A/A_i according to the offshore sediment loss and sediment reduction rates. Figure 1 shows that all results converge to $(1 - \alpha)$ over time. In addition, Fig. 1 shows that the greater the offshore loss rate, the faster the convergence to equilibrium.

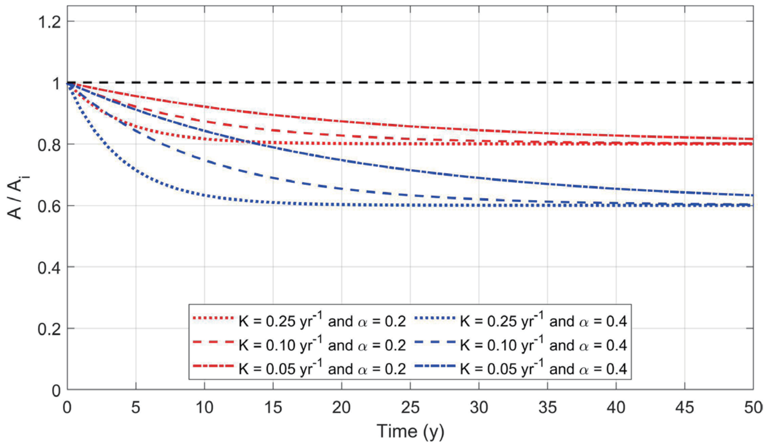

Fig. 1. (Color online) Temporal changes in A/A_i according to offshore sediment loss and sediment reduction rates.

2.2 Background erosion according to sediment source reduction rate

Lee and Lee[14] derived the governing equations for background erosion by assuming that α is constant over time. However, after dams or harbors are installed, it takes a certain amount of time to converge to α, and the beach responds to the new equilibrium accordingly. Therefore, assuming that $\alpha(t)$ is a value that changes linearly with time, the following equation is satisfied:

$$\alpha(t) = \frac{\alpha_o}{T_r} t \quad \text{for } t \le T_r, \tag{7a}$$

$$\alpha(t) = \alpha_o \quad \text{for } t > T_r. \tag{7b}$$

Here, α_o is the sediment reduction rate owing to the construction of a dam or harbor structure and T_r is the time duration it takes to converge to the sediment reduction rate. The equilibrium beach area A_{eq} according to $\alpha(t)$ can be defined as

$$A_{eq} = \left(1 - \alpha(t)\right) A_i. \tag{8}$$

Therefore, by substituting Eq. (8) into Eq. (5), an equation for background erosion according to the equilibrium beach area that changes with time is derived as

$$\frac{dA}{dt} = K\left(A_{eq} - A\right). \tag{9}$$

By solving Eq. (9), the governing equation is obtained as

$$A(t) = A_{eq} + \left(A_i - A_{eq}\right)\exp(-Kt), \tag{10}$$

where A_o is the beach area preceding $A(t)$ by time t. Figure 2 shows the temporal changes in A/A_i according to the offshore sediment loss rate and time duration when α_o = 0.4. Figure 2 shows that the longer the time duration, the slower the convergence to equilibrium.

In this study, a gradual sediment reduction model was formulated on the basis of beach area because historical aerial photographs provide a practical means for model validation. However, most shoreline response models, including one-line models, are expressed in terms of shoreline position rather than beach area.(26–28) By dividing the beach area by the shoreline length, the proposed model can be readily transformed as a function of shoreline position as follows:

$$\frac{dy}{dt} = K\left(y_{eq} - y\right), \tag{11}$$

where y is the shoreline position, defined as the beach area A divided by the shoreline length L. The above equation is similar in form to the shoreline change model of Miller and Dean.(27) While their model describes wave-induced shoreline response, the present model is governed by sediment supply and loss within the littoral cell, making it suitable for long-term shoreline evolution. This similarity suggests the potential for a hybrid model incorporating both processes.

3. Results

3.1 Study sites

In this section, the methodology of this paper is applied to two beaches (i.e., Maengbang Beach and Sokcho Beach) located on the east coast of Korea [see Fig. 3(a)]. As shown in Fig.

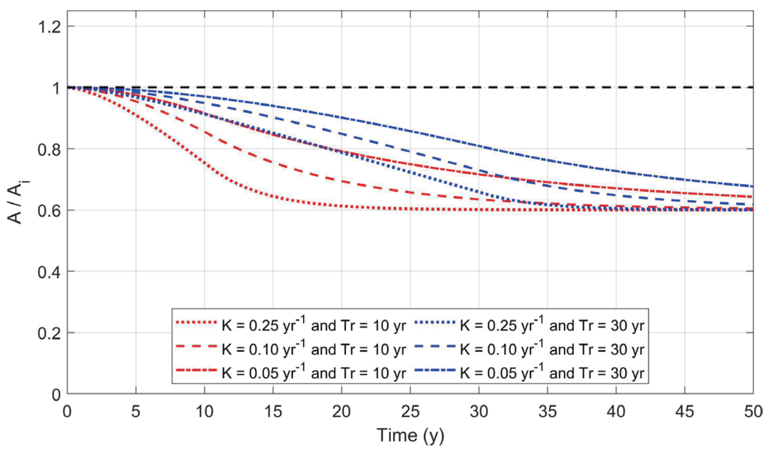

Fig. 2. (Color online) Temporal changes in A/A_i according to offshore sediment loss rate and time duration when α_o = 0.4.

3(b), the beach area of Maengbang Beach is preserved by sediments entering from the Osip-cheon (river) estuary in the north and the Maeup-cheon (river) estuary at the center. However, the sediment budget collapsed when Samcheok Port was built at the mouth of the Osip-cheon. Likewise, Sokcho Beach, balanced by the sediment inflow from the Cheongchoho (lake), suffered a collapse in its sediment budget due to the construction of Sokcho Port [see Fig. 3(c)]. Sokcho Beach and Maengbang Beach did not respond immediately after harbor structures were constructed at both study sites. However, the beach area began to gradually decrease at some point. Therefore, both regions implemented coastal management projects to reduce additional damage caused by coastal development and wave climate.

The proposed methodology is applied to comprehend the long-term beach area change in the two study sites using aerial photographs provided by the National Geographic Information Institute (NGII), Republic of Korea. The common ground of these research branches is to conduct an overlap analysis using remote sensing data, such as aerial photographs, or an investigation of changes through in situ measurement. However, the most rational way to acquire the material of the period is to analyze past imagery if there was no remote sensing data available or insufficient measurement techniques existed. Figures 4 and 5 show a series of aerial photographs after the installation of port structures at Maengbang Beach and Sokcho Beach, respectively. Table 1 also shows the beach areas extracted from the aerial photographs. Here, aerial photographs are used to ensure that wave climate does not affect the beach area.

3.2 Application of the proposed methodology

In this subsection, the proposed methodology is applied to the two research areas mentioned above. The governing equation proposed by Lee and Lee[14] was derived on the basis of physical

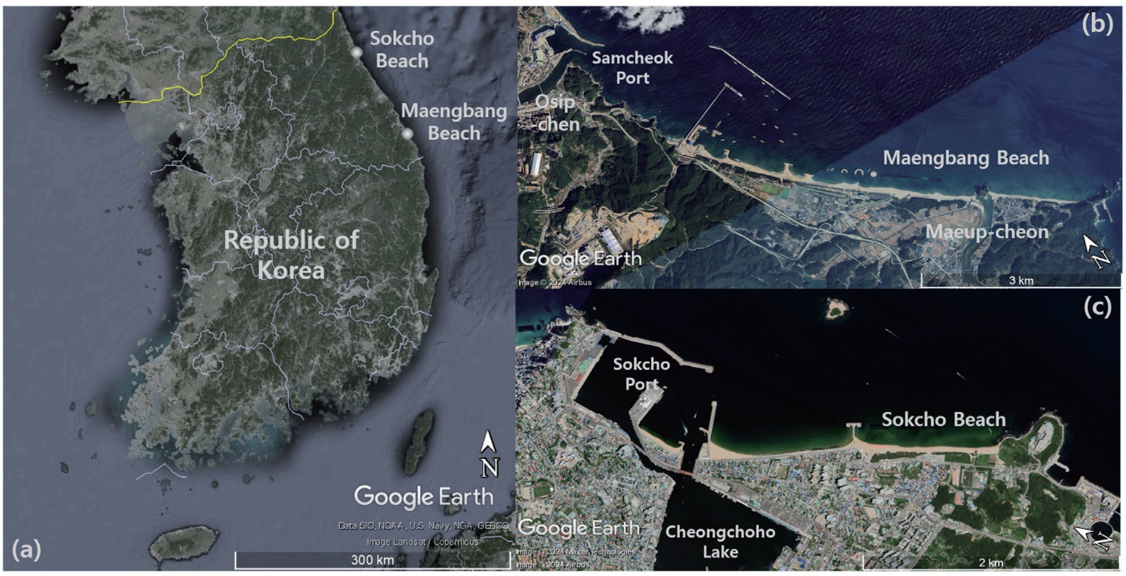

Fig. 3. (Color online) Study sites: (a) geographic locations, (b) overview of Maengbang Beach, and (c) overview of Sokcho Beach (images from Google Earth).

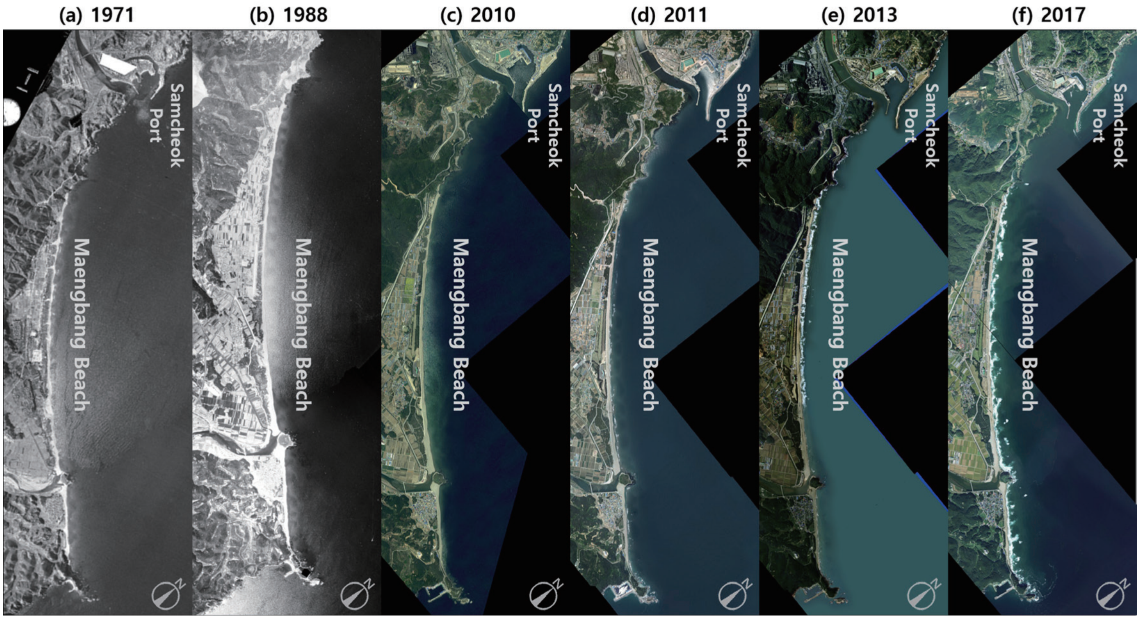

Fig. 4. (Color online) Changes in the beach area of Maengbang Beach from 1971 to 2017: (a) 1971, (b) 1988, (c) 2010, (d) 2011, (e) 2013, and (f) 2017 (images from NGII, Korea).

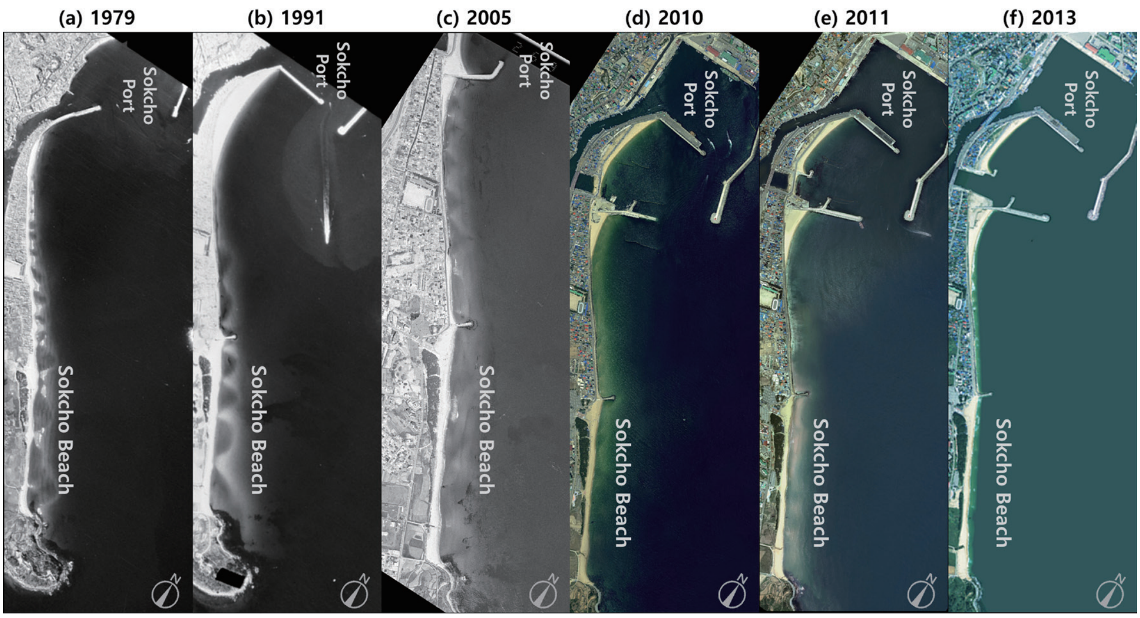

Fig. 5. (Color online) Changes in the beach area of Sokcho Beach from 1979 to 2013: (a) 1979, (b) 1991, (c) 2005, (d) 2010, (e) 2011, and (f) 2013 (images from NGII, Korea).

Table 1
Changes in the beach area of study sites.

Maengbang Beach	Time (yr)	1971	1988	2010	2011	2013	2017
	Area (m^2)	413835	377526	305416	289703	292515	283065
Sokcho Beach	Time (yr)	1979	1991	2005	2010	2011	2013
	Area (m^2)	49681	50137	45974	41822	41963	43727

natural processes. However, coastal phenomena are a complex mixture of various natural phenomena, making it impossible to accurately predict them.[15] Additionally, it is impossible to quantitatively observe the amount of sediment supply and loss within a littoral cell. Therefore, Lee and Lee[14] estimated physical coefficients, such as offshore sediment loss and sediment reduction rates from the beach width in reverse. In this study, we estimated and analyzed physical coefficients that are difficult to estimate in coastal areas. Here, we assumed that the initial beach area is in equilibrium.

Figure 6 shows the results of applying the methodology to Maengbang Beach. Here, the offshore sediment loss rate (K), sediment reduction rate (α), and time duration (T_r) are 0.045 yr^{-1}, 0.4, and 22.2 yr, respectively. In addition, Fig. 7 shows the results of applying the methodology to Sokcho Beach. Here, K, α, and T_r are 0.035 yr^{-1}, 0.3, and 28.6 yr, respectively. On the basis of the applied results, K and T_r are estimated to be inversely proportional to each other. The correlation between the two physical coefficients may be reasonable given that both are related to sediment transport velocity.

As shown in Figs. 6 and 7, the conventional instantaneous reduction model predicts an abrupt response immediately following sediment supply reduction, whereas the proposed model reproduces the gradual adjustment observed in the field. Both study sites exhibit a clear gradual decrease in beach area after a certain point in time, compared with when the port structures were first built. The beach area of Maengbang Beach has been significantly reduced compared with that of Sokcho Beach. Unlike Sokcho Beach, Maengbang Beach has another estuary in the middle of the beach. Therefore, it is presumed that factors other than the construction of Samcheok Port may have affected the sediment budget of Maengbang Beach.

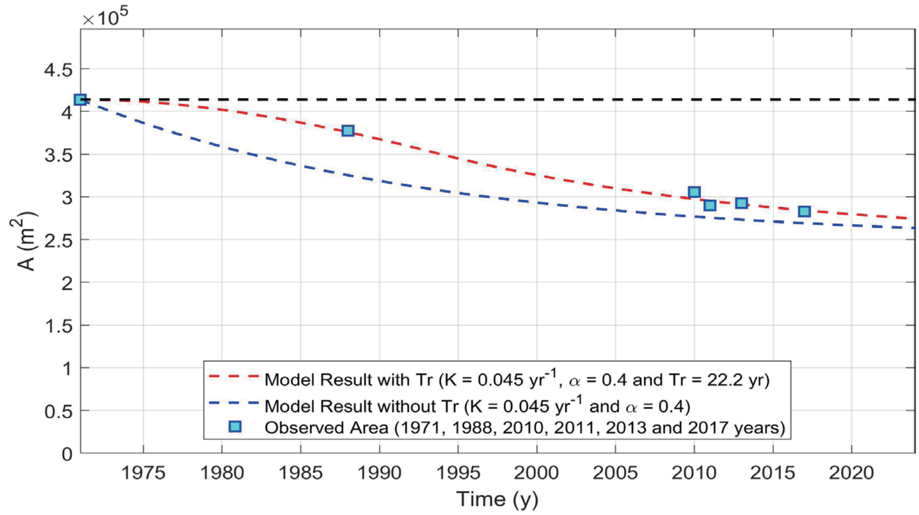

Fig. 6. (Color online) Predicted results of beach area responses at Maengbang Beach due to changes in sediment budget.

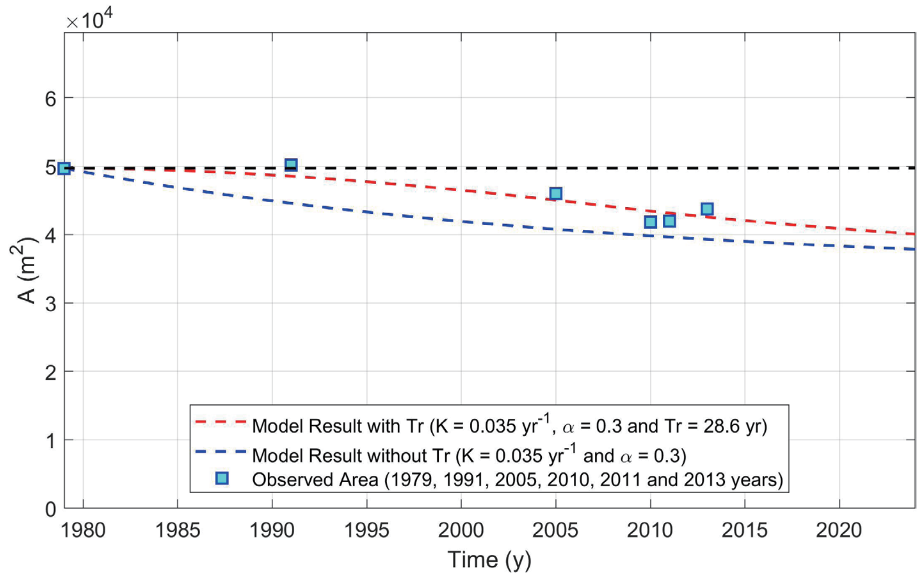

Fig. 7. (Color online) Predictected beach area responses at Sokcho Beach due to changes in sediment budget.

4. Discussion

4.1 Limitations

Sediment budgets have a significant positive/negative impact on coastal environments. Lee and Lee[14] derived a governing equation for shoreline changes caused by the sediment budget based on sand mass conservation. The derived formula includes physical coefficients for sediment supply and loss (i.e., offshore sediment loss and sediment reduction rates). However, Lee and Lee[14] assumed that these coefficients are constant because they cannot be observed precisely.

The beach gradually retreats when the sediment supply is affected by the construction of a dam or harbor structure. These structures do not immediately reduce the supply of sediment to the coast. In this paper, we propose a methodology to analyze beach area responses by gradually decreasing the sediment reduction rate. However, it is nearly impossible to quantitatively analyze how much/fast the sediment supply is changing.

The proposed methodology introduces the time duration, which is the time required for the sediment supply to reach equilibrium. The time duration is defined assuming a constant reduction rate. However, both the sediment reduction rate and time duration may vary under changing environmental conditions. These parameters can be affected by factors such as river discharge, wave climate, and the relative location of sediment sources and coastal structures. In addition, extreme weather events, such as typhoons and severe storms, may temporarily alter sediment transport processes.

These coefficients such as sediment reduction rate and time duration are difficult to observe and verify quantitatively. Therefore, assuming these coefficients as constant values may be reasonable for practical applications, although this simplification limits the ability of the model to account for their temporal variability. Future advances in artificial intelligence, numerical modeling, and monitoring techniques are expected to improve the estimation accuracy of these parameters.

4.2 Elapsed time to converge to equilibrium in beach areas

To preserve coastal environments, it is necessary to analyze the elapsed time for beach area changes due to a decrease in sediment supply. If sediment supply decreases instantaneously without time duration T_r, the elapsed time can be expressed as a function of the offshore sediment loss rate K as follows.[14]

$$\tau_m = -\frac{\ln\left(1 - m/100\right)}{K} \tag{12}$$

Here, τ_m represents the elapsed time taken to converge to m% of the equilibrium beach area. In other words, the beach area decreases by $m\alpha A_i/100$ after the elapsed time τ_m. However, τ_m becomes larger than the value calculated by Eq. (12) if the sediment supply gradually decreases with the time duration T_r. Figure 8 shows numerical calculations of the elapsed time to equilibrium convergence (25, 50, and 75%) according to offshore sediment loss rate K and time duration T_r. The elapsed time required for Maengbang Beach to converge to 25, 50, and 75% of its equilibrium is estimated to be 17.9, 27.5, and 42.9 years, respectively. On the other hand, for Sokcho Beach, the elapsed time is estimated to be 22.9, 35.3, and 55.1 years, respectively. It is expected that analyses of these elapsed times can be used in future coastal management plans, such as beach nourishment.

4.3 Beach nourishment for responding to changes in sediment budget

Beach nourishment is one of the most immediate responses to changes in beach areas due to reduced sediment supply. In this subsection, we analyze the response of the beach area to beach nourishment. Figure 9 shows the predicted beach responses obtained from beach nourishments after 15, 30, and 45 years from the initial conditions. Figure 9 shows that the faster the beach is nourished, the longer the beach area will last.

However, all cases eventually converge to an equilibrium beach area because beach nourishment does not solve the fundamental problem about the changes in sediment budget. Therefore, continuous beach nourishment is necessary to secure a certain beach area. Figure 10 shows the predicted beach area response from beach nourishment every 15 years. If continuous beach nourishment is not possible, countermeasures should be explored, such as installing a breakwater to prevent offshore sediment loss.

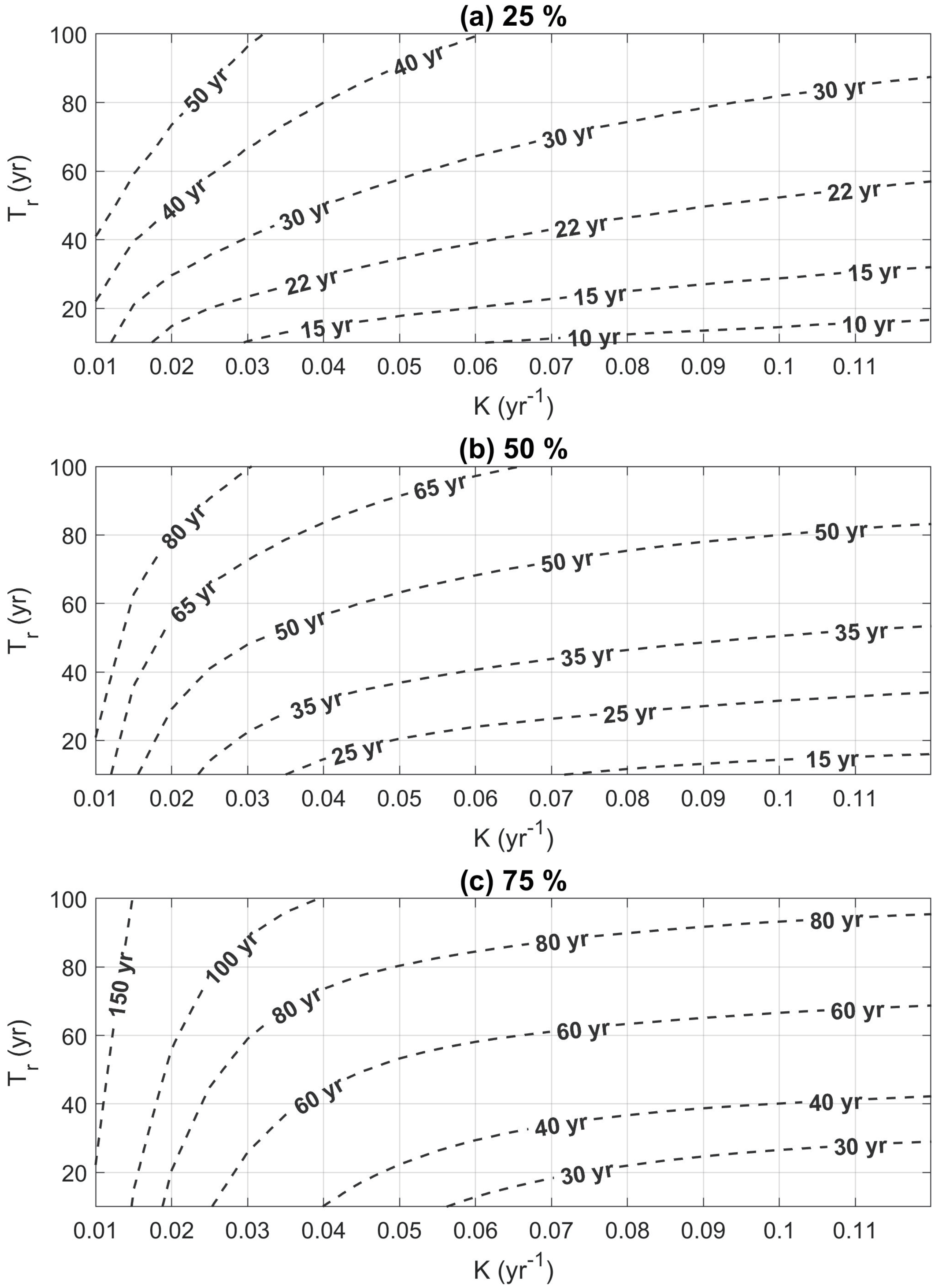

Fig. 8. (Color online) Elapsed time to converge to equilibrium according to offshore sediment loss rate and time duration: (a) 25, (b) 50, and (c) 75%.

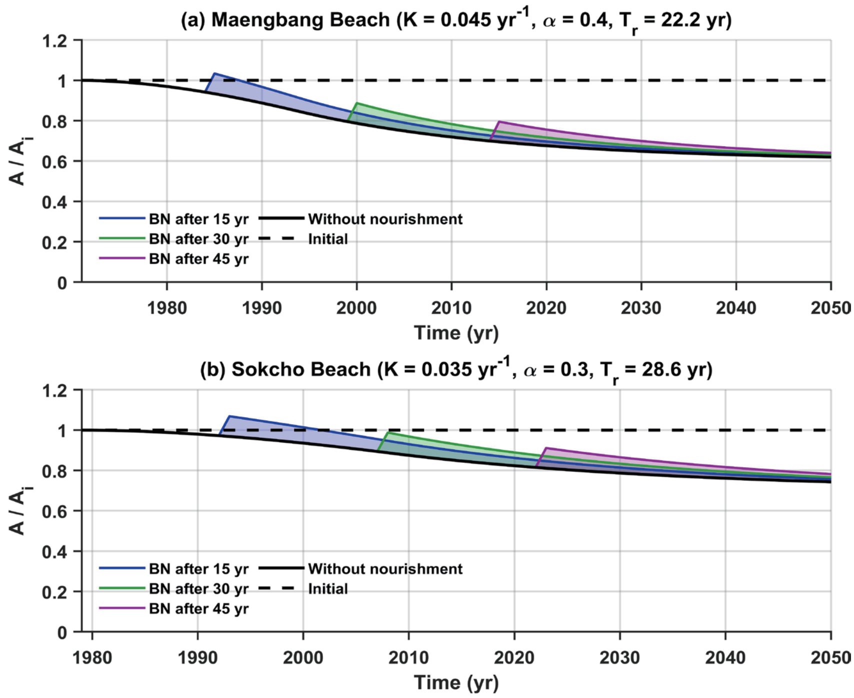

Fig. 9. (Color online) Predicted beach area responses obtained from beach nourishments after 15, 30, and 45 years from the initial state: (a) Maengbang Beach and (b) Sokcho Beach.

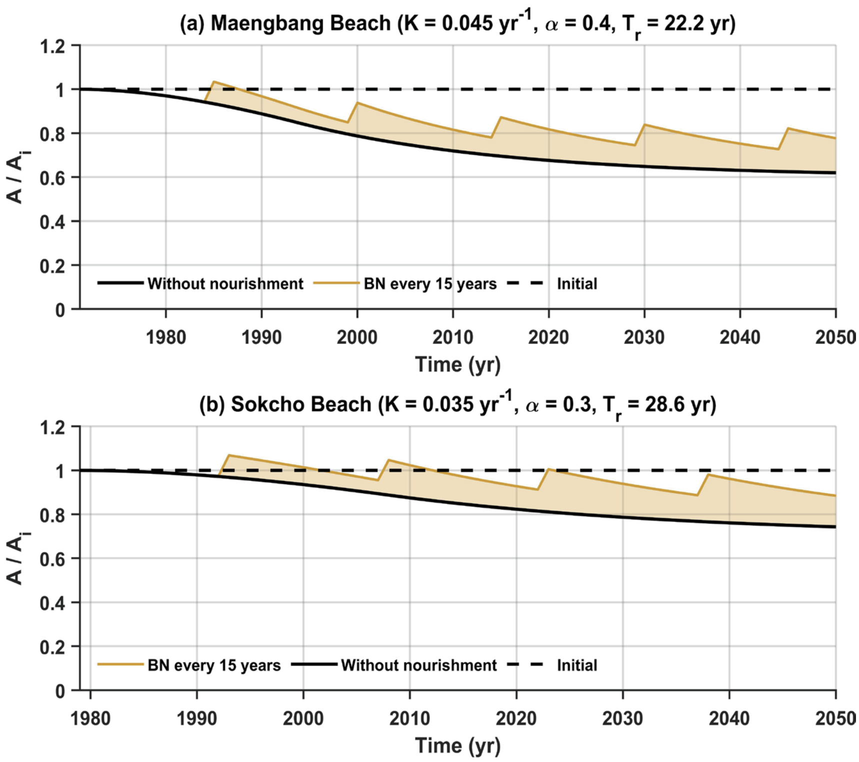

Fig. 10. (Color online) Predicted beach area responses obtained from beach nourishment every 15 years: (a) Maengbang Beach and (b) Sokcho Beach.

5. Conclusion

The beach area is governed by the sediment budget within a littoral cell. In particular, sediment supply may decrease owing to human interventions such as the construction of dams, ports, and other coastal structures, resulting in long-term beach erosion. On the basis of the long-term shoreline response model of Lee and Lee,(14) we analyzed beach responses under gradually decreasing sediment supply conditions. The proposed methodology is verified for applicability using beach area data extracted from aerial maps of Maengbang Beach and Sokcho Beach.

Unlike previous models, the proposed model introduces time duration T_r to account for the gradual reduction in sediment supply. By incorporating this parameter, the model is capable of reproducing the gradual shoreline adjustment induced by coastal structures, rather than the abrupt initial shoreline response predicted by conventional models. In addition, the results indicate that time duration T_r is inversely related to the offshore sediment loss rate K. The proposed methodology can also be applied to estimate shoreline response times and equilibrium convergence associated with sediment-budget changes. Although we focused on beach area variations in this study, the model may be further integrated with wave-driven shoreline change models to develop a hybrid approach for predicting long-term shoreline changes. The proposed methodology is expected to provide useful information for the planning and management of beach nourishment and other coastal protection projects.

References

1 J. D. Milliman and R. H. Meade: J. Geol. **91** (1983) 1. https://doi.org/10.1086/628741
2 J. D. Milliman and J. P. M. Syvitski: J. Geol. **100** (1992) 525. https://doi.org/10.1086/629606
3 D. E. Walling: Geomorphology **79** (2006) 192. https://doi.org/10.1016/j.geomorph.2006.06.019
4 D. E. Walling and D. Fang: Glob. Planet. Change **39** (2003) 111. https://doi.org/10.1016/S0921-8181(03)00020-1
5 G. M. Kondolf: Environ. Manage. **21** (1997) 533. https://doi.org/10.1007/s002679900048
6 World Commission on Dams: Dams and Development: A New Framework for Decision-Making (Earthscan, London, 2000) Chap. 1.
7 C. J. Vörösmarty, M. Meybeck, B. Fekete, K. Sharma, P. Green, and J. P. M. Syvitski: Glob. Planet. Change **39** (2003) 169. https://doi.org/10.1016/S0921-8181(03)00023-7
8 J. P. M. Syvitski, C. J. Vörösmarty, A. J. Kettner, and P. Green: Science **308** (2005) 376. https://doi.org/10.1126/science.1109454
9 D. L. Inman and J. D. Frautschy: Proc. Coastal Eng. Speciality Conf. (ASCE, 1966) 511–536.
10 J. D. Rosati: J. Coast. Res. **21** (2005) 307. https://doi.org/10.2112/02-475A.1
11 A. J. Bowen and D. L. Inman: Budget of Littoral Sands in the Vicinity of Point Arguello, California. USACE Technical Memorandum **19** (1966).
12 G. B. Griggs: Production, Transport, and Delivery of Coarse-Grained Sediment by California's Coastal Streams (1987).
13 K. Runyan and G. B. Griggs: J. Coast. Res. **19** (2003) 336.
14 S. Lee and J. L. Lee: J. Mar. Sci. Eng. **8** (2020) 551. https://doi.org/10.3390/JMSE8080551
15 C. Lim, T. K. Kim, S. Lee, Y. J. Yeon, and J. L. Lee: Nat. Hazards Earth Syst. Sci. **21** (2021) 3827. https://doi.org/10.5194/nhess-21-3827-2021
16 J. A. Warrick, A. W. Stevens, I. M. Miller, S. R. Harrison, A. C. Ritchie, and G. Gelfenbaum: Sci. Rep. **9** (2019) 50387. https://doi.org/10.1038/s41598-019-50387-7
17 M. M. Foley, J. A. Warrick, A. Ritchie, A. W. Stevens, P. B. Shafroth, J. J. Duda, M. M. Beirne, R. Paradis, G. Gelfenbaum, R. McCoy, and E. S. Cubley: Ecol. Monogr. **87** (2017) 552. https://doi.org/10.1002/ecm.1268
18 E. B. Thornton, A. Sallenger, J. C. Sesto, L. Egley, T. McGee, and R. Parsons: Mar. Geol. **229** (2006) 45. https://doi.org/10.1016/j.margeo.2006.02.005

19 M. Ford: Remote Sens. Environ. **135** (2013) 130. https://doi.org/10.1016/j.rse.2013.03.027
20 K. D. Splinter, M. D. Harley, and I. L. Turner: Remote Sens. **10** (2018) 1744. https://doi.org/10.3390/rs10111744
21 K. Vos, K. D. Splinter, M. D. Harley, J. A. Simmons, and I. L. Turner: CoastSat: Environ. Model. Softw. **122** (2019) 104528. https://doi.org/10.1016/j.envsoft.2019.104528
22 M. Yun, B. Y. Mo, J. Kim, and K. Do: J. Ocean Eng. Technol. **39** (2025) 404. https://doi.org/10.26748/KSOE.2025.029
23 E. R. Thieler, E. A. Himmelstoss, J. L. Zichichi, and A. Ergul: U.S. Geol. Surv. Open-File Rep. 2008-1278 (2009). https://doi.org/10.3133/ofr20081278
24 J. A. Simmons, K. D. Splinter, M. D. Harley, and I. L. Turner: Coast. Eng. **152** (2019) 103507. https://doi.org/10.1016/j.coastaleng.2019.103507
25 S. Vitousek, P. L. Barnard, P. W. Limber, L. H. Erikson, and B. Cole: J. Geophys. Res. Earth Surf. **122** (2017) 782. https://doi.org/10.1002/2016JF004065
26 H. Hanson: J. Coast. Res. **5** (1989) 1.
27 J. K. Miller and R. G. Dean: Coast. Eng. **51** (2004) 531. https://doi.org/10.1016/j.coastaleng.2004.05.006
28 C. Lim, T. K. Kim, and J. L. Lee: Geomorphology **415** (2022) 108409.

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