DOI: 10.22616/j.landarchart.2021.18.09

Geomorphing effect of sand fences in primary dunes of Gulf of Riga

Jānis Lapinskis
University of Latvia, Department of Geography and Earth sciences, Latvia

Abstract. Finding a the most appropriate solution for the problems caused by coastal eros ion is very important, as erosion prevention and habitat management measures must promote the restoration of the natural balance (order of things before anthropogenic disturbances) and restore the coastal status quo as much as possible [6; 2].

Dune fences are a very widespread erosion management tool on developed sandy coastal areas due to ease of installation, inexpensiveness, and generally positive public attitude [1]. Effectiveness and impact of fences have also been studied in many places around the world, however previous studies in Latvia have been very limited and episodic [16].

This article shows the observed dune and high beach area evolution of the coast in Riga, a somewhat developed coastal section on the top of the Gulf of Riga, Latvia, over a 4-year period from 2017 to 2020. Dune fences were installed along several short, but significantly disturbed sections of coast in 2018 and 2019. Implementation area is one of the busiest parts of the coast of Latvia dealing with the highest level of anthropogenic disturbance. Data has been derived from cross-shore transects (n=12) along the 17 km long coastal section between Daugava and Gauja river mouths.

The findings generally indicate a very intense initial wind driven sand accumulation in the target areas compared to the background situation. It also seems that such a method may in the longer term be responsible for reduction of the primary dune height and beach width.

Keywords: foredune morphology, dune fencing, anthropogenic influence, coastal processes, oastal landscape

Introduction

Gulf of Riga coastal zone is area of particular economic and social vulnerability to erosion due to its relatively high extent of development and high recreational load [7]. Coastal features in this area have been formed during the last transgression of the Littorina Sea in the convergence zone of long-shore sediment flows and have been significantly augmented by sediments from the three largest rivers of Latvia (Daugava, Gauja and Lielupe). A low and flat coastal landscape has developed, which has historically been dominated by sediment accumulation. Nowadays, high recreational pressure (mainly causing dune vegetation trampling), the reduction of river sediment influx (due to dams and alterations caused by drainage systems) and pressure from climate change related stressors, have all contributed to the development and acceleration of dune erosion. In most cases however, erosion does not pose a significant risk of coastal retreat but lowers the quality of primary dune habitats and makes the landscape less attractive. The first published scientific information concerning coastal processes in Gulf of Riga date from the 1930's and 1940's [22]. One of the most comprehensive looks at coastal origin, morphology, and recent coastal processes was the monograph by V. Ulsts [23].

The best-known feature of sandy coasts is a continually evolving ridge-like primary dune, which is formed over time through mutual feedbacks between aeolian sediment movement and vegetation growth [3; 15]. As dune-building pioneer plant species grow (e.g., *Ammophila arenaria, Salsola kali* and *Leymus arenarius*), they enhance sediment deposition by reducing wind generated shear stress below the critical threshold for sediment transport. On freshly accumulated sand, the dune grasses continue to grow actively creating a self-sufficient feedback loop that promotes further foredune growth [10; 17]. On Gulf of Riga coastal section near capital city Riga, natural dune-building processes are often somewhat modified by several management activities designed to improve beach conditions: removal of beach wrack by mechanized raking, installation of paths and footbridges, as well as installation of temporary buildings and recreational infrastructure. The impact of such measures on the stability and parameters of the coastal dune can be generally negative, creating additional focal points of wind deflation and reducing the potential for natural vegetation to spread [21; 18; 16].

Dune-building fences are commonly used to enhance sand accumulation, and thus to provide increased level of coastal protection, because they are inexpensive (natural materials usually are available nearby) and easily constructed by coastal management providers [12; 11]. Although dune building fences have been used in the coastal dunes of Latvia for several centuries [7], in the study area (prior to 2018 measures), they have not been widely used since the middle of the 20th century.

Since 2018 "dune planting" and "dune fencing" measures were implemented in several sections. Fences were emplaced seaward of the existing natural primary dune, or close to the basis of it to

Fig. 1. Left: A sand catcher fence made of reeds, shortly after installation in the summer of 2018 near Carnikava. Right: The sand catcher fence has greatly increased the accumulation of sand [photographed in the autumn of 2019]

initiate the formation of a new embryonic dune (Fig. 1). Although previous observations in similar circumstances have repeatedly shown an increase in the rate of immediate sand accumulation [16], there is still no certainty that this measure will make a lasting positive contribution to improving the stability of the dune belt.

The aim of the study is to assess and compare the changes in the volume of primary dunes in the target areas versus the background situation, based on coastal slope cross-section monitoring data. The working hypothesis was also put forward that the negative aspects of the fence installation results do not outweigh the positive aspects.

Materials and Methods

Study area. Data was collected from the area located on the top of the Gulf of Riga between the mouths of the Daugava and Gauja rivers, in the central part of the Nature Park "Piejūra". The total length of this coastal section is 18.0 km, but the dune fences included in the study are installed in the total length of approximately 2.6 km (Fig. 2). Coastline of the study area stretches in concave shape mostly in direction from SW to NE and thus is exposed to dominant southwesterly (SW) and westerly (W) winds, as well as rare, but impactful NW storms. The coastal features are relatively recent, formed in Holocene sediments. Study area is represented by some of the most notable foredune ridges in Gulf of Riga reaching more than 5 m in height. Wide beach made of fine-grained sand is present in all of the study area. It has a very important role in the coastal system. During storms, together with the primary dunes, beach acts to ensure the long-term stability of the system, accumulating sediments in calm conditions, and supplying it under extreme conditions to sediment-deficient zones of the coastal slope, simultaneously dissipating and dispersing incoming wave energy [19; 13; 15]. During the hurricane of 2005, study area was subjected to severe conditions due to particularly high surge level. Erosion rate reached maximum in proximity of the mouth of the Gauja River, where 20-40 m3/m of fine-grained sand was eroded by wave action [9; 8].

Most of the coastal section is almost completely undeveloped, but several sections closer to the capital city Riga and other smaller population centers have experienced moderate development. The whole area is characterized by a very high-quality landscape of low-lying coasts, which is considered to be an important tourist attraction. It can still be argued that in the vast majority of studied coastal area, development can only be attributed to the construction of small-scale recreational infrastructure, therefore, the natural landscape typical of the territory has been preserved. Inland areas in the oldest wooded dunes are also built up in only a small part of the coastal section. Fences are installed in coastal sections close to the developed areas (Fig. 2), except for the part of the coast where the anthropogenic load is the highest in the study area and where the formation of embryonic dunes has not been possible at all for a long time (Fig. 3).

Environmental conditions. According to data from levelling cross-sections established in the area in 1989, periods dominated by erosion and accumulation followed each other several times, however, in general there is a weak prevalence of accumulation in most areas. The predominance of erosion, as an exception to this regularity, occurs where the highest concentration of holidaymakers is observed (Fig. 3). Since 1989, the average accumulation rate of wind-blown sand in the study area has been 1.0-2.5 m^3/m per year. Episodes of catastrophic erosion of the coastal slope are very rare. Significant cases of erosion were observed only during the storms of 1993, 1999, 2001 and 2005, when 2-40 m^3/m of sand was washed away in each episode [4; 14]. Today, coastal sections with historical (since the mid-20th century) conditions of heavy wind induced erosion, as well as the main concentration areas of holidaymakers, are at higher risk of wave induced erosion, which in turn affects

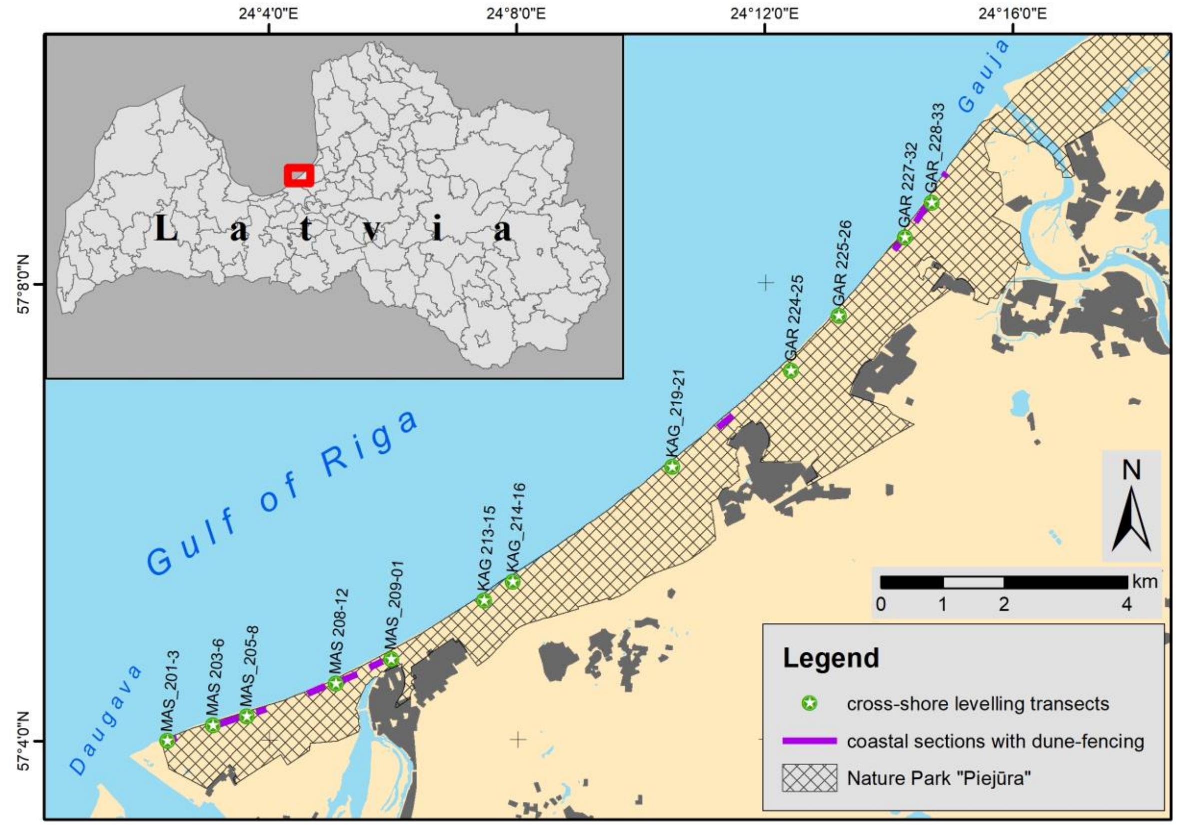

Fig. 2. Study area – coastal section between Daugava and Gauja river mouth`s within the Nature Park "Piejūra". Map shows location of cross-shore levelling transects (cross sections) used in this study, as well as location of coastal sections with installed dune-fences [created by author]

Fig. 3. Beach and dune area in the coastal area, where the highest concentration of holidaymakers is usually observed (opposite the center of Vecāķi). Natural dune formation is not possible in this place, as well as fences were not installed here, therefore this section was excluded from the assessment made in the study [photo from author private archive]

the condition of existing primary dune habitats, beach width and beach sand volume.

Data acquisition. Coastal geological processes monitoring network in study area consists of 12 cross-shore leveling stations that are perpendicular to the coastline and are covering subaerial part of the coastal slope (Fig. 4). Leveling profiles are located both in dune fences implementation area and in adjacent coastal sections with no fences (Fig. 2). The measurements have been conducted on the yearly basis in late summer and early autumn. Using local fixed benchmarks of known elevation during leveling data analysis, adjustments are made, to consider for deviation of sea level from the mean sea level datum. The data are available in the database of the Laboratory of coastal processes at the Faculty of Geography and Earth Sciences of the University of Latvia.

Data analysis. Analysis of changes (dynamics) in the volume of sediment, was undertaken separately for the beach and the active aeolian relief employing a least squares technique. For the purpose of this study, assumption was made, that the upper limit of the beach is the foot of the primary dune. Accordingly, the upper limit of primary dune was taken as the point where vertical changes resulting from aeolian processes do not exceed 0.02 m in one year.

The amount of beach and primary dune forming sediments were processed by using the formula [15]:

$$V = \sum_{i} \frac{(Q_i + Q_{i+1}) \cdot L_i}{2}$$ *, where (Fig. 5):*

- V – volume of sediments in a particular coastal area (m^3);
- i = 1, 2, ... n.;
- Q – area of coastal slope cross-section (m^2);
- L – distance between coastal slope cross-sections (m).

The calculated data from each section are arranged in 2-D graph, where X is the year of survey, and Y is the eroded or accreted sediment

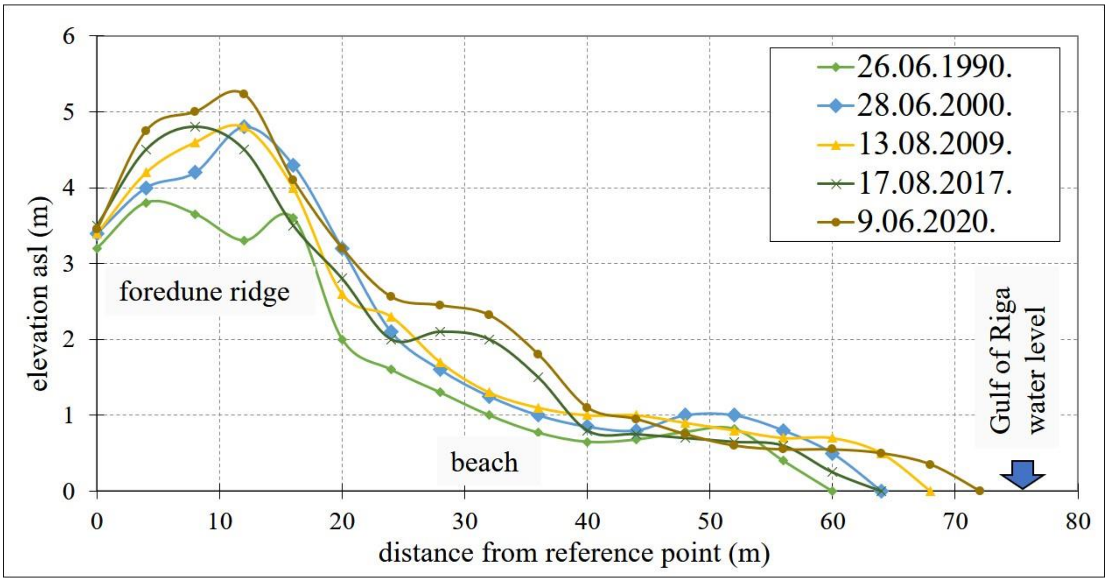

Fig. 4. An example (visualization of one of the cross-section profiles of a coastal slope) that illustrates in a simplified way the changes in surface relief between 1990 and 2020. Data on sediment volume changes obtained from 12 cross-shore levelling transects (cross-sections) were also used to assess the background situation [created by author]

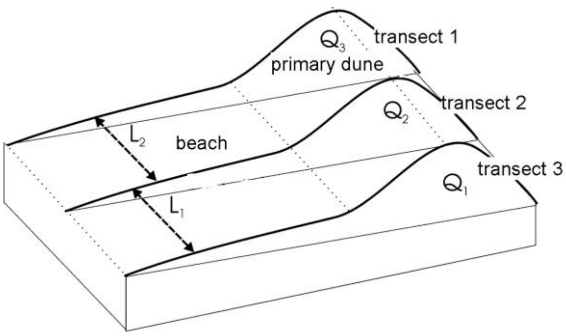

Fig. 5. Parameters used for primary dune deposits volume calculation [created by author]

volume relative to the first year of survey. This permits the determination of annual changes in sediment balance. Coastal changes in sections between measurement sites are interpolated.

After an analysis of the data obtained from the on-site cross-shore leveling stations, a map of the predominant coastal processes of study area was made, maximum coastal changes (sediment balance in primary dunes) were determined in m^3/m/year. To test for the statistical significance of differences in dune morphology comparing the pre-fencing and post-fencing change in primary dune volume Kolmogorov-Smirnov test was performed.

Results

The average change in primary dune elevation for the study period is +0.30 m, representing an overall growth in natural dune elevation since the beginning of the study period. Non-fenced and fenced areas both experienced increase in elevation, but non-fenced areas experienced an average elevation change of +0.38 m while fenced areas experienced an average change of +0.25 m.

Increase in dune widths was significant, with natural dunes in non-fenced and fenced areas broadening over time. The mean natural dune width in increased overall for 3.0 m. Non-fenced dunes widened for 2.1 m while fenced dunes experienced an average widening of 4.9 m. Natural dune building processes involved in the formation of a new embryonic dune are dependent mostly upon the ability of pioneering vegetation to survive seaward of the previous vegetation limit. In contrast, the formation of a dune in the presence of a sand fence requires only sediment input.

It was found that in most of the fenced dune areas the accumulation of sand brought by the wind took place in the amount of approximately 3.0-5.0 m^3/m/year, which significantly exceeded the background level of non-fenced dunes – 1.0-2.5 m^3/m/year. Particularly active accumulation took place in the immediate vicinity of the fences (mainly on the leeward side), as well as in a strip about 5-10 m wide near the fences. Observation was made, that after the implementation of fences the dune which had been growing vertically slowed its growth concurrent with vertical accretion of the non-fenced dune (Fig. 6).

Two summers after the implementation the very significant initial accumulation rate has decreased, but it should be noted that the implemented measures are "self-sufficient”, and their functionality will remain for several years even if the fences are not restored.

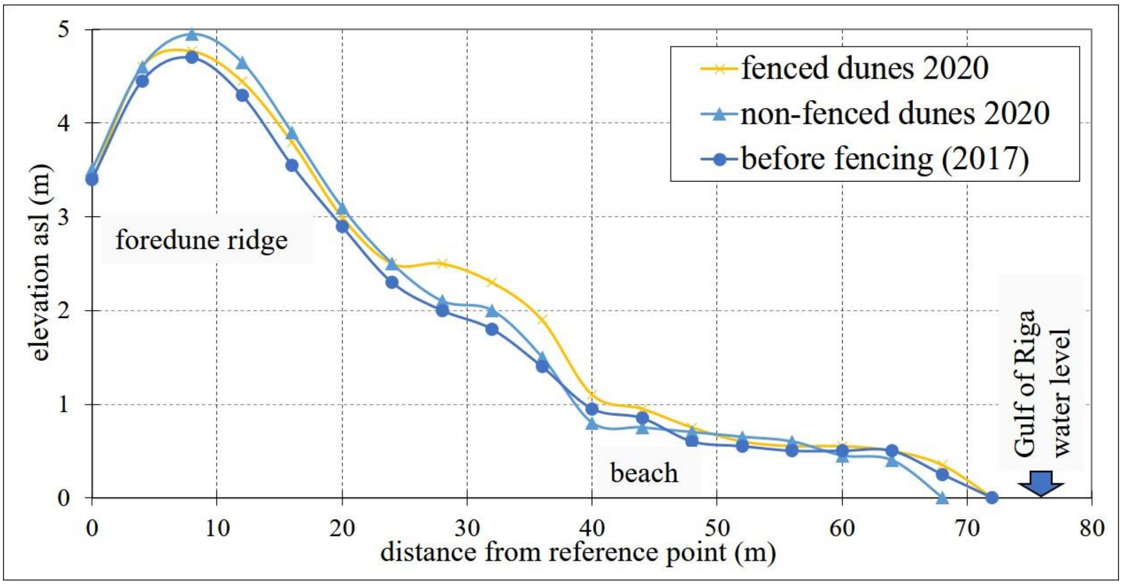

Fig. 6. The resulting agglomerate (composite): foredune and beach cross-section changes since 2017 (line with circles) in coastal sections where "dune fencing" anti-erosion measures were implemented (line with squares) versus the coastal sections where no fences were installed (line with triangles) [created by author]

While much greater spatial resolution of data may be required to analyze differences more clearly between fenced and non-fenced dunes, changes in natural dune elevation and width demonstrate that growth in volume of the fenced dunes came due to growth in width and not in height. Nevertheless, the very significant predominance of accumulation in these dunes suggests that the long-term intensive accumulation will also lead to an acceleration of the height increase of these fenced dunes. Probably at the cost of decreased growth of the natural non-fenced ones.

It is generally believed that a higher primary dune provides more protection against storm induced wave erosion [20], still, the lower but wider dune ridge (as in fenced areas) may be more resistant against wind erosion and against the trampling by the coastal visitors [5]. The second option is considered more desirable in this recreational coastal area.

Conclusions

- The data clearly shows the role of dune fences in initiating rapid sand accumulation. Observed high efficiency must, however, be viewed within a context of favorable conditions existing during study period – continuous sand supply from the nearshore zone combined with the absence of significant storm events.
- Analysis of the changes in morphology of primary dune crossections shows that there has been a statistically significant difference in shape and volume of fenced and non-fenced dunes. It should be noted that the difference in dune parameters is somewhat marginal and may be explained by the selection of locations for fence installation and / or locations of measurement cross-sections.
- In order to increase spatial resolution of surveys and deepen the understanding of relationships between recreational load, habitat maintenance measures and dune stability, the use of low-altitude unmanned airship photogrammetry system is necessary. The application of such a method would significantly increase the number of coastal cross-sections analyzed in the study.

Acknowledgements

This work was funded by the LIFE Nature and Biodiversity sub-program, LIFE15 NAT/LV/000900 "Coastal Habitat Conservation in Nature Park "Piejūra"". The author is declaring no competing interests.

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AUTHOR:
Jānis Lapinskis, Dr. geol., Assistant Professor at the Department of Geography and Earth Sciences, University of Latvia, 1 Jelgavas street, Riga, Latvia, LV-1004. E–mail: janisl@edu.lu.lv. Field of research: Coastal geological processes, development and protection of coastal areas, hydromorphology.

Kopsavilkums. Meklējot risinājumu krasta erozijas radītajām problēmām, ļoti svarīgi ir izvēlēties tādus piekrastes apsaimniekošanas pasākumus, kas veicina dabiskā līdzsvara atjaunošanos, nodrošinot īpaši aizsargājamo biotopu un ainavas kvalitātes saglabāšanu, kā arī rekreācijas iespējas. Vēja nesto smilšu uzkrāšanos veicinoši žogi ir ļoti plaši izplatīts apsaimniekošanas rīks teritorijās, kuras tiek intensīvi izmantotas un sastāv no smiltīm. Šādu žogu ierīkošana ir relatīvi vienkārša un lēta. Piekrastes apmeklētāju attieksme pret tiem kopumā ir pozitīva. Žogu efektivitāte un ietekme ir pētīta daudzviet pasaulē, tomēr iepriekšējie pētījumi Latvijā ir bijuši ļoti ierobežoti un epizodiski. Rakstā tiek apskatīta primāro kāpu un augstās pludmales attīstība Rīgā, Dabas Parka "Piejūra" teritorijā, Rīgas jūras līča virsotnē. Pētījums aptver četru gadu periodu no 2017. līdz 2020. gadam. Kāpu žogi 2018. un 2019. gadā tika uzstādīti vairākos īsos, bet samērā aktīvi apmeklētos piekrastes posmos. Pētījuma teritorija ietver vienu no rekreācijas ziņā noslogotākajām Latvijas piekrastes daļām. Dati iegūti, veicot tehnisko nivelēšanu krasta šķērsprofilos (n=12), kas izvietoti 17 km garā piekrastes posmā starp Daugavas un Gaujas grīvām. Rezultāti liecina par ļoti intensīvu smilšu uzkrāšanos pastiprināšanos tajos krasta posmos, kur uzstādīti žogi. Konstatēts arī, ka šāda piekrastes apsaimniekošanas pasākuma masveidīga izmantošana, ilgtermiņā var izraisīt primāro kāpu maksimālā augstuma un pludmales platuma samazināšanos.

Atslēgas vārdi: priekškāpu morfoloģija, "smilšu ķērāji", antropogēna ietekme, krasta procesi, piekrastes ainava.