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THE EFFECTS OF SEAWATER ON THE DURABILITY OF HYDROTECHNICAL (CONCRETE) STRUCTURES IN THE PORT OF KLAIPEDA

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Abstract. Seawater has a significant impact on hydrotechnical concrete structures in the Port of Klaipeda. This factor must be properly examined and evaluated designing reinforced concrete structures exploited in seawater. The basic aim of research is to assess the effects of seawater on concrete and to form an algorithm for studying the durability of hydrotechnical structures affected by seawater. The conducted investigation showed the impact of seawater on hydraulic engineering (concrete) structures.

Serious defects are caused by corrosion in hydrotechnical concrete. The key factors indicating the durability index of hydrotechnical concrete include damage to the concrete due to environmental, mechanical and physical-chemical effects.

Physical-chemical environmental effects occur due to changes in temperature, the speed of the wind and fluctuations in the sea-level. Multiple environmental impacts can simultaneously affect hydrotechnical concrete.

Mechanical external effects occur due to constant stevedoring works and vessels moored at the Port of Klaipeda.

Keywords: Port of Klaipeda, hydraulic structures, effects of seawater, analysis, hydrotechnical concrete, durability, corrosion.

1. Introduction

The Port of Klaipeda is the northernmost ice–free port on the Eastern Coast of the Baltic Sea. The Port is fast growing because of the reconstruction and renovation of quays. Lithuania holds about 100 km of coastline, and the waters of its territorial and economic zone make 1.5% of all area of the Baltic Sea. 413 km^2 of the Lagoon basin – central and northern parts of the Curonian Lagoon, including the Port of Klaipeda established in the entrance channel of Klaipeda – belongs to Lithuania.

The Curonian Lagoon receives water from 75% of Lithuanian territory (i.e. fresh water from rivers); the sea makes an impact on the condition of waters of the Baltic Sea. Inflow water contains nutrients, including nitrogen, phosphorus and various specific contaminating substances such as oil hydrocarbon and heavy metals. Besides fresh water inflow into the Lagoon basin, environmental effects have a big impact on hydrotechnical concrete.

The paper also analyses environmental effects on hydrotechnical structures determining damages to exploitation – defects to present hydrotechnical structures.

All abovementioned factors have an impact on the condition of reinforced concrete quays in the Port of

Klaipeda where hydrotechnical structures (quays etc.) are built from concrete. They make a part of the main quay supporting system, the place where durability factor plays an important role. Thus, an algorithm for determining the durability of hydrotechnical structures can be made.

2. Environmental Factors Having an Impact on Hydrotechnical Structures Built in the Port of Klaipeda

During visual observation of hydrotechnical structures in the Port of Klaipeda, the following main factors making an impact on the intensity of decomposing hydrotechnical concrete have been determined: chemical effect (corrosion), concrete structure (examination of microstructure includes compositions of cement stone, crystals, micro pores, capillary and air pores having an impact on durability and resistance of concrete to cold), climatic conditions (temperature, humidity, etc.), the level of concrete pores filled with water (Ataskaita 2007).

Hydrotechnical concrete must be strong, thick, water-resistant, cold and resistant to an aggressive environment (Ramonas 1995).

Sulphate corrosion caused by seawater may occur pursuant to standard EN206-1:2000 when the amount of sulphates in water is from 600 to 3000 mg/l (exposure class XA2 – moderately aggressive chemical environment) and intensely – when the amount of sulphates in water makes from 3000 to 6000 mg/l (exposure class XA3 – highly aggressive chemical environment). Also, seawater may cause magnesium corrosion when the amount of Mg^{2+} ions in water exceeds 1000 mg/l (exposure class XA2 – moderately aggressive chemical environment) and 3000 mg/l (exposure class XA3 – highly aggressive chemical environment). The water of the Baltic Sea has a big impact on hydrotechnical concrete; thus, it is necessary to ensure that the ph of seawater getting into hydrotechnical concrete should be less than 4 when the amount of salts is 5000 mg/l and the amount of sulphates – 600 mg/l (Ataskaita 2007).

In order to evaluate and determine if the main parameters, having an impact on the hydrotechnical structures at the Port of Klaipeda do not exceed the established amounts, the analysis of the abovementioned parameters was performed (STR 2.02.06:2004).

Physical and chemical parameters making an impact on hydrotechnical concrete, including the temperature of water, salinity of water, speed and direction of flow, level of water, air temperature, direction and speed of the wind, pressure of atmosphere have been discussed and analyzed (dissolved oxygen, pH, nutrients: N general, NO_3-N, NO_2-N, NH_4-N, P general, PO_4 – P, SiO_2-Si, floating substances, hydrogen sulphide in the sea) (EN 206-1:2000).

The temperature of water in the Curonian Lagoon depends on the effects of the advection of air masses, solar radiation, sea and rivers. As the Curonian Lagoon is shallow, its thermal regime quickly responds to changes in climatic conditions. The temperature of water makes a high impact on the formation of a hydrochemical environment in the basin of the Port of Klaipeda. The lowest temperature of water on the surface, besides ice covering, is before and after it is frozen. If a season is warm, the temperature of water regularly decreases as it gets deeper. This law does not work when the amount of salty and fresh water of different features (including temperature) mixes or makes layers. Absolutely lowest annual temperature in the port basin of Klaipeda was recorded in January (Fig. 1) (Stankevičius, Barkauskas 1997).

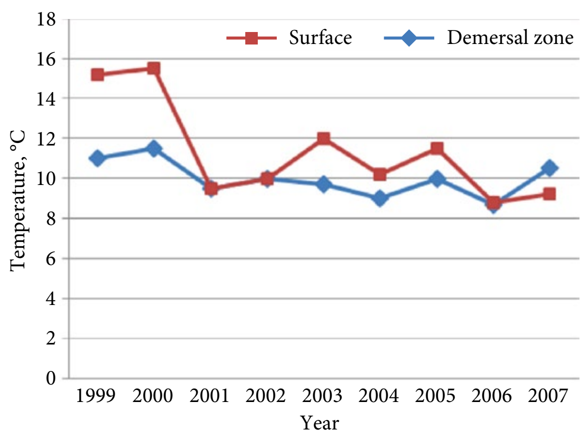

Fig. 1. Fluctuations in the average water temperature in the Curonian Lagoon

When getting deeper, the temperature of water in winter slightly increases: in the northern part of the Curonian Lagoon, near the bottom, the temperature of water reached –0.11 °C at a depth of 8m and –0.13 °C at a depth of 7.8 m.

The salinity of water in the Curonian Lagoon depends on the outflow and inflow of constant Baltic Sea water. At a similar level of Lagoon and Baltic Sea waters, the seawater of higher density starts seeping into the Lagoon through the Klaipeda Strait.

Salinity in the Lagoon may vary depending on wind force and duration, fluctuations in water levels between the Curonian Lagoon and the Baltic Sea (Fig. 2). In spring, Nemunas seeps the largest amount of water, thus salinity is the lowest in the Lagoon Basin. The biggest inflows of salty sea water into the basin occur in autumn.

In many cases (81%), the duration of flows into the Curonian Lagoon does not exceed one day, which is the time when salty seawater partially or completely fills the basin of the Klaipeda strait.

Salty seawater spreads over the northern part of the Lagoon only within intense and longer inflows and usually occupies a deeper part of the Curonian Lagoon.

Earlier, salty water used to spread mostly only to Juodkrante and more rarely – to Pervalka.

The amount of salts in the water of the Baltic Sea is presented in Figure 3 (diagram). The largest amount of salt, i.e. Na^+ and sulphates, chlorides (1487 mg/l), has been found in the water taken from the Curonian Lagoon (STR .05.15:2004; Volzenskij 1986; Vyšniauskas 2003).

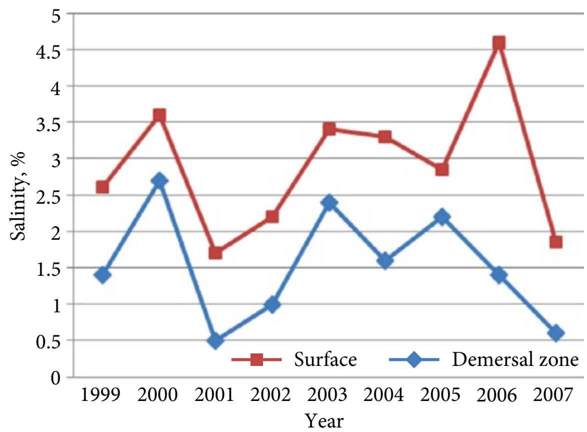

Fig. 2. Multi-seasonal fluctuations in salinity in the Curonian Lagoon

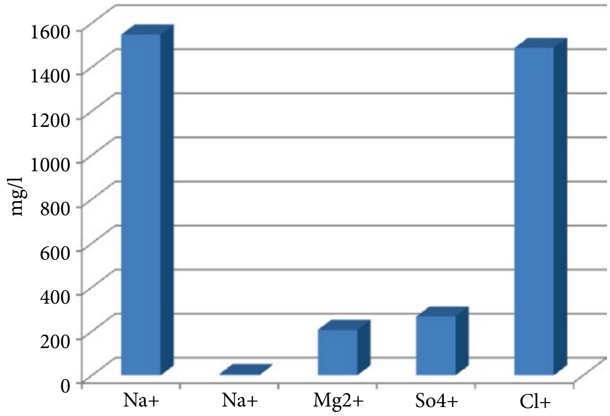

Fig. 3. The content of salt in lagoon water

Intensive underwater and extension works in the Port of Klaipeda in the 9th decade increased the permeability of the Strait and the inflow of salty water into the Curonian Lagoon. The concentration pH of hydrogen ion in the water of Curonian Lagoon is usually alkaline (Fig. 4) and may vary from 7.6 to 8.6 depending on the season and area of the Lagoon. The average pH of fluids in the Eastern and Western Curonian Lagoon reaches 8.2 (Paulauskas 2004; RSN 156-94).

In winter and March, pH values in the Klaipeda Strait are mostly equal and make 8.0–8.5. The values at the rest of time within the year are different. Pursuant to EN206-1:2000, standard pH must be not less than 5.5. Based on the information on monitoring the examination of the Curonian Lagoon, we received 8.2; thus, the obtained pH does not exceed the limit and does not make threat to the durability of hydrotechnical concrete.

The dynamics of pH indicator is related to the concentration of CO_2 that may vary due to the process of photosynthesis, exchange with atmosphere and the inflow of HCO_3 ions, including fresh water from rivers (Ataskaita 2007).

Extreme values are usually related to the events of non-typical water circulation. The port of Klaipeda belongs (1) to the region of Western Lithuania (1a – coastal sub-region). The Curonian Spit and a narrow coastline stretching for a few kilometres in width along Klaipeda – Sventoji is a sub-region of this region (1a). Westerly winds predominate here and bring humid weather from the sea (Fig. 5). In winter, due to the air from the ice-free sea, temperature in Klaipeda is usu-

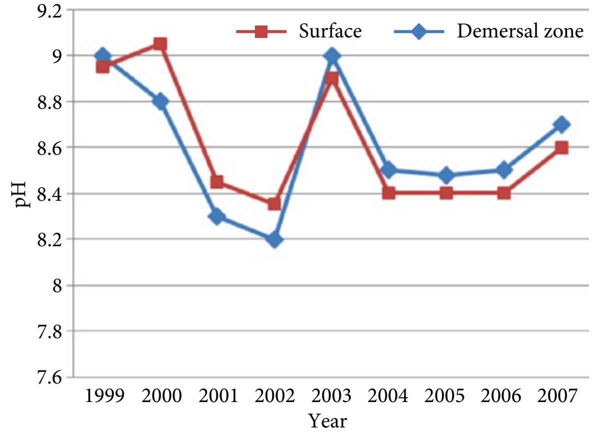

Fig. 4. Fluctuations in multi-seasonal hydrogen ion concentration (pH) in the Curonian Lagoon Channel

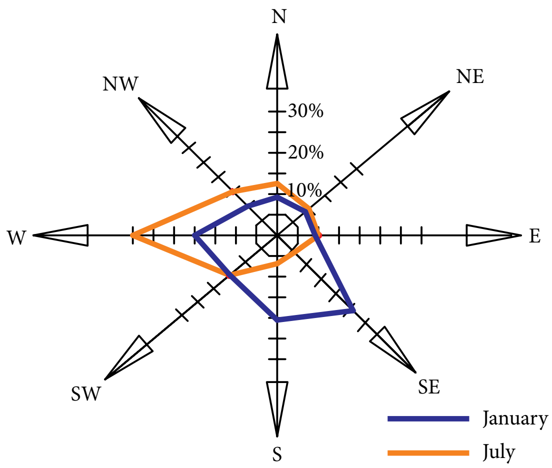

Fig. 5. Wind-rose

ally above zero or higher comparing to other places of Lithuania and makes 31 m/s (116 km/h) and 37 m/s (133 km/h) (Ataskaita 2007).

Hurricanes in Klaipeda at a speed of 26 m/s (93 km/h) not further than 30–40 km inland can occur every 5 years and practically are not likely. The period from 1999 to 2007 was not windy in Klaipeda as northerly and westerly winds were predominating. Only in January, August and November, winds reached more than 20 m/s. The strongest wind was blowing on January 8–9. When hurricane *Ervinas* stroke, the wind increased up to 32 m/s in Palanga, up to 27 m/s – in Nida, up to 28 m/s – in Klaipeda (Melnrage) and up to 32 m/s – in the port of Klaipeda (Ataskaita 2007).

Small and big waves were observed in the Curonian Lagoon. For the period 1999–2007, the height of waves reached from 0.25–0.5 m to 3.0 m (Fig. 6). Under strong Eastern, Southeaster and Southern winds, the highest waves reached 0.75–1.25 m. Maximum waves up to 3.0 m could be observed under Northern and Northeast winds. The height of waves depends on the force and direction of the wind.

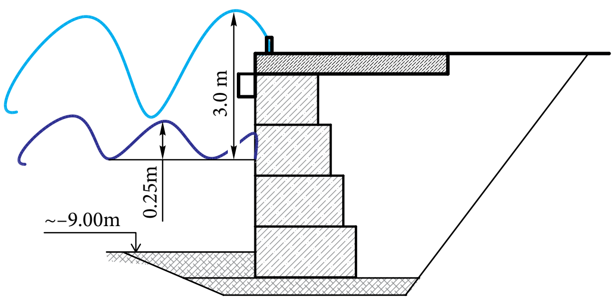

Fig. 6. The average annual height of waves for the period of 1999–2007 at the berths of the Port of Klaipeda

Oil hydrocarbon and heavy metals, including Hg, Cd, Cu, Cr general, Zn and Pb detergents have been found in specific – contaminating substances in the water of the Curonian Lagoon. Sediments at the bottom of the Curonian Lagoon contain oil hydrocarbon and heavy metals: Hg, Cd, Cu, Cr general, Zn, Pb, Ni, Sn, Al and As.

All above mentioned parameters cause the decomposition of the surface of hydrotechnical concrete (Ataskaita 2007).

3. Possible Mechanisms for the Decomposition of Hydrotechnical Concrete

The durability of hydrotechnical concrete depends on environmental effects under which hydrotechnical structure is exploited. Environmental effects are not as sudden as mechanical effects for the process of decomposition; however, together with other parameters, hydrotechnical concrete decomposes in time (Shalimo 1986).

The durability of hydrotechnical structures depends on the quality of used materials and products, constructive solution, protective layers and limiting physical climatic or other external effects on structure (EN 206-1:2000).

Since hydrotechnical concrete is affected by constant humidity, i.e. seawater, a multiple water freezing and unfreezing process occurs in the pores of hydrotechnical concrete. Such multiple effects of freezing and unfreezing decompose hydrotechnical concrete. Resistance to cold at the quays of the Port of Klaipeda is one of the most important parameters for decomposing hydrotechnical concrete taking place due to cyclic freezing and unfreezing for a few reasons embracing the hydrostatic pressure of water that occurs when water is freezing and its volume increases, the formation of ice crystals, an increase in capillary pores, osmotic pressure happening because of differences in the concentration of alkalis and salts in the liquid phase (STR 2.05.04:2003; Klaipėdos uosto ... 2001).

Hydrotechnical structures and their components are affected by an aggressive environment. Fluctuations in water level hasten the process of decomposition forming in the Curonian Lagoon under moderate and maximum winds, i.e. when wind force reaches 32 m/s and the height of waves increases up to 3.0 m. Hydrotechnical concrete is affected by salty seawater, temperature fluctuations, freezing and unfreezing cycles and the constant humidity of seawater affecting the quay at the Port of Klaipeda (STR 2.05.04:2003; Klaipėdos uosto ... 2001; Nevill 1972; LST 1428.18:1997).

Considering all above mentioned effects, various defects to hydrotechnical concrete may appear (Fig. 7) (STR 1.04.01:2002; Bazenov 1987; STR 1.12.03:2000).

Damage to the surface of hydrotechnical concrete occurs due to washed out soluble composites and a destructed 50 mm protective layer at the quay of the Port of Klaipeda. Also, a choice of properly filled hydrotechnical concrete is essentially important for the corrosion process. The filling of hydrotechnical concrete has to comply with requirements for resistance to cold even under harsh conditions (Gumuliauskas, Skripkiūnas 2010).

A few following types of the corrosion of hydrotechnical concrete can be distinguished based on the conducted analysis: leaching soluble compounds, sulphate corrosion, magnesia corrosion, reinforcement corrosion (Shalimo 1986; LST CEN/TS 12390-9).

The process of leaching soluble compounds – corrosion – appear in hydrotechnical constructions due to wave effects and causes "white coverage" on the surface of hydrotechnical concrete (Figs. 7 and 8).

Sulphate corrosion starts when sulphates affect concrete rocks reacting with Ca $(OH)_2$, C_3A (tricalcium aluminate), gypsum and calcium hydrosulphoaluminate forms, the trisulphate form of which is known as ettringite. When formed, it combines a big amount of water constantly entering together with waves and increasing the volume of the solid phase by 1.63 times and containing $Ca(OH)_2$ – by 2.23 times. This causes great inner tensions and decomposition of hydrotechnical concrete stone.

At the beginning of sulphate corrosion on the surface of hydrotechnical concrete, a membrane of gypsum crystals is formed. At a later stage, ettringite is produced and cracks in concrete appear in parallel with the surface and become wider until hydrotechnical concrete breaks.

A considerable amount of damage is caused to hydrotechnical concrete exerted by external mechanical effects because of stevedoring works at the Port of Klaipeda, the place for mooring ships responsible for harm done to hydrotechnical constructions (Figs. 8 and 9) (LST EN 1504-3:2006).

Seawater gets on the surface of quays at different levels and affects hydrotechnical concrete inside it, i.e. makes an impact on forming calcium salts that melt in water and are washed out by waves. Seawater contains chloride salts $MgCl_2$ and $MgSO_4$, and therefore magnesia corrosion occurs (Ataskaita 2007).

Fig. 8. Mechanical damage to the quay at the Port of Klaipeda

Fig. 7. External damage to the quay at the Port of Klaipeda

Fig. 9. Mechanical damage to the quay at the Port of Klaipeda

The alkaline corrosion of fillers starts in cement used for hydrotechnical concrete when sodium and potassium hydroxides (alkalis) react with active SiO_2 found in some of the fillers. The reaction brings strong inner extensions in hydrotechnical concrete, which causes deformations and cracking. However, the reaction is slow, and thus damage to hydrotechnical concrete occurs only in a few months or years' time.

Corrosion in hydrotechnical concrete and its reinforcements is a visible process (Fig. 10). Reinforcements for dense hydrotechnical concrete are not affected by corrosion, because this type of concrete protects it from environmental effects and creates an alkaline environment passivating corrosion in electro chemical steel. If the protective layer of hydrotechnical concrete is damaged, the environment and pH of hydrotechnical concrete changes and corrosion in reinforcements can start (STR 1.12.03:2000; Ramonas 1995).

Corrosion factors in metal structures and reinforcements can be visible at the quay of the Port of Klaipeda. In the majority of cases, hydrotechnical structures have been affected by mechanical and weather conditions STR 1.04.01:2002; Klaipėdos uosto... 2001; LST ISO 4012:1995).

Fig. 10. Valve lesions at the quay of the Port of Klaipeda

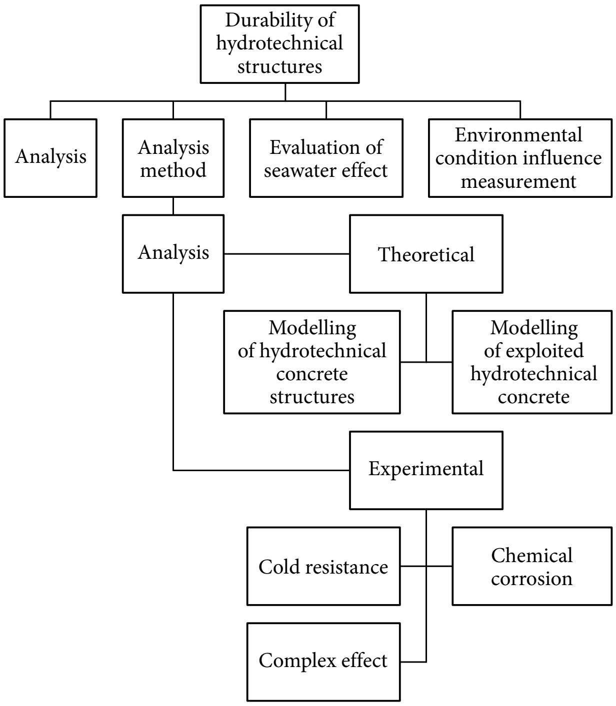

Fig. 11. Algorithm for evaluating the durability of hydrotechnical structures

4. Algorithm for Evaluating the Durability of Hydrotechnical Structures

The analysis of hydrotechnical structures and damage to hydrotechnical concrete allows determining an algorithm for defining the durability of the structures and measuring theoretical and experimental data on hydrotechnical structures.

Besides environmental and external effects, the durability of hydrotechnical materials depends on the structure of hydrotechnical concrete (Skripkiūnas 2007; EN 206-1:2000).

The findings on the water of the Curonian Lagoon and examination of monitored water led to making an algorithm for calculating the durability of hydrotechnical structures. The durability of hydrotechnical structures and constructions can be rated applying the method based on the analysis of forming a few factors. The method consists of the analysis of the hydrotechnical structure, the evaluation of the effects of seawater on hydrotechnical structures and evaluation of an impact on environmental conditions. The method employing the analysis of hydrotechnical structures is divided into theoretical and experimental. The theoretical method of hydrotechnical structures should be focused on forming hydrotechnical concrete and modelling exploited hydrotechnical concrete. Experimental analysis should be performed in two directions – checking resistance to cold and chemical corrosion. Following tests on all above mentioned criteria, it is necessary to provide a complex evaluation of hydrotechnical structures that allows estimating a number of parameters affecting hydrotechnical structures (Figs. 10 and 11) (LST CEN/TS 12390-9; LST EN 1542:2002; LST L 1428.17:2005; Marchand 1994).

5. Conclusions

1. Physical, chemical (hydrological and meteorological) and specific (corrosion factors) parameters have a great impact on the durability of hydrotechnical concrete structures.
2. Great harm done to hydrotechnical concrete structures at the quay of the Port of Klaipeda is obviously visible. Defects have been caused by seawater, environmental, mechanical and physical – chemical effects.
3. The salinity of water in the Curonian Lagoon remains very unstable (varies from 2.5 to 7 ppm). Salinity makes an impact on the durability of hydrotechnical concrete.
4. The analysis of water in the Curonian Lagoon shows that the quantity of sodium (1548 mg/l), magnesium (206.7 mg/l) chloride (1487 mg/l) sulphate (267 mg/l) salts in water is large enough to affect the durability of hydrotechnical concrete.
5. The salinity of water and the number of freezing – unfreezing cycles have to be considered while designing hydrotechnical concrete structures.
6. Possible cases of concrete corrosion include soluble elements washed out by seawater, sulphate corrosion, magnesia corrosion, filling alkaline and reinforcement corrosion.
7. Seawater and environmental effects have to be evaluated when a factor in the durability of hydrotechnical structure and its materials (hydrotechnical concrete) is determined.

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JŪROS VANDENS POVEIKIS KLAIPĖDOS UOSTO HIDROTECHNINIŲ STATINIŲ (BETONO) ILGAAMŽIŠKUMUI

Santrauka. Klaipėdos uosto hidrotechniniams statiniams jūros vanduo daro didelį poveikį. Šis veiksnys turi būti ištirtas ir vertinamas projektuojant gelžbetonines konstrukcijas, eksploatuojamas jūros vandenyje. Darbo tikslas – įvertinti jūros vandens poveikį betonui bei sudaryti paveiktų jūros vandens hidrotechninių konstrukcijų ilgaamžiškumo tyrimų algoritmą. Tyrimų metu atlikta jūros vandens poveikio hidrotechniniams (betono) statiniams analizė. Klaipėdos uosto krantines veikia agresyvioji aplinka. Didelius defektus sukelia hidrotechninio betono korozijos. Hidrotechninio betono pažeidimai nuo aplinkos ir mechaninių, fizikinių ir cheminių poveikių yra pagrindinis veiksnys, darantis įtaką hidrotechninio betono ilgaamžiškumo rodikliui. Fizikiniai ir cheminiai aplinkos poveikiai atsiranda dėl temperatūrų kaitos, vėjo greičio, jūros vandens lygio svyravimų. Hidrotechninį betoną vienu metu gali veikti keli aplinkos poveikiai. Mechaniniai išoriniai poveikiai atsiranda dėl nuolat Klaipėdos uoste vykstančių krovos darbų, prišvartuotų laivų.

Reikšminiai žodžiai: Klaipėdos uostas, hidrotechniniai statiniai, jūros vandens poveikis, analizė, hidrotechninis betonas, korozija, ilgaamžiškumas.

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