Multi-Temporal Aerospace Imagery in Coastal Dynamics Studies at Kara Sea

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Development of natural gas production at Russian offshore and coastline requires construction of new sea ports, access channels, manmade islands, drilling rigs, terminals, overground and underwater pipelines. The knowledge of natural processes and, in particular, the coastal dynamics helps to ensure the geotechnical and geo-ecological safety of the construction and operation of the facilities. This is especially important in the Arctic conditions, where the natural environment defines the methods of offshore and coastal operations. Natural mortho-lithodynamic processes [2; 3], such as coastal erosion (abrasion), thermal abrasion, thermal washout, deflation, water and thermal erosion and ice gouging can lead to significant material loss, reduce the cost efficiency of production and transportation.

The distinct feature of the Kara sea, as in fact any other arctic sea, is that the coastal area develops within the contact of atmosphere and hydrosphere with the dispersed permafrost — cryolithic zone. Mortho-lithodynamic properties of this zone are among the main factors determining the location of the submerged pipeline landfall, as well as pipeline burial depth and type of pipeline construction. Regardless of the extended ice season (9 months a year), the remaining warm season is marked by extensive dynamic activity [4]. Thus, within the study region of Bayadartskaya Bay of Kara Sea (Figure 1), over half of the coastline is affected by the abrasion; the degradation rates at certain sections of the coastline in the natural conditions reach 1-3 m/year (Figure 2). The potential anthropogenic impact involved in development of frontier territories, as well as the projected global climate warming in 21 century can cause the coast wear rates increase significantly. Routing the pipeline through intensively degrading seacoast increases the risk of coast destruction due to potential denudation, sagging and mechanical deformation. Burial of engineering facilities, landfilling and other safeguards are often inefficient, because the abrasive coast areas not only typically have sea cliffs recessing into the inland, but also have directed

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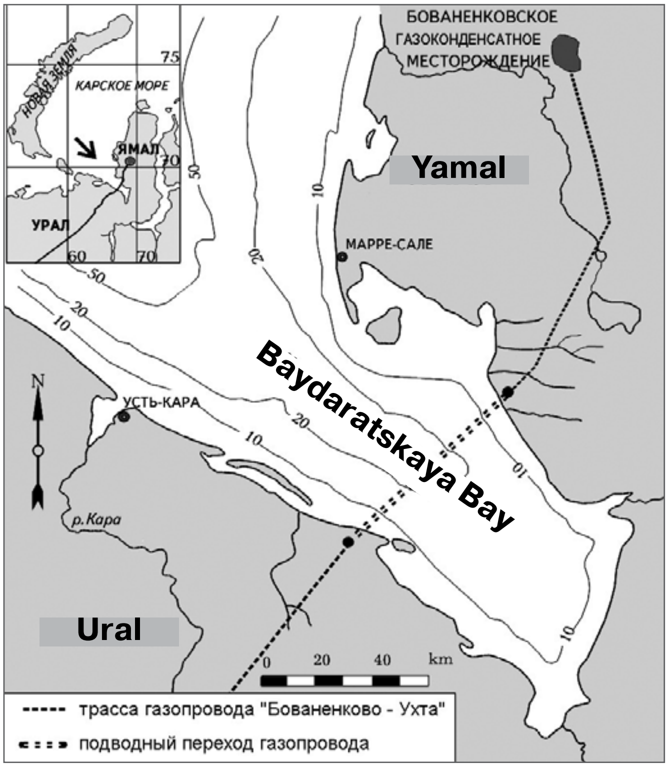

Figure 1. Submerged crossing of gas mainline Bovanenkovo-Ukhta over Baydaratskaya Bay, Kara Sea

abrasion of the beach and offshore slope. Besides, bared sections of the pipeline could be exposed to the dynamic impact of the sea ice. Displacement of the fast ice onshore, creating ice piling, could destroy the onshore facilities and pipelines.

Therefore, geotechnical safety of the pipeline and geo-ecological safety of the territories around the landfall could be ensured, first off all, by the proper selection of dynamically stable coast, and secondly, by the selection of the appropriate estimated depth of the pipeline burial (based on the projected coastal dynamics during construction and operation of the pipeline).

In order to determine the rate of shoreline recession and coastline profile deformation within the sites the designers pre-selected in late 90s for the pipeline to cross Baydaratskaya Bay on Yamal and Ural coasts, approximately 50 benchmarks have been set up to create a monitoring grid to determine the dynamics. Elevations of the benchmarks were referenced to Baltic height system 1977 [1]. Observations of coastline dynamics based on the permanent benchmarks are integrated with the direct measurements and trigonometric levelling method. Echo-sounding survey is completed at the extensions of the monitoring grid to determine the deformation of sea-floor relief at the offshore slope. However, the direct instrumental monitoring in remote Arctic regions is extremely expensive due to inaccessibility of the survey site; and it still does not show the full picture of the long-term tendencies in terms of coastline development within the confines of these sites. The latter is critical for the purpose of projecting the coastal changes and deformation of offshore slope profile within the fairly long operational life-time of the main pipeline and other facilities (between 30 to 50 years). This case requires a thorough analysis of the overlaid multitemporal aerospace imagery.

One of the most reliable methods to determine the long term coastal dynamics is the study of the multitemporal satellite imagery in high and super-high resolution. The most interesting for our purpose and available archive imagery is Corona (USA) imagery acquired in the period of 1961-1970. The benefits of these images are the availability, coverage of practically the whole Earth surface and high resolution (4-7 m). Corona images help to assess both the general coastline dynamics since 1962 to the present time, as well as specifics of such dynamics back in 1960s. There are some issues with the aerial imagery which is generally available in hard copies in various organizations and is often not commercially available. Other imagery includes super-high resolution IKONOS and QuickBird satellite imagery, which also features a significant part of the surveyed sites.

The advancing technology made high quality remote sensing (ERS) images commercially and instantly available over Internet. The most popular are medium resolution images from Landsat 3-7 satellites with the maximum image

Fig. 2. Intensive coast degradation due to thermal abrasion and thermal denudation, Ural coast, 15 km west of the gas mainline route

resolution (panchromatic band) up to 15 m. The benefit of Landsat imagery is mainly in the wide variety of free images for an extended time period (for example, Landsat 7 imagery are available from 1999 to present and, despite the issues with the image quality in the last few years, they are quite adequate for preliminary assessment of lithodynamic situation in the region).

Among the most important information resources reflecting the variations in Russian Arctic sea coastline are national topographic maps and nautical charts. As a rule, these resources serve as the mapping base for the studies. These resources are processed, which includes referencing them to WGS-84 coordinates and assignment of metadata; and, in many cases, in order to make the further analysis easier, the resulting maps are then vectored in GIS ArcGIS 9.x.

Preparation of the acquired aerospace imagery is a critical stage in studying the coastline dynamics. Special attention should be paid to referencing of the aerospace imagery. IKONOS and QuickBird images are supplied in package with the reference files, created based on the satellite orbit parameters. This type of referencing is fairly accurate for the coastal areas, as they produce an insignificant onsite elevation error against the geoidal surface. We estimated the accuracy of the initial referencing based on overlaying the images on the detailed topographic maps and found that the error is not more than 5 m. This error value is quite sufficient for the studies of coastal area dynamics.

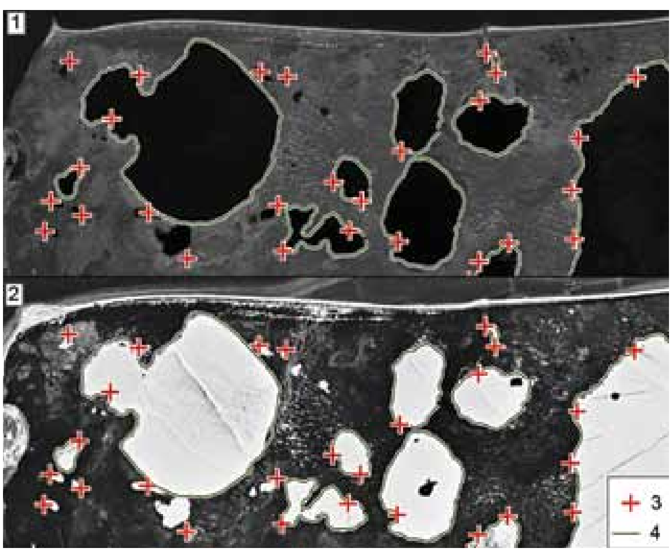

Fig. 3. Referencing method for multitemporal satellite imagery, which includes gradual "tuning" (based on a set of reference points at the referenced image #2) against the outlines of the hydrographic grid, digitized at the referenced image # 1:3 — benchmark reference points, 4 — hydrographic outlines

Spatial referencing of the Corona and aerial imagery, which are produced in simple raster-format files, is a far more complicated challenge. In order to reference such files, IKONOS and QuickBird images serve as the benchmark data, as well as (when available) referenced topographical maps and plans and GPS field points. Because Corona satellite images cover significant area, they can be trapezoidally deformed in the periphery of the images; thus their referencing requires methods that allow to curve the initial data (polynomial transformations, rubber sheeting). The major issue is the shortage of reference points due to sparsely populated area of the study regions. Therefore, the objects of inland fresh water system, such as rivers, lakes, gullies and creeks are often used for referencing. They often have unstable banks which increases the chance of errors. In order to avoid such errors, referencing included vectoring the outline of the inland fresh water system to the pre-referenced high resolution image. Overlaying of resulting outlines with the referenced image and subsequent setting in the images by creating a set of reliable benchmark reference points produced a fairly accurate alignment of the referenced images (Figure 3). Referencing of the aerospace images to the areas with extended system of ravines and creeks is very effective when the reference points are set at the confluence of ravine and creek tributaries, at the headstreams leaving lakes, along the centerlines of short channels connecting the neighbouring lakes, because the horizontal position of such points tends to stay fairly stable over time. The resulting resolution of the referenced image should keep as much of the initial information as possible: thus, if the image resolution before referencing is about 10 m and oriented diagonally, the recommended resolution of the product is 5 m per pixel.

Geo-referencing of all multitemporal aerospace imagery available for the area is followed by the interpretation. Among the common and readable interpretation indicators in the conditions of thermo-abrasive and depositional arctic seacoasts are the sea cliff outlines and the edge of solid vegetation. Satellite imagery provides the source for digitization of the cliff crest (for abrasive sections) and the edge of continuous vegetation (for depositional coasts). Overlaying the edges of the land forms digitized in multitemporal images can help estimate the deformation, in particular, recession or progradation of the coast within a certain period. Satellite images can also help to detect the location and the evolution of submerged coastal levees, which are quaziephemeric relief shapes capable of dramatically changing their position in a few years (the levee moves to a location previously occupied by a swale, and vice versa). Another easily

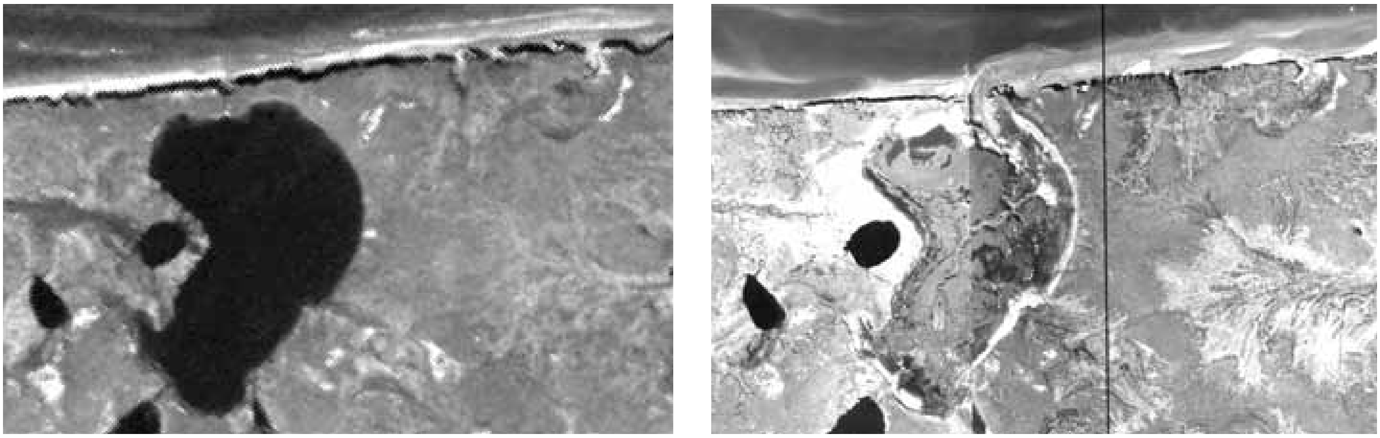

Fig. 4. Emergence of the freeze-thaw cycle (drained lake). Left — image acquired in 1964, right — 1988. Ural coast, Baydaratskaya Bay or Kara Sea

interpretable geomorphological process in the permafrost terrains is the freeze-thaw cycle (alas and thaw lake basins): for example, a pronounced freeze-thaw cycle has formed at the Ural coast terrain of Baydaratskaya Bay in the Kara Sea (Figure 4) between 1980 through 1986. Its formation is closely linked to the thermal abrasion process which has destroyed the northern shore of the lake and eventually led to the lake's emptying.

Coastal dynamics was mapped based on the multitemporal remote sensing imagery (Figure 5). Next step is analysis of such maps and comparison of the deliverables and field instrumentation measurement data. The result of this upcoming work may be the basis for typification and segmentation maps of the sea coast, which would include various specifications of the coastal morphology, structure and dynamics.

The study of the coastal dynamics in the area of active oil and gas development in the Russian shelf is one of the high priority challenges, because the intensity of hazardous morpho- and lithodynamic processes affects the geo-ecological safety of the industrial development and geotechnical safety of construction and operation at the infrastructural engineering facilities. Thus, for example, the results of the coastal dynamics studies, which included the comparison of the multitemporal aerospace imagery we referred to earlier in our article, helped to adjust the designed route of gas pipeline Bovanenkovo — Ukhta at the Ural junction. The site of the landfall of the submerged pipeline on the coast has been moved from the intensively degrading section of the coast (due to thermo-abrasion) to a dynamically stable location. The expected deformation of the coastal terrain based on the direct monitoring of the coastal dynamics, enabled us to estimate the optimal burial depth of the pipeline. Excessive burial depth drives up the construction cost significantly, whereas the insufficient burial would, on the other hand, pose a high risk of potential emergencies and environmental disasters due to deformation of the bare pipeline.

Maps and layouts resulting from the overlaid multitemporal aerospace images are the common elements in the GIS designed for this type of areas. Our studies allowed us to complete a few geoinformation projects targeting various regions of oil and gas development (from Kola peninsula to Sakhalin) and containing the initial data package (textual, relational data, geographical maps, aerospace images, etc.), set of electronic maps, hardware data upload subsystem (electronic tachometers, echo sounders, sidescan sonars), and a natural process simulator. The designed GIS systems allow to display, edit and organize the data in a single software application (ArcGIS Engine), as well as provide the access to the information in the most common GIS-applications and computer-aided design systems (CAD).

The relevance of the coastal dynamics studies in the Artic will increase with the further development of the Arctic hydrocarbon resources and the changing climate. Because there is a limited knowledge of the costal conditions in the Russian Arctic in 20 century, the multitemporal aerospace imagery have a huge potential in the costal dynamics studies in the region and it can provide a significant amount of data, providing which otherwise could be extremely difficult or impossible. With the growing amount of available Earth remote sensing data, including archives, the geo-information based analysis of such data becomes increasingly important.

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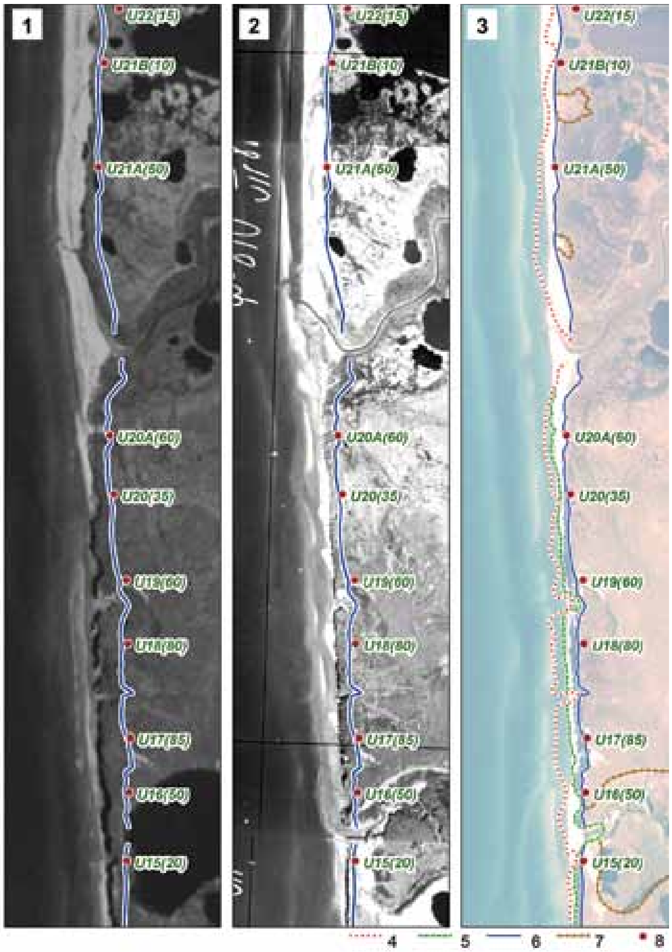

Fig. 5. Map of Coastal dynamics for Ural coast of Kara sea near Bovanenkovo-Ukhta crossing, based on multitemporal aerospace images. 1 — image acquired in 1964, 2 — 1988, 3 — 2005; 4 — sea cliff in 1964, 5 — 1988, 6 — 2005; 7 — the freeze-thaw cycles replacing the lakes drained due to coast recession, 8 — reference points of coastal dynamics monitoring grid (captions — number of the profile, in brackets — coast recession in 1964-2005 in meters)

Using Multi-Temporal Aerospace Imagery for Coastal Dynamics Investigations at Kara Sea. By S. Ogorodov, N. Belova, D. Kuznetsov, A. Noskov

Construction and operation of engineering facilities in the coastal zone of the Arctic seas taking into account the requirements of the geotechnical and geo-environmental safety require consideration of hazardous natural processes in the contact zone between atmosphere, hydrosphere and permafrost. The article describes an example of using multi-temporal aerospace imagery for coastal dynamics investigations along the main gas pipelines system "Bovanenkovo - Ukhta" across Baidaratskaya Bay, Kara Sea.

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