Rates and Patterns of Migration of Shoreface-Connected Sandy Ridges along the Southern North Sea Coast

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ABSTRACT


Geological studies of shoreface ridges along the southern North Sea coast are still at a rudimentary stage but are being intensified. This is largely because of the growing awareness of the potential impact of the dynamics of the ridges on nearshore projects. This preliminary report mainly focuses on the rates and patterns of migration of these ridges. It is observed that (1) headward (coastwise) ridge trough elongation occurs at a rate ranging from 80-500 m/y; (2) in addition to the latter pattern, ridges may migrate either diabatically, or exclusively shoreward or seaward at a maximum rate of 100-200 m/y, with the shoreward component being more significant; (3) no definite time-progressive variation in cross-shore migration pattern is evident; (4) compared with the deeper water ridges, those proximal to the coastline more frequently migrate seaward, which is suggestive of a response to the stronger impact of the recurring ebb storm-surge flow; and (5) on the whole, no significant coastwise differences in cross-shore rates of ridge translation were evident. The above-documented ridge migration rates represent the highest recorded anywhere in the world to date. Detailed flow measurements, made exclusively during fairweather conditions over the ridge morphology, lead to the conclusion that ridge migration is largely storm induced. Future studies in the region should aim at characterizing the storm flow-field.

ADDITIONAL INDEX WORDS: Shoreface-connected ridge, North Sea, migration rates, storm surge.

INTRODUCTION

DUANE et al. (1972) considered shoreface-connected ridges to be nontidal in origin, linear in shape, mostly sandy in texture, shoreline-oblique in orientation, and situated in a maximum water depth of about 10 m. Those occurring in waters up to 40 m deep are considered isolated. The ridges reported here from the North Sea typically occur in water depths of 8-25 m. However, because of the lack of consensus in the literature on the definition of the term shoreface, and in particular its depth range, the above ridges are herein considered as shoreface-connected.

The pioneering studies on shoreface-connected ridges have been made along the Atlantic seaboard of the U.S. The results of investigations conducted by SWIFT and co-workers along the U.S. Atlantic coast have subsequently been extended to other localities, e.g., the southern North Sea (SWIFT et al., 1978), the Canadian shelf (HOOGENDOORN and DALRYMPLE, 1986), the Brazilian shelf (FIGUIEREDO et al., 1982), and the Argentine shelf (PARKER et al., 1982).

With the exception of the data of MOODY (1964) presented by DUANE et al. (1972) and observations documented in SWIFT and FIELD (1981), both from the U.S. Atlantic coast, no other field-based report is known to this writer which dwells on the migration of the shoreface ridge morphology. The model study for the Scotian (Canada) shelf ridge migration reported by BOZAR-KARAKIEWICZ et al. (1990) is instructive in as much as their predicted range of migration rate (0.4-4.9 m/y) favourably compares with the natural observations of, e.g., SWIFT and FIELD (1981).

However, in comparison to the U.S. Atlantic coast, geological studies of shoreface-connected ridges along the southern North Sea counterpart are still at a rudimentary stage, and information on their dynamic characteristics is lacking. Therefore, the dual objectives of this preliminary report are (1) to present data on the rates and pattern
of ridge migration along the North Sea coast which, as rightly noted by Swift et al. (1978), is indispensable in environmental management projects, given the potential impact of ridge migration on the stability of the seabed, and (2) to compare the North Sea shoreface-ridge migration characteristics with those reported from other localities in the literature, in an effort to gain some insight on the still open questions regarding the molding and maintenance of the ridges in the different coastal environments.

STUDY AREA

The main study area is the shoreface of Spiekeroog barrier island (Figure 1), with additional data from the adjacent island of Wangerooge. The bathymetry of Spiekeroog island shoreface shows that the ridge morphology is most pronounced in water depths of 8–18 m (Figure 2). The crestlines of the ridges, four of which are distinguishable, are stippled in the latter figure. The ridges are >10 km in length, 1–2 km wide, 3–5 m high, <1° steep, and tend to converge toward the proximal (ESE) end of the island shoreline, with a westward-opening acute-angle of 14–17°.

The fluid motion in the study environment is very intense, and incorporates those of tides, waves and storm currents. Tides are semi-diurnal and have a mean range of 2.6 m. The fairweather peak near-bottom (1 m above the seabed) spring and neap tidal current velocities across at shoreface locations shown in Figure 2 typically range between 30–60 cm/s (Figure 3).
rents are dominant, exhibiting 30–50% higher peak velocities than ebb currents.

The fact that the ebb-current flow direction (Az 278–290°) exactly coincides with the shore-oblique orientation of the ridges, in contrast to the more variable (ENE to ESE) flood counterpart, has led to the speculation that the ebb component of the tidal current probably plays a more significant role in the maintenance of the ridges (Antia, 1993a). Even in the absence of wave action, the above velocities exceed the threshold velocities of a broad range of sand size fractions of which the ridges are constituted (Antia, 1993a). In effect, transport of bottom sediments is likely to occur daily in the study area in the course of a tidal cycle.

Waves in the study region are dominantly westerly to northwesterly and exhibit a period of 4–8 s and significant wave height in the range of 1.5–2.3 m (Dette, 1977; Klein and Mittelstaedt, 1992). Wave orbital currents computed by Antia (1993a), based on nearshore records of Dette (1977), suggest that the threshold motion of sediments in the finer than medium-sand (> 2 phi) range at depths shallower than 20 m is exceeded daily at least 80% of the time.

Finally, based on a long-term meteorological and tidal gauge record for the study region compiled annually by the Coastal Engineering Research Station, Norderney, it was ascertained that the study area is subjected to between 10–30 days of storm condition annually, during which sediment transport competency of all flow types is accentuated.

DATA BASE AND METHODS

High resolution sounding charts (1:10,000) of the German Hydrography Institute, Hamburg (currently Federal Department of Navigation and Hydrography) covering the time interval 1950 to 1987 constitute the main data base. The density of depth soundings for the above charts was in the range of 28 to 33 per km², and the shore-normal sounding lines were spaced at distances as narrow as 20 m apart, but commonly in the 20 to 100 m range. All sounding depths are related to NN (normal null) or the German topographic chart datum, after correction for tidal elevation. Any inaccuracies in soundings are likely to be systematic.

These charts were complemented with their counterparts from the Water and Navigation De-
RESULTS AND DISCUSSION

Results and the discussion of the results relate to the temporal and spatial patterns of shoreface-connected ridge migration, the prospects of coastline-parallel bars as a precursor of the ridges, and a comparison of ridge migration rates in the study area and the Atlantic coast of North America.

Figure 6. Temporal variations in absolute magnitudes of shoreface-connected ridge trough axis translation.

Temporal Pattern of Ridge Migration

One of the first important observations from Figure 5 is that in spite of the potential high frequency of mobility of bottom sediments on the shoreface, the ridges have not only persisted in time but have also retained their general shoreline-oblique orientation. These observations suggest that the ridges must be in a state of morphodynamic equilibrium with the prevailing (non-storm) flow field.

It is also evident that translation along the length of any given pair of ridge trough axis can either be exclusively landward or seaward, or diabathic in character. The above cross-shore dynamic patterns, also depicted in Figure 6, is speculated to be a response to a net flow momentum of coastal surges and the ebb counterparts associated with storm conditions. This is more so because, as earlier stated, the fairweather mean flow pattern is to a very large extent oriented along the ridge trend, rather than shore-normal to it.

The pooled absolute translational values of the trough axes shown in Figure 6 did not reveal a definite time-progressive variation in any cross-shore direction. This result might reflect the rapidity of reversals in the direction of ridge migration. Quite instructive, however, is the fact that over an interval of just one year, the extent of seaward and shoreward translation may amount to about 100 m and 200 m, respectively.

On the average, shoreward translation seems to be slightly larger in magnitude. A possible implication of Figure 6 is that the shore-normal com-
ponent of flow of some storm conditions is more energetic during the flooding phase, whereas others display a higher energy during the ebbing phase. This assertion, admittedly, needs to be verified in future studies involving direct and multiple measurements of storm currents.

It is, for instance, not clear at this stage from the local tide gauge records what level of storm surge elevation, if considered a surrogate to current intensity, might cause a marked asymmetry between both cross-shore components of a storm flow to which the diabathic migration of the ridge is tentatively related. It is presumed, however, that the storm direction will be more valuable in predicting the latter. For example in Figure 7, the shoreward translation of the ridge morphology, at least at the eastern sector, seemed to be particularly pronounced (maximum 200 m/y) during the 1967 storm condition, although the storm surge height was less than 3 m. The latter rate compares well with that of the 1982/83 storm counterpart which had a higher surge height but was associated with a more variable storm-wind direction.

Spatial Pattern of Ridge Migration

The results given in Figure 8a suggest that ridge dynamic patterns vary spatially. With the excep-
Coast-Parallel Bars: A Precursor of Shoreface-Connected Ridges?

According to McBride and Moslow (1991), one of the "vexing" problems associated with the origin of shoreface-connected ridges is to account for their shore-oblique orientation. Swift et al. (1978), among others, rightly observed that in both hemispheres, the ridges generally opened to the direction of the major flow or sediment transport on the shelf. However, recent studies such as Boczar-Karakiewicz et al. (1990, 1991) suggest that ridge orientation need not relate to the direction of net or major sediment transport. Shoreface ridge sediment studies along the southern North Sea coast corroborate the latter viewpoint (Antia, 1993b).

It is however interesting to evaluate an assertion that the shoreface-connected ridges in the present study area might have evolved through a re-orientation of coast-parallel bars. For the present purpose, the exact generating mechanism of the bars is immaterial. However, in the 8–18 m water depth of interest, one possible process of bar formation relates to the breaking storm-waves. In the study area, such waves have about 0.1% frequency of occurrence (for all onshore shoaling directions).

Essentially, any re-alignment process of a coastline-parallel bar to form a shore-oblique ridge must be a consequence of disparity in rate of cross-shore translation along the length of the bar. This could be either as a result of a higher onshore ridge translation at the eastern or proximal sector of the bar and/or a higher rate of seaward translation at the western or distal counterpart. In both cases, a difference in magnitude of translation (at least 1.5 km) at either end of the morphology, consistent with the aforementioned cross-shore directions, would be required to re-align a coast-parallel bar to the ridge trend.

Figure 9 shows, however, that the above supposition is unlikely, largely because: (1) the direction of translation at the ridge ends will not result in a re-alignment of a coast-parallel bar to
Comparisons of Shoreface Ridge Migration Rates and Patterns

Apart from the foregone cross-shore migration patterns discussed, the studied ridges also reveal, like their U.S. Atlantic shelf counterpart (Swift and Field, 1981), headward trough erosion resulting in their coastwise elongation. Data from the islands of Spiekeroog and Wangerooge given in Figure 10 at different time intervals clearly illustrate this pattern. In addition, however, shoreface retreat is well marked on Spiekeroog. The coastwise elongation of the ridges through headward trough erosion in this case seems to be compensated for by erosion at their tips.

By comparison with the U. S. Atlantic shelf ridges, the North Sea counterparts reveal a much higher migration rate. For instance, Swift and Field (1981) reported no change on Assateague Island ridges over a 9-year period. The data of Moody (1964), on the other hand, showed a maximum migration rate of 6 m/y over a 42-year period, and a migration rate of 5–45 m/y between 1961 and 1963. The latter migration rate, presumably, was a consequence of the 1962 storm condition—the most severe in historical times.

The ridges offshore of Spiekeroog Island, on the other hand, display an average landward migration of 80 m/y over a time span (1965–1973) comparable to that of Swift and Field (1981) for the Maryland inner shelf. However, as earlier mentioned and also depicted in Figure 6, cross-shore migration rates of 100–200 m/y are quite common even after less severe storm conditions as that of 1962.
Of particular interest in Figure 10 is the intense headward trough erosion of Wangerooge ridge troughs. The latter occurs at a mean rate of 500 m/y over the time interval 1990–1992, whereas the maximum rate at Spiekeroog is 80 m/y.

Swift and Field (1981) further reported a tendency for the landward and seaward flanks of the ridge to erode and accrete, respectively, over time. A similar tendency is revealed in Figure 11a from a 15-year (1960–1975) sediment budget analysis of a shoreface ridge offshore of Spiekeroog Island. However, the landward flank in this case was not well-defined. Nevertheless, an offshore diminishing magnitude of volumetric erosion per unit area is evident from the trough (1.1) to 50% of the trough value on the seaward flank.

It is, however, difficult to conclude that the above pattern actually reflects a cross-shore sediment transport of winnowed trough sediments and subsequent deposition on the seaward flank. An alternate view is that the scale of erosion within each of the ridge provinces is dictated by the intensity of the coastwise currents. In this respect, the highest erosion within the trough may be a response to the channelization of the storm currents which accentuates the rate of seafloor scouring, compared to the other ridge provinces.

Longitudinal variation in sediment erosion within a ridge trough (Figure 11b) tends to support the above view-point in the sense that the rate of erosion actually diminishes from the trough head towards the mouth. This trend is probably a response to flow expansion and consequent weakening (diminished scouring competency) of currents with a broadening of the trough dimension at the mouth.

CONCLUSIONS

This report provides the first documented information on the rates and pattern of migration of shoreface-connected ridges along the southern North Sea coast. The temporally-persistent form and orientation of the ridges, in spite of the potentially high frequency (80%) of bottom sediment mobility on a daily basis, suggest that they are in morphodynamic equilibrium with the non-storm flow field. Conditions contrary to the latter would have culminated in a degradation of the ridge morphology.

The studied ridges display cross-shore and coastwise migration patterns which are considered to be storm induced. Their annual migration rates are a factor of 5 to 40 times higher than those reported from the North American Atlantic seaboard.

Evidence presented does not support the proposition that coast-parallel bars, irrespective of their generating mechanism, are a precursor of shoreface-connected ridges. Modelling the morphodynamics and molding of the ridges will certainly entail detailed information on the storm flow pattern, and it is envisaged that future work will place emphasis on the acquisition of such flow data. One practical importance of the present result is that long-term coastal facility or pipeline projects in the study locality should have their foundations at depths not shallower than 2 m beneath the ridge trough floor, especially at its head section, in order to minimize the risk of being exposed and damaged.

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