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DUNE GROWTH DUE TO AEOLIAN SEDIMENT TRANSPORT AND THE ROLE OF THE BEACH AND INTERTIDAL ZONE.

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Abstract: The development of dunes is characterized by the alternating effects of erosion during storm events and growth during milder conditions. The quantification of dune growth due to aeolian processes has received some attention but uncertainty remains on where the dune sand, which accommodates growing dunes, originates from in the coastal profile. In this paper we hypothesize that sediment eroded from the upper beach is the main sediment supply for aeolian sediment transport governing dune growth. To test this hypothesis we have analyzed morphological profiles collected monthly at three different field sites (Noordwijk, Vlugtenburg and Narrabeen) during several years. No significant erosive trend due to aeolian processes was found at the upper beach at this temporal resolution. We conclude that it is highly unlikely that the main supply for aeolian sediment transport governing dune growth was located at the upper beach. The intertidal zone might be a relevant alternative source of sediment in the cross shore profile.

Introduction

In many places around the world, dunes provide safety from flooding for low lying hinterlands. Dune systems are however dynamic and dune morphology depends on varying conditions in time and space. During storms, dunes sometimes erode due to marine processes. During calmer periods dunes can grow due to aeolian processes. The quantification of dune erosion has received much attention in ongoing research and predictive tools for dune erosion are widely available, see for instance Roelvink et al (2009). The quantification of dune growth due to aeolian processes on the other hand has received less attention. To predict long-term (years) coastal evolution, knowledge and predictive tools to quantify dune growth are, however, essential.

Recent studies on beaches and dunes along the Dutch coastline have shown that annual accretion volumes in the dune area can be significant. At several locations, accretion rates of up to 40 m^3/m/yr have been found (de Vries et al., 2012). The source of the sediment which accumulates in the dunes is however unclear.

Some general modelling frameworks implicitly assume a potential source area for aeolian transport at the beach from the swash line to the dune line (see for instance Bauer et al., 2002). Differences in erodibility (or sediment supply) in cross shore direction can however exist due to variability in surface moisture content (Davidson-Arnott et al., 2008) but also due to lag deposits (Carter, 1976). Since surface moisture, which can limit sediment supply, is large at the water line, it can be expected that most erosion of the beach will occur from the (dry) upper beach. In this paper we therefore test the hypothesis that sand eroded from the upper beach is the main sediment supply for aeolian sediment transport governing dune growth.

Methodology & Field sites

To quantify dune growth and the sediment eroded from the beach, we analyze measured cross-shore beach profiles collected at three well documented but distinct coastal locations. The three locations include two sites in The Netherlands: Vlugtenburg (see for details de Schipper et al., 2012) and Noordwijk (see for details Quartel et al., 2008); as well as one site located in Australia, Narrabeen (see for details Harley et al., 2011).

Because the three data sets have been collected with different intentions, the measurement plans and collected data are somewhat different. Table 1 summarizes the survey parameters and relevant conditions at the different sites.

Vlugtenburg

Morphological data were collected at Vlugtenburg beach in The Netherlands at monthly intervals between 2008 and 2012. Vlugtenburg beach is located at the south-west of the Holland coast (see Figure 1). In 2008 this beach was nourished and since then, several aspects of this beach including foreshore and dune behavior were studied (see de Vries et al. 2011, de Schipper et al. 2012). Before the nourishment in 2008, typical dune growth rates at annual to decadal timescales amounted to 20-40 m^3/m/yr (de Vries 2013, Chapter 3).

Table 1. Overview of the survey parameters at the different field sites

Location	**Noordwijk (NL)**	**Vlugtenburg (NL)**	**Narrabeen (AUS)**
Field Characteristics			
Wave climate	sea (1.2m 5s)	sea (1.2m 5s)	swell (1.6m 10s)
Dominant wind direction	side/onshore	side/onshore	Onshore
Grain size (D_{50} [mm])	0.3	0.3	0.3-0.4
Classification (Short and Hesp, 1982)	dissipative	dissipative	intermediate
Tide Range [m]	1.8	2	2
Survey parameters			
Survey period	10-2001 till 10-2004	7-2009 till 12-2012	7-2005 till 4-2010
Frequency	monthly	monthly	monthly
Cross shore extend	+3 to -1 m NAP	+6 to -10 m NAP	+6 till 0 m
Alongshore distance	1.5 km	1.8 km	3.6 km
Nr. of transect locations	31	22	5

Vlugtenburg can be characterized as a dissipative beach in the framework presented by Short et al. (1982) with a mild beach slope and a potential abundance of sediment supply to the aeolian system. While it could be argued that the application of this framework to nourished beaches is invalid, we intend to still use the framework to compare the different sites.

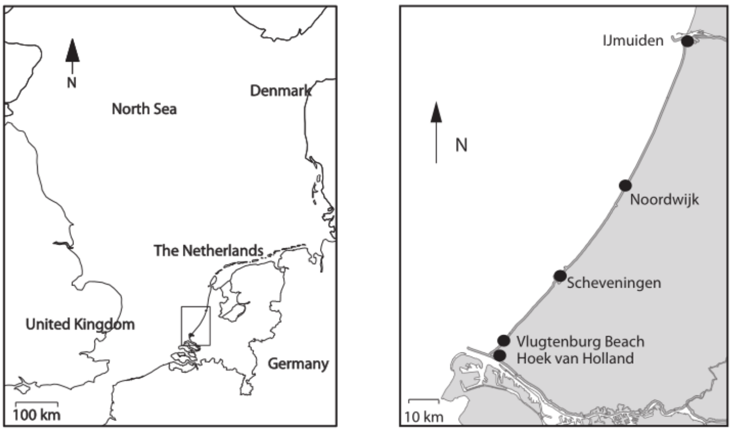

Figure 1 The location of the Vlugtenburg and Noordwijk sites in The Netherlands

Figure 2 shows the monthly measured morphological profiles at profile #1. The mean waterline (approx. 0 m NAP) moved landward with time. At the same time a dune grew with time landward from the 0 m cross shore location. The behavior of the upper beach at the location of profile #1 was representative for all 22 measured profiles at the Vlugtenburg location.

The measured growth of the dune is shown in the lower panel of Figure 2 and indicates a near linear growth of the dune volume. The volume of growth was in the order of 30 m^3/m/yr, similar to the derived dune growth volumes prior to the nourishment.

The landward movement of the coastline indicates retreat, which was likely the result of the adaptation of the nourished profile to a more natural cross-shore profile. While the coastline retreated, there are 4 periods of about one year during which the upper beach was relatively static with respect to the lower beach. These periods correspond with the 4 different shades of gray in the top panel of Figure 2.

The static upper beach indicates that there is no evidence for significant erosion from the upper beach by aeolian processes. Moreover, during the 4 periods where the upper beach is static, the width of the upper beach is different between periods. Assuming that the upper beach is an important source area for aeolian sediment transport, one might expect the difference in beach width to be reflected in the measured growth of dune volume (lower panel of Figure 2). However, no link between the dimensions/behavior of the upper beach and the growth of the dune was found at this location.

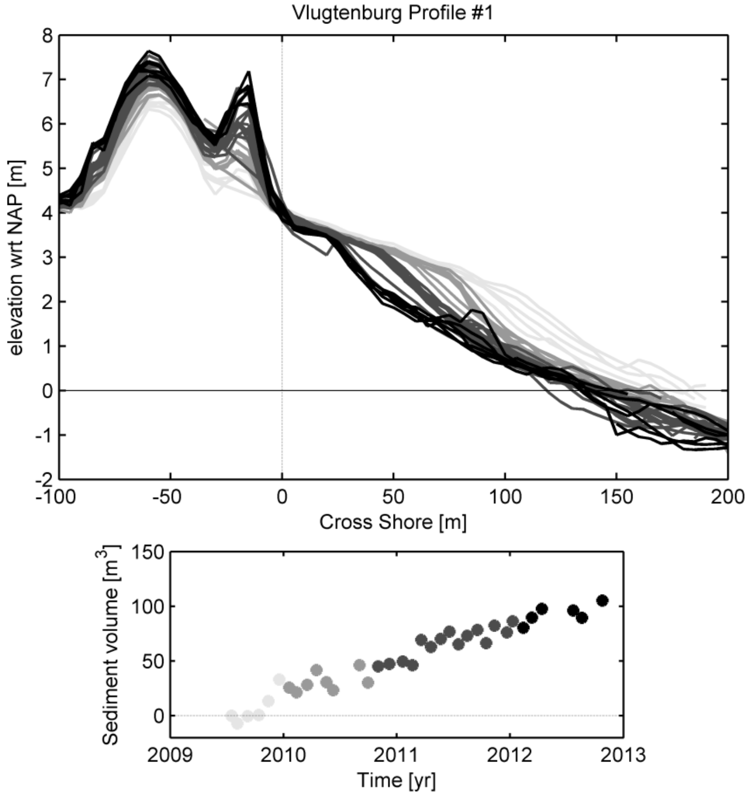

Figure 2. Profile #1 measured at the Vlugtenburg location where four years of data are shown. The black and gray lines represent monthly measurements. The lightest colors show the earliest measurements. The plotted colors are darker for the more recent measurements where each year a darker color is used to stress the signature of the latest storm season. The left side of the profile shows a growing dune where sediment was trapped by vegetation (landwards of the 0 m cross shore location). The right side shows the intertidal zone (around the 150 m cross shore location) which was relatively dynamic, showing mostly erosion but also some sedimentation. The upper beach (seaward adjacent to the 0 m cross shore location) profile shows periods of relative stability.

Noordwijk

Noordwijk is located along the Dutch coast some 35 km north of Vlugtenburg, see Figure 1. Quartel et al. (2008) collected morphological data at Noordwijk beach in the Netherlands between November 2001 and November 2004 with monthly intervals. Data were collected using conventional RTK GPS techniques and cover the beach between the low water line and the dunefoot at roughly -1 m and +3 m NAP respectively.

Quartel et al. (2008) collected and analyzed this dataset to investigate seasonal patterns in beach accretion and erosion in monthly observed morphologies and to relate these patterns to variations in the wave forcing conditions. Through defining cross shore zones and quantifying their horizontal extent and volumes, they found that while variability in beach width was typically governed by hydrodynamic forcing, variability in beach *volume* was not. Although it can be assumed that beach volume is some product between beach width and an average vertical level, the variability in vertical morphology could play a governing role. This variability in vertical morphology was not addressed any further but might be relevant to, and influenced by, aeolian processes.

Like Vlugtenburg, Noordwijk can be characterized as a dissipative beach in the framework presented by Short et al. (1982) with a mild beach slope and a potential abundance of sediment supply to the aeolian system (see Table 1 for the comparison with the other sites). The beach slope was steeper (1:20-1:25) than at Vlugtenburg and there was no shoreline retreat associated with a prior nourishment situation.

In addition to the Quartel dataset, the Dutch JARKUS dataset is available to provide annual measurements of morphology at the Noordwijk site. Figure 3 shows yearly measured morphological profiles at the Noordwijk site for the period of 1996-2008 (several years around the Quartel measurements). The seaward slope of the dune and the dune crest were accreting during the selected period. Assuming the dune volume to be the volume above +3 m NAP, the corresponding dune growth was derived by de Vries (2013, Chapter 3) to be in the order of 5-8 m^3/m/yr. The upper beach shows some vertical variability indicating periods of erosion and accretion at the upper beach at this temporal scale.

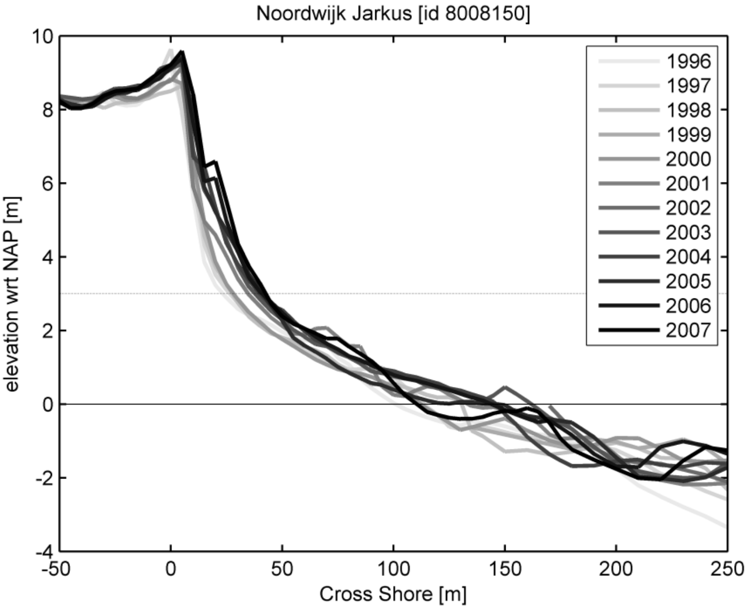

Figure 3 At the Noordwijk location the dune (roughly above +3m NAP) was growing steadily at an annual to decadal timescale. The beach surface (below +3m NAP) shows inter-annual variability.

Figure 4 shows the same morphological profile on the higher resolution of the monthly time scale. The monthly dataset does not contain the dune and therefore dune growth is not measured at this timescale. During the measured months between 2001 and 2004 (40 months available) the coastline location did not show significant trends of coastal retreat or advance. At the upper beach (at cross shore location between 50-100 m in Figure 4) the standard deviation with respect to profile’s mean was relatively small which indicates relatively small changes in vertical elevation at the upper beach. The upper beach was relatively static and while dune growth rates were significant, no significant erosion of the upper beach was measured.

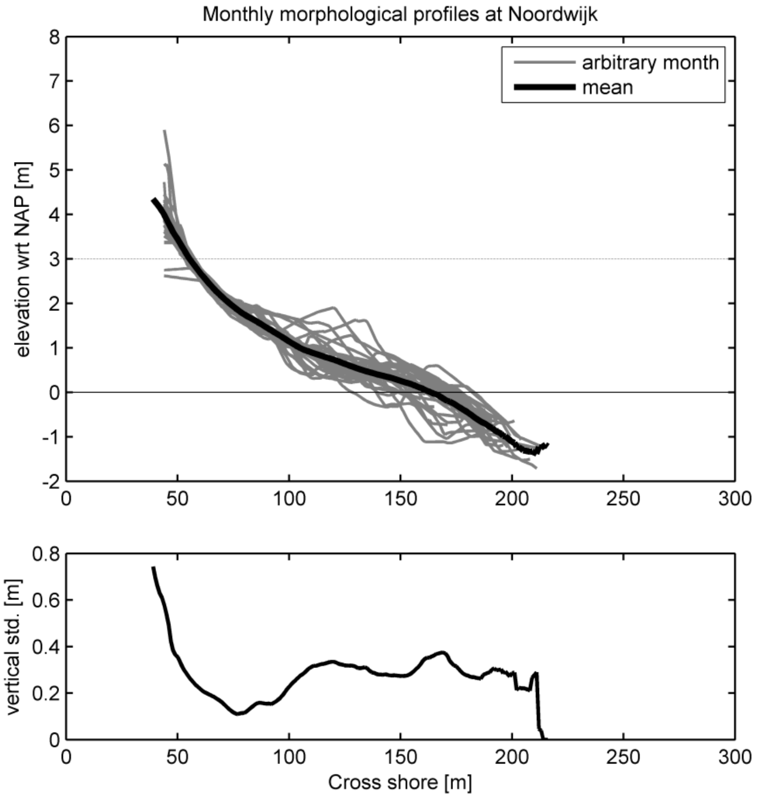

Figure 4. The top panel shows all measured profiles at the Noordwijk location in gray together with the temporal mean in black. (Note that for comparison of the profile shape the axis scaling is identical to the top panel of Figure 2.). The lower panel shows the vertical standard deviation along the measured profile.

Narrabeen

Narrabeen is located along the east coast of Australia. Narrabeen beach has been surveyed since 1976 (Short et al. 2004). Between July 2005 and April 2010, monthly high resolution profiles measurements using conventional RTK GPS technology were collected at 5 profiles located along the entire 3-4 km beach (Harley et al. 2011). The surveyed profiles are indicated in Figure 5 and cover the beach and intertidal zone. The dune area was relatively small (close to non-existent) where roads and buildings were located very close to the beach. As a result, detailed behavior of the dune was not documented in a comparable way with respect to the Dutch sites.

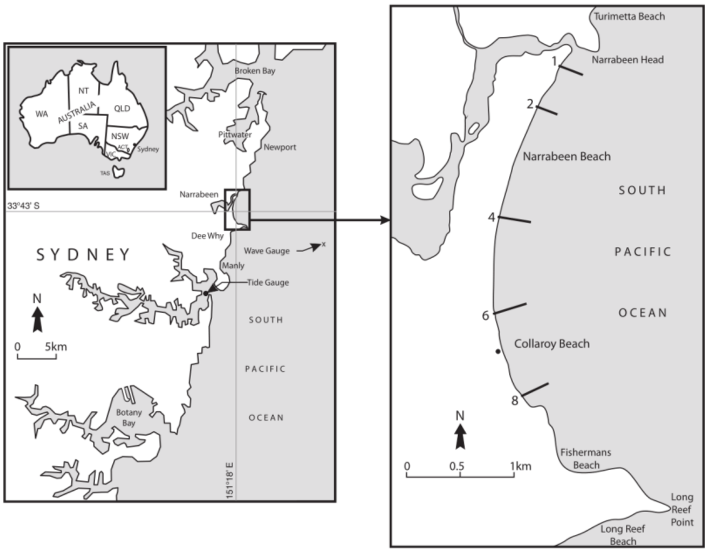

Figure 5. Overview of the Narrabeen field site. Adapted from Harley et al. (2011)

Narrabeen beach was discussed by Short et al. (1982) to be an intermediate beach which is characterized by an almost continuous exchange of sediment between the beach and surf zone. See also Table 1 for comparison with the other sites.

The top panel of Figure 6 shows all measured morphological profiles at the transect #4 location. The full coastal profile was changing significant over the measurement period.

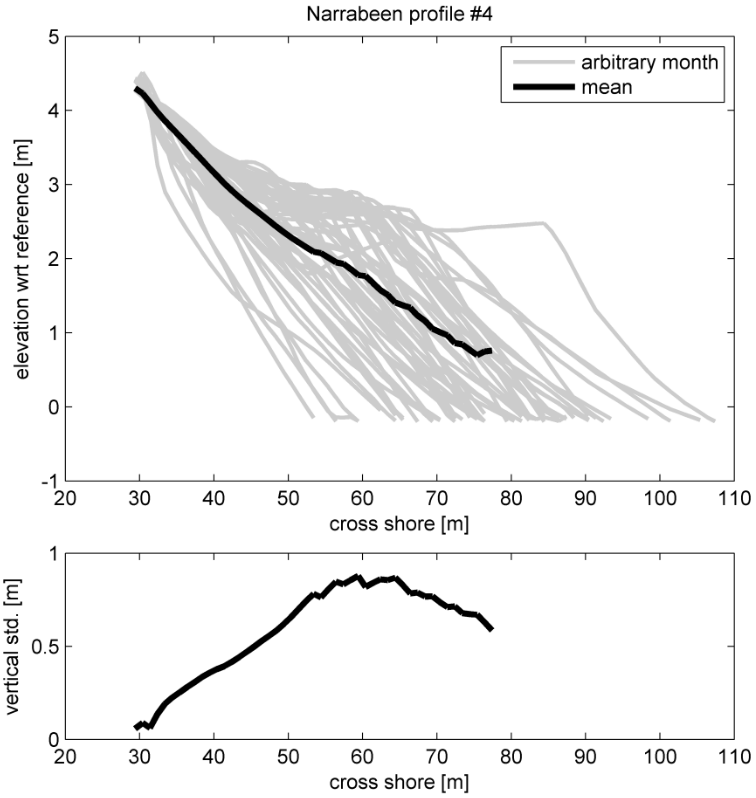

Figure 6. The top panel shows all surveys in gray including the average profile in black. The lower panel shows the vertical standard deviation of the measured surface elevation.

The lower panel of Figure 6 shows the vertical standard deviation with respect to the mean at every cross shore location. This standard deviation was smaller moving towards the upper beach. This indicates smaller vertical profile changes at the upper beach. The large standard deviation at the lower beach and the decrease in upper beach direction is likely caused by high energy waves near the shoreline and relatively small wave related influences on the upper beach.

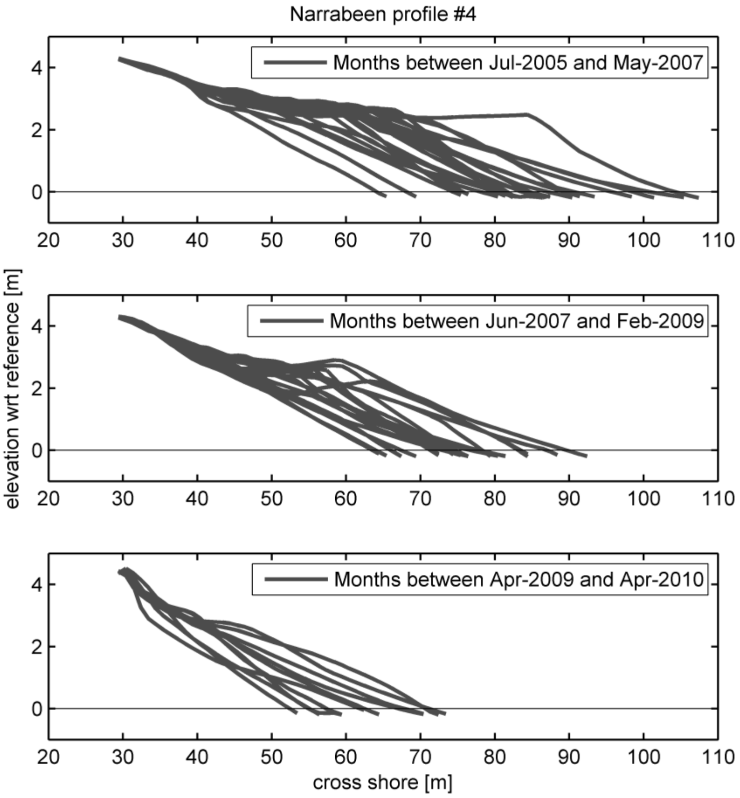

Figure 7. Subsets of all measured profiles at location #4 at Narrabeen. The upper beach above the 3m level was relatively static when compared with the lower beach.

Figure 7 shows subsets of the data where periods are chosen when the upper beach (adjacent to the 30 m cross shore location) was relatively static compared to the lower beach. The periods when the upper beach was static indicate no significant trends of erosion due to aeolian transport. Therefore no evidence of aeolian erosion is found at the upper beach.

Discussion

Sand dunes were located at the landward side of the three considered sites which indicates that aeolian sediment transport had occurred at some moment. In the case of Noordwijk and Vlugtenburg, detailed measurements of growing dunes are shown during the selected period. When dune growth was in the order of 0-40 m^3/m/yr it could be expected that significant erosion of the beach supplied this sediment volume to the aeolian system. However, the considered monthly measurements from the three sites (and profiles) have showed no evidence of significant erosion due to aeolian processes on the upper beach.

The upper beach was static in all measured cases and is therefore not likely to have been a significant source for aeolian sediment transport in the direction of the dunes. The limited aeolian erosion from the upper beach might be explained by the effects of armoring (or shell pavement) due to sediment sorting at the upper beach's sediment surface (Carter, 1976). Armoring occurs due to the process that relatively heavy deposits stay behind where easily erodible sediment is eroded by wind from the sediment surface. These heavy deposits at the sediment surface prevent the light deposits below the sediment surface to erode further.

The lower beach of the measured profiles showed more dynamic behavior. Armoring is not likely to occur at the lower beach since marine processes stirs the sediment top layer, removing the armoring layer. However, no erosive trend due to aeolian processes was visible. This erosive trend, if present, was likely overshadowed by the morphological changes due to marine processes at the lower beach. It is therefore possible, but not proven, that the sand that governs dune growth originated from the lower beach/intertidal beach.

Conclusions

We have hypothesized that sand eroded from the upper beach is the main sediment supply for aeolian sediment transport governing dune growth. After analyzing all cross shore profiles measured at the different locations (Vlugtenburg, Noordwijk and Narrabeen) we conclude that:

- Morphological changes, at the beach of the analyzed cross-shore profiles, due to marine processes was significantly larger than morphological changes due to aeolian processes.

- The upper beach remained relatively stable under aeolian forcing while limited morphological changes occur. Therefore, erosion or sedimentation due to aeolian transport was limited.

- Due to the limited morphological activity at the upper beach, the upper beach was unlikely to have functioned as a source area for aeolian transport processes.

- Sediment supply to the aeolian system may have originated from the lower beach/intertidal zone.

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