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Research article

Seismic profiling of the sea-bottom in recognition of geotechnical condition

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Abstract: Seismic surveys are widely applied in research on the recognition of geological and geotechnical conditions of seabed and ocean floor sediments. The methodology and equipment needed to carry out shallow seismic and direct geotechnical surveys, as well as the analysis of the results based on the survey of the Polish Baltic Sea bottom, shall be presented here. The interpretation of the seismic survey results is based on the analysis of the registration of different acoustic levels, characteristics of seismo-acoustic layers, their degree of readability and slope angles of individual acoustic reflections. The author deals with the analyses of seismic reflection data and tries to understand the wave image as best as possible. Based on the seismic registrations obtained by the Geofizyka-Toruń company, the author has elaborated interpretation patterns for the Polish Baltic sediments, which are also presented here. The seismic surveys were used to construct maps of specific levels with different geotechnical conditions in the sea-bottom and at a depth of 10, 20 and 30 m below the seabed. The author presents here new results of research related to the geotechnical characteristics of the Polish Baltic substrate at a depth of 30 m below the seabed. The geotechnical map of the Polish Baltic Sea of the substrate at the depth of 30 m below the sea-bottom, as prepared by the author, is very important for building deep foundations of marine constructions, such as oil and gas exploration and production platforms. Seismic surveys allow a good degree of recognition of various geotechnical types of soils in the Polish Baltic sea-bottom, for which approximate values of characteristic geotechnical parameters have been determined.

Keywords: seismic profiling; reflective method; equipment and methods of geotechnical research; sea-bottoms; geotechnical characteristics; geotechnical maps

1. Introduction

The substrate of Quaternary sediments that occurs at the bottom of seas and oceans can be well recognized by means of seismic surveys, where the interpretation of seismic registration is based on the analysis of the wave image of different levels of reflection events, the characteristics of the boundaries of seismo-acoustic layers, their degree of readability and the inclination angles of the reflections occurring there. The next step in the interpretation of seismic datasets is to correlate the information with the geological structure of adjacent land as presented on geological maps or contained in borehole data from the coastal zone, taking into account the lithology, stratigraphy and depth of the analyzed seismo-stratigraphic levels and important angular unconformities of surfaces [1]. This provides a visual representation of the rock substrate structure and allows the correlation between the morphology of the sub-Quaternary surface and the lithological composition of the sediments. The seismic surveys carried out within the Quaternary sediment cover provide the basis for distinguishing specific seismo-stratigraphic units, which closely match the separated litho-stratigraphic units of the analyzed geological period [1]. Seismic surveys of the Polish Baltic sea-bottom were carried out by the geophysical company “Geofizyka Toruń”.

In the interpretation of seismo-acoustic record, it is also important to analyze the degree of absorption of acoustic energy by different geological layers along with the analysis of the internal seismic character as the degree of clarity of the registered seismic reflections. An important objective in the interpretation of seismic record is also the tracking of the main acoustic horizons and the analysis of angular inconsistencies of the reflections recorded there.

It should be noted that the determination of the velocity of seismic waves in a substrate indicates its volume density as one of the important geotechnical parameters of the soil. A very important purpose of seismo-acoustic surveys in the geotechnical reconnaissance of the seabed is also to determine the thickness of individual geological layers for the design of specific marine constructions [1]. These studies may also allow recognition of the occurrence of tectonic faults, especially those along which geological layers currently move, encompassing areas which may constitute a hazard for the previously designed, in-built and already existing marine constructions. The analysis of the structure of the seismic record as a way of arranging reflections, as well as its internal character of registration may allow the recognition of the geological structure (arrangement of layers as horizontal, monoclinalic and folded) of the seabed layers and preliminary determination of the environmental conditions [1].

Apart from seismic surveys, the results of numerous geological-engineering and geotechnical surveys of the northern part of Poland, especially the coastal zone of the Baltic Sea and selected seabed fragments [2–4] as well as the analysis of geological maps of the Baltic Sea bottom in the scale 1:200,000 were taken into account to characterize the geotechnical diversity of the Polish Baltic Sea bottom: [5–20]. It should be noted that the bottom of the Baltic Sea is mostly made up of sediments, which are a continuation of the geological structure found on the nearby land. On this basis, the geotechnical types of the Polish Baltic seabed, for which the approximate values of the leading geotechnical parameters have been determined, have been specified and characterized. The given characteristics of particular geotechnical types of the Polish Baltic sea bottom concern the lithology, the origin and the age of soils as geological criteria and the index of density (I_D), the index of plasticity (I_L) the angle of inner friction (ϕ), the cohesion (c), the compression strength (Rc), the shear strength (τ_f) and the oedometric original bulk modulus (Mo) as geotechnical criteria.

2. Mathematical formulas for geotechnical parameters

The specified geotechnical parameters assume the following mathematical formulae [21]:
Index of density I_D,

$$I_D = \frac{e_{\max} - e}{e_{\max} - e_{\min}} \tag{1}$$

e_{max}—index of porosity at the loosest arrangement of grains (molecules), e_{min}—index of porosity at the densest arrangement (maximum density) of grains (molecules), e—index of porosity.

The index of density of non-cohesive soils assumes the following ranges:

- loose soil $0 < I_D \leq 0.33$;
- medium density (compacted) soils $0.33 < I_D \leq 0.67$;
- high density soils $0.67 < I_D \leq 0.80$;
- very high density soils $0.67 < I_D \leq 0.80$.

Index of plasticity I_L,

$$I_L = \frac{w - w_p}{w_L - w_p} \tag{2}$$

w—humidity, w_p—limit of plasticity, w_L—limit of liquidity according to Casagrande.

The index of plasticity of cohesive soils assumes the following interval values:

- compact and semi-compacted soils $I_L < 0$;
- hard plastic soils $0 < I_L \leq 0.25$;
- plastic soils $0.25 < I_L \leq 0.5$;
- soft-plastic soils $0.5 < I_L \leq 1.0$;
- liquid soils $I_L > 1.0$.

The inner friction angle Φ can be calculated from the following relationship: $\tau_f = c_u + \sigma \text{ tg}\Phi$.

Cohesion c can be calculated from the following ralationship: $\tau_f = c_u + \sigma \text{ tg}\Phi$.

The compression strength R_c—the highest unit load absorbed by the ground during uniaxial compression of a specimen of intact structure, expressed in MPa.

The shear strength τ_f,

$$\tau_f = c_u + \sigma \text{ tg}\Phi \tag{3}$$

τ_f—shear strength, c_u—cohesion, σ—normal tension.

The oedometric original bulk modulus Mo expressed in MPa,

$$\mathrm{Mo} = \frac{\mathrm{d}\sigma}{\mathrm{d}\varepsilon_0} \tag{4}$$

dσ—increase of the effective normal stress, $\mathrm{d}\varepsilon_0$—increase of the total relative deformation.

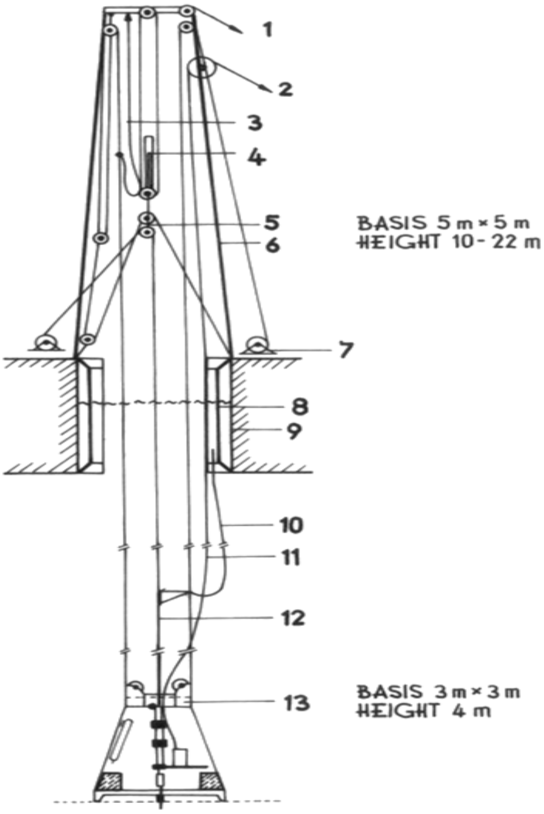
A very important aspect of this paper is represented by the top layer of the seabed, where different geotechnical conditions occur, being controlled by the direct influence of the Baltic Sea waters [4]. In places where the seabed is made up of cohesive soils, the sediments present there are soft-plastic and in some cases even in a liquid state. On the other hand, when the seabed is built of non-cohesive soil, the sediments there are fully saturated with sea water. The unusual zone of the seabed analyzed here has a thickness of 1.5–2.0 m.

3. Equipment and methods of the geotechnical research

The geotechnical research, aimed at identifying the physical and mechanical properties of the marine substratum, is often carried out in situ, where the foundation for marine hydrotechnical construction has been designed. The penetration cone tests (CPT) are most commonly performed. Implemented penetration cones are usually 1000 mm² (diameter 35.7 mm), where the measurements of cone resistance and the friction on the sleeve side area of 15,000 mm², are carried out by means of string sensors [22]. Penetration cones with a cross-section of 500, 1500, 2000 and 4000 mm² have also been used. The maximum load capacity of a 1000 mm² penetration cone reaches up to 150 kN. This high load capacity is mainly controlled by the large resistance of thick sands on the seabed. Such a popular device, employing the above-mentioned method and built in the years 1972–1973 by the Fugro-Cesco Company is a device called SEACALF (Figure 1). Pressure force (max. 200 kN) of this device is induced by hydraulics and controlled from the ship, and the reaction is taken by the own weight of the device. This probe can work at a water depths of up to 300 m, the depth of penetration reaches 20–40 m depending on the type of seabed soils. The speed of descent is estimated at 16–20 mm/s. The base of this unit has dimensions of 3 m × 3 m, height 4m, weight 8000 kg, ballast from 0–20,000 kg. The SEACALF probe, herein discussed, can be also equipped with a device to load the tests of the seabed soil [22].

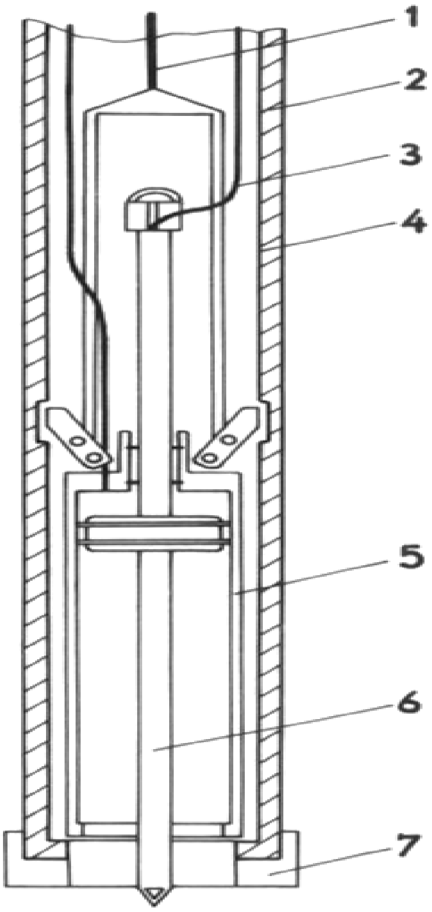
In addition to the conical probes, the static, dynamic and vane probes have also been used. For example, Wison's static probe constructed by Fugro Company (Figure 2) equipped with an electrical blade and placed within the drill poles (of 100 and 128 mm in diameter) is actuated by means of a rope. The drilling equipment with a diameter of 220 mm and a central stopper, extracted by means of a rope, has a structure analogous to the rope drilling installations. The probe consists of a set of blocks, situated at the bottom of the drilling pole set and is controlled by means of a rope. It also includes a hydraulic press, operated on the vessel, exerting pressure of 20–30 kPa depending on probe's operating conditions [23]. The press's pole, with a maximum leap of 2 m, is equipped with the probe's spearhead. Retraction of the spearhead is conducted manually by means of pulling the probe back on vessel through the appropriate maneuvering of the rope. The necessary on-board equipment used to operate the probe include: drilling equipment and devices used for starting, controlling and measurement operations of the probe. Drilling equipment commonly used consists of: a 128 mm rotary key for plunging of the pole, a drilling winch and a rotodynamic pump pumping drilling mud in an open circuit as well as tanks for the slime. Among the special features of the probe there are: a winch used for pulling the central stopper and the probe itself, a hydraulic set for controlling the press and recording unit connected by an electrical cable to the probe's spearhead. The weight exerted upon the device, derived from the mass of the drill poles and the poles itself, is of 50–60 kN. The penetration of the probe extends to a depth of 5–10 meters below the seabed [23].

The research on the mechanical properties of the seabed soils have also been carried out by using the Menard pressurimeter. This device includes a pressurimetric probe, immersed in a probing borehole by means of a set of poles, which extends in the radial direction depending on the applied pressure upon its walls, a measuring apparatus and a mechanism for creating the pressure within the probe [22]. The pressurimetric research allows to determine the in situ soil stress-strain constituting a central measuring chamber and the outer rubber membrane forming two protective chambers.



1—drilling lift; 2—control cab; 3—safety rope; 4—block vertical movements compensator; 5—sensor; 6—the basis (5m × 5m), the height (10–22 m), 7—a capacity winch (200 kN); 8—a lead frame; 9—shaft; 10—probe's wire; 11—operational wiring; 12—research poles; 13—Seacalf (the basis (3 m × 3 m), the height 4 m).

Figure 1. Diagram of the Dutch Seacalf Probe. Source: after Mazurkiewicz BK (1985) [22].

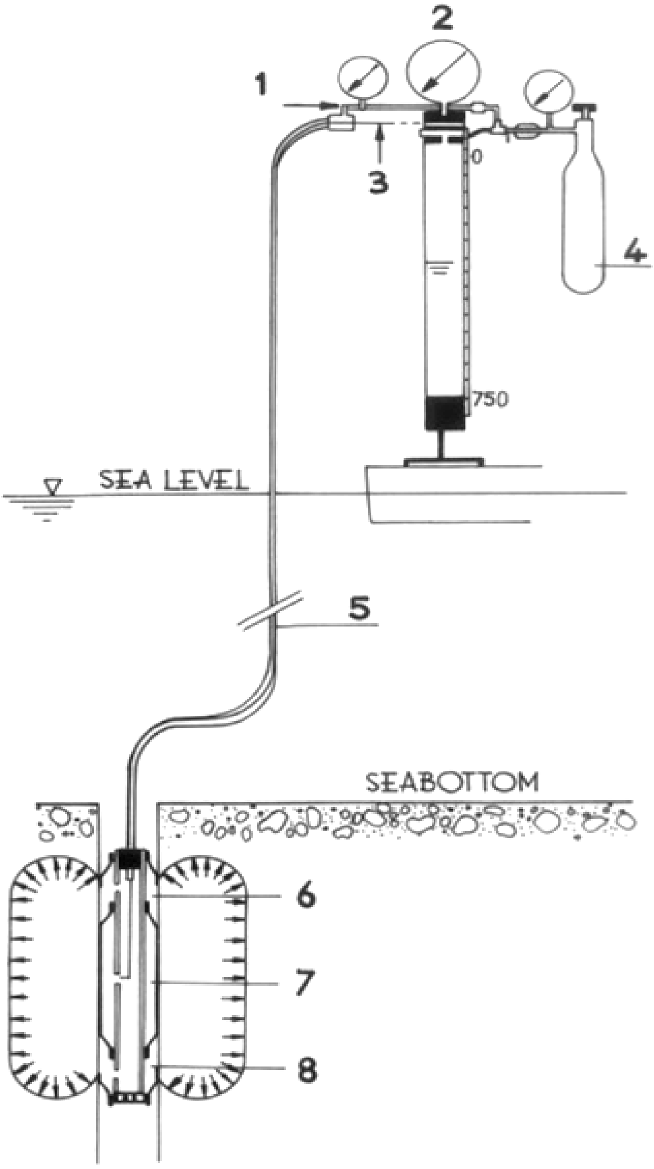


1—bearing wire; 2—the drill pipe; 3—measurement wire; 4—inner diameter (90 mm); 5—hydraulic piston (2 meters steps; force—30 kN); 6—electric probe; 7—drilling apparatus.

Figure 2. Diagram of the Wison's cable probe. Source: after Dembicki E (1987) [23].

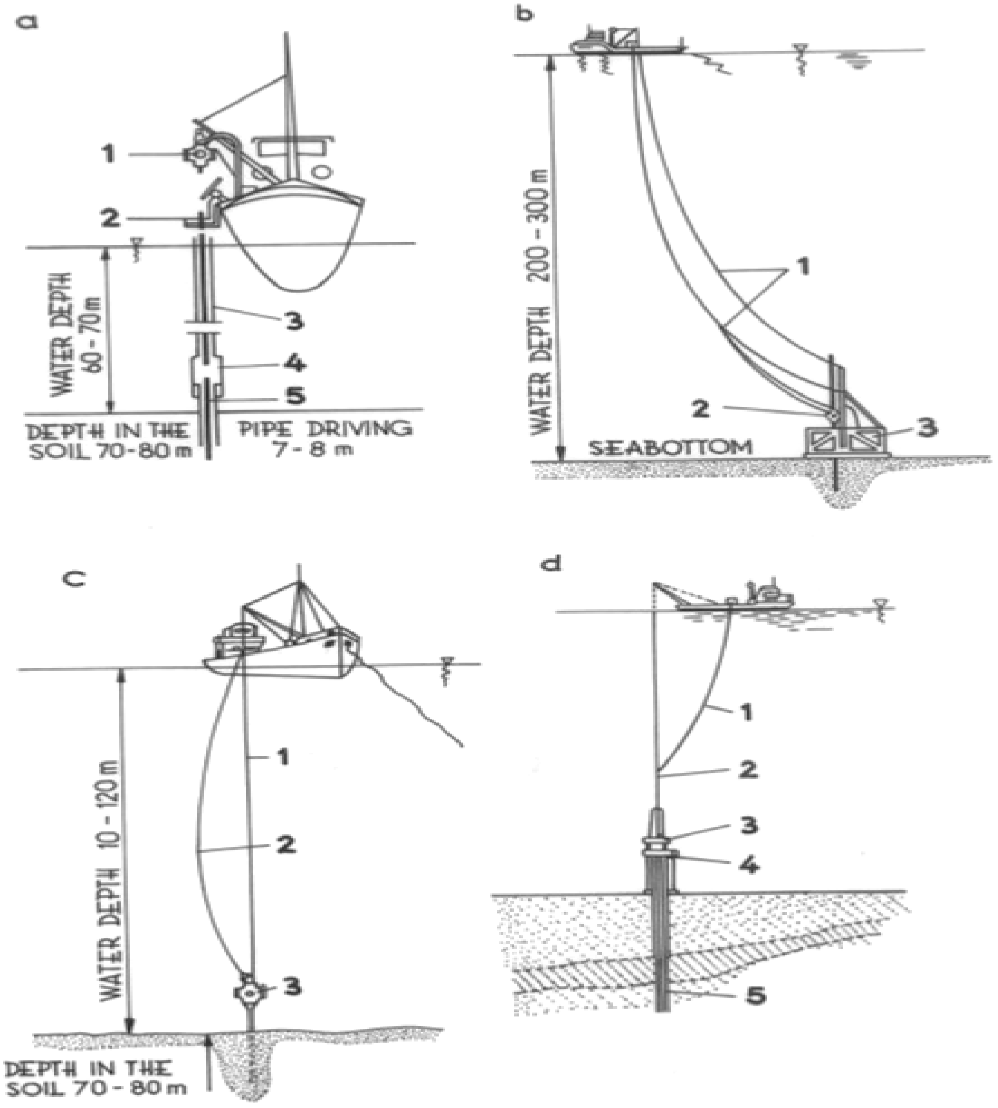
By analyzing the soil's strain-displacement curve, a motion is formulated for the soil deformation module, which is the yield strength used to determine the seabed's bearing capacity and stress in slither state. The most seabed researchers use pressurimetric probes encased in a metal sheath, consisting of a steel tube with an inner rubber membrane chambers (Figure 3). The total length of the probe is from 60–70 cm. The length of the inner measuring chamber is about 20 cm. Both the pressure, applied in the probe, and its expansion depend on the employed model. Within metal probes, the maximum useable pressure is 2.5 MPa and maximum dilatation (enlargement) corresponds to a volume of 700 cm³. The pressurimeter works discontinuously, measuring the mechanical properties of soil, where measurements are used at intervals of 1–2 m. The pressurimetric indications depend partly on conditions during the probe's descent due to the possibility of a major or minor damage to the seabed [23]. A typical pressurimetric test should be performed with nine steps of pressure, maintained more or less constantly, until reaching the pressure limit (assumed to be 6–14 steps of pressure application). The volume read-outs within a function of time are carried out every 15 and 30 s and 1 minute after the applied pressure termination at each of its steps. The standard duration of the pressurimetric test, at each level of probing, is 15 minutes. The pressurimetric research is an examination of soil’s saturated shear resistance. The duration of the standard test (1 minute per pressure step) does not allow for the dissipation of water pore pressure arising due to the descent of the probe. The resulting penetration depths depend on the way the probe is immersed, ranging from 20–50 m to a maximum of 60–80 m [23].

The methods for immersing the pressurimetric probe depend on the type of soil and on the water depth. A method of descent through the guiding tube (Figure 4), 85 mm in diameter, running down from a mobile platform attached to the ship’s side and located at average depth of 7–8 m is commonly used. The poles, needed to start the pressurimetric probe and running along the guiding tube, are added depending on the level of their insertion into the soil. The insertion occurs due to vibratory driving or prior drilling or pipe driving, depending on the degree of consolidation of the soil. During drilling the injection can be used in order to maintain the stability of the borehole. The maximum depth of probing ranges from 70 to 80 m [23]. The descent of the pressurimetric probe with a vertical cable (Figure 4) is used only in conjunction with vibratory driving of the pressurimeter probe into the soil. The connection between the seabed and the deck is half-flexible and consists of a flexible connection between the ship and the vibrating device, which is fixed on the outer end a set of poles. The connection between the vessel and the vibration device is obtained through a line supporting the vibration device, with a weight of 4.5 kN and a set of poles having a weight of 40 N/m and diameter of 44 mm, and by flexible hoses connecting the hydraulic pump (positioned on the vessel) with the vibration driver. This method enables probing depth of 40–50 m [23]. The descent of pressurimeter probe with a vibratory driving of the pressurimeter (Figure 4) involves replacing the vibratory device, positioned on the poles, with a vibratory hammering half-flexible and consists of a flexible connection.



1—manometer gauge; 2—air; 3—water; 4—gas cylinder; 5—plastic pipe; 6—protective chamber; 7—measuring chamber; 8—protective chamber.

Figure 3. Diagram of Menard pressurimeter. Source: after Mazurkiewicz BK (1985) [22].



a) by means of a guiding tube: 1—hammer drill; 2—side platform; 3—the guiding tube; 4—yoke; 5—poles; 6—pipe hammering in the ground (7–8 m); 7—recess (70–80 m); b) by means of an underwater frame: 1—hydraulic hoses; 2—vibrating ring; 3—underwater frame; 4—seabed; c) by means of a vertical wire installed hammer drill: 1—bearing wire; 2—hydraulic hoses; 3—hammer drill; 4—recess (70–80 m); d) by means of a vibrating ring: 1—flexible wires; 2—bearing wire; 3—vibration ring; 4—leading pipe and actuators; 5—pressuremeter probe.

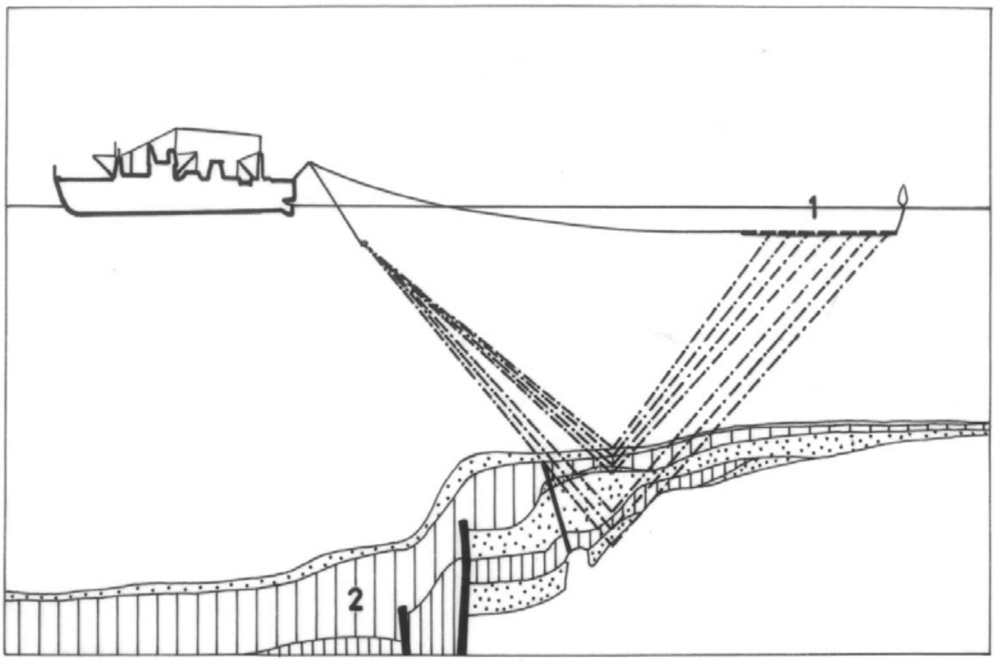
Figure 4. Methods for Pressurimetric probe's submersion. Source: after Mazurkiewicz BK (1985) [22].

The result is a probing depth of 100–200 m and more. The connection between the seabed and the deck is flexible and consists of a tow rope hosting the vibratory hammer ring weighting 10 kN and a set of poles, a flexible hose connecting the hydraulic pump with the hammer ring, flexible hoses placed along a set of poles between the pressurimeter probe and the measuring chamber located on board. Verticality of the poles, at low current speed, is ensured by an applied swimmer. The vibratory hammering ring is placed at a height of 2–3 m above the seabed, on the guide tube equipped with two press. Pipe driving takes place in steps [23]. The pressurimeter probe’s descent through underwater frame (Figure 4) is performed by using Kullenberg Drilling Method. In Kullenberg Method the point of the drill pipe was replaced by a pressurimeter, placed at a height of 2–6 m inside the pipe, maintained by ballast and the ring-off device [23].

The pressurimeter is used for obtaining both basic soil parameters and parameters used directly for building design. Results of pressurimeter test give the information about two most important soil parameters for designing purposes: soil strength (bearing capacity) and compressibility. In this regard, pressuremeter tests should be combined with coring in order to obtain the necessary data regarding the type and depth to the individual layers of the seabed [22].

4. Seismic equipment and interpretation of the research

Seismic surveys in the Polish sector of the Baltic seabed have been carried out in the 1970s by the former Department of Geomorphology and Marine Geology of the Institute of Meteorology and Water Management in Gdynia. In these investigations, the seismic reflection method has been used, where the source of the waves was towed behind the ship and the seismic cable, composed of arrangement of hydrophones, has received the seismic waves reflected from the geological layers (Figure 5). Depending on the frequency of the seismic waves, the depth of these waves into the geological strata and their resolution can be determined. The higher is the frequency of the seismic waves, the shallower is the range of these waves deep into the geological strata, with a high resolution. On the other hand, at a lower frequency of seismic waves, a greater depth of penetration into the geological layers is achieved, but at a cost of lower resolution. Shallow seismic investigations, in which the seismic record is performed continuously, are performed with continuous ship motion along the planned grid of profiling. The determination of the test position is carried out with the use of satellite navigation with GPS method. In the region of sea basins [24], the source of seismic vibrations is transported in the near-surface water depth (Figure 5). In deeperparts of the oceans, on the other hand, seismo-acoustic surveys are performed using profilers, where the source of vibrations is towed at the ocean floor.



1—Hydrophone; 2—Geological layers.

Figure 5. Reflection method in seismic investigations [24].

On the terrain of the Polish Baltic Sea, seismo-acoustic profiling was performed using the Huntec M-2A hydrosounder from Canada or the E.G.G. system from the USA. In the 1980s and 1990s, seismo-acoustic and geological surveys were also carried out by the Marine Geology Division of the Polish Geological Institute in Gdańsk on the basis of which geological maps of the seabed in the scale 1:200,000 were developed. Research using continuous seismo-acoustic profiling in the region of shallower marine basins is carried out with the use of three different seismic wave vibration generators (sources):

- BOOMER (UNIBOOM)—the 230 model operates in the frequency range from 500 Hz to 15 kHz. The optimum speed of the vessel during the tests should be 4 knots. The average range of seismo-acoustic waves using this generator is from 150–200 m at a resolution of about 15 cm. The single pulse energy is up to 700 J (Figure 6).
- SPARKER—the 267A (triple-amp) model operates in the frequency range from 100 Hz to 2 kHz. The single pulse energy reaches a maximum of 1000 J. When using an extended power supply unit, the single pulse energy may reach 8000 J. Seismo-acoustic waves induced by a sparker can reach a depth of 1000 m at a resolution of 2 m (Figure 7).
- PINGER—It is a source of vibrations of very high frequency and very high resolution. However, it is relatively rarely used in seismo-acoustic surveys. It gives a very good result in locating buried pipelines.

Figure 6. Source of seismo-acoustic waves—Boomer [25].

Figure 7. Source of seismo-acoustic waves—Sparker. Marine Multi-Tip Sparker System [26].

In many parts of the Polish Baltic Sea, seismo-acoustic investigations were also carried out using the E.G.G. seismic system manufactured by the USA. An example of such studies comes from the Gdańsk Gulf and Gdańsk Basin, where a very large number of these surveys have been carried out (Figures 8 and 9). Seismo-acoustic surveys from the Gulf of Gdańsk present the geological situation in the contact zone with the underwater slope of the Hel Spit (Figures 9 and 10). The lower level of the seismo-acoustic profile is made up of Upper Cretaceous [27] sediments, which show parallel layers (1; Figure 10). Glacial tills, probably belonging to the Vistula Glaciation sediments with specific diffraction waves reflected in the seismic record (2; Figure 10), are located higher. Above this layer there are stratified sandy sediments genetically associated with the glaciofluvial delta (3; Figure 10). The next layer is formed by Baltic Ice Lake sediments represented by laminated clays [27], fine-ribbed and clearly deformed in the lower parts (4; Figure 10). In the upper parts of the seismo-acoustic section there are sandy sediments associated with the Hel Spit (5; Figure 10) formed in the coastal barrier environment. The lower level of the spit structures is covered by sandy-silty sediments of the Littorina Sea and Post-Littorina period (7; Figure 10), which are parallel stratified by sandy sediments.

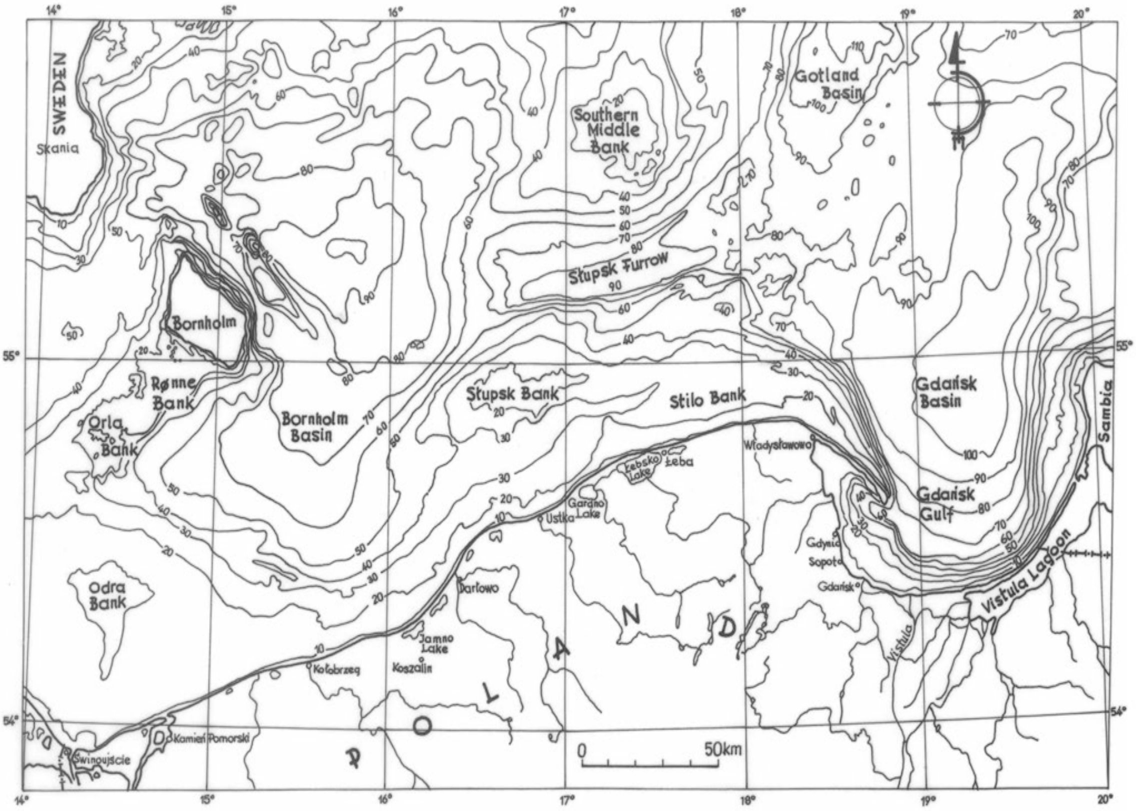


Figure 8. Bathymetric units of the Polish Baltic sea-bottom [1].

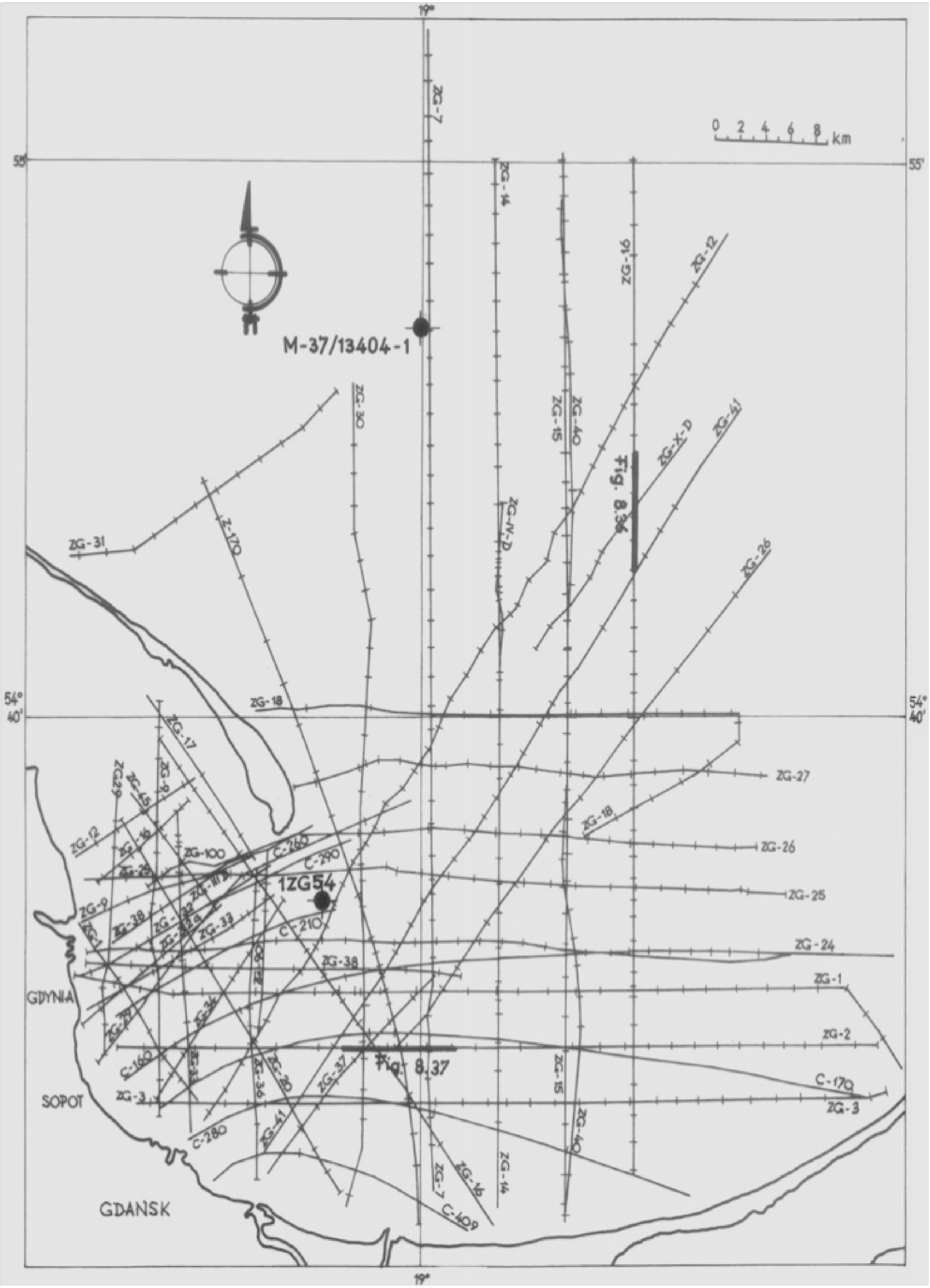
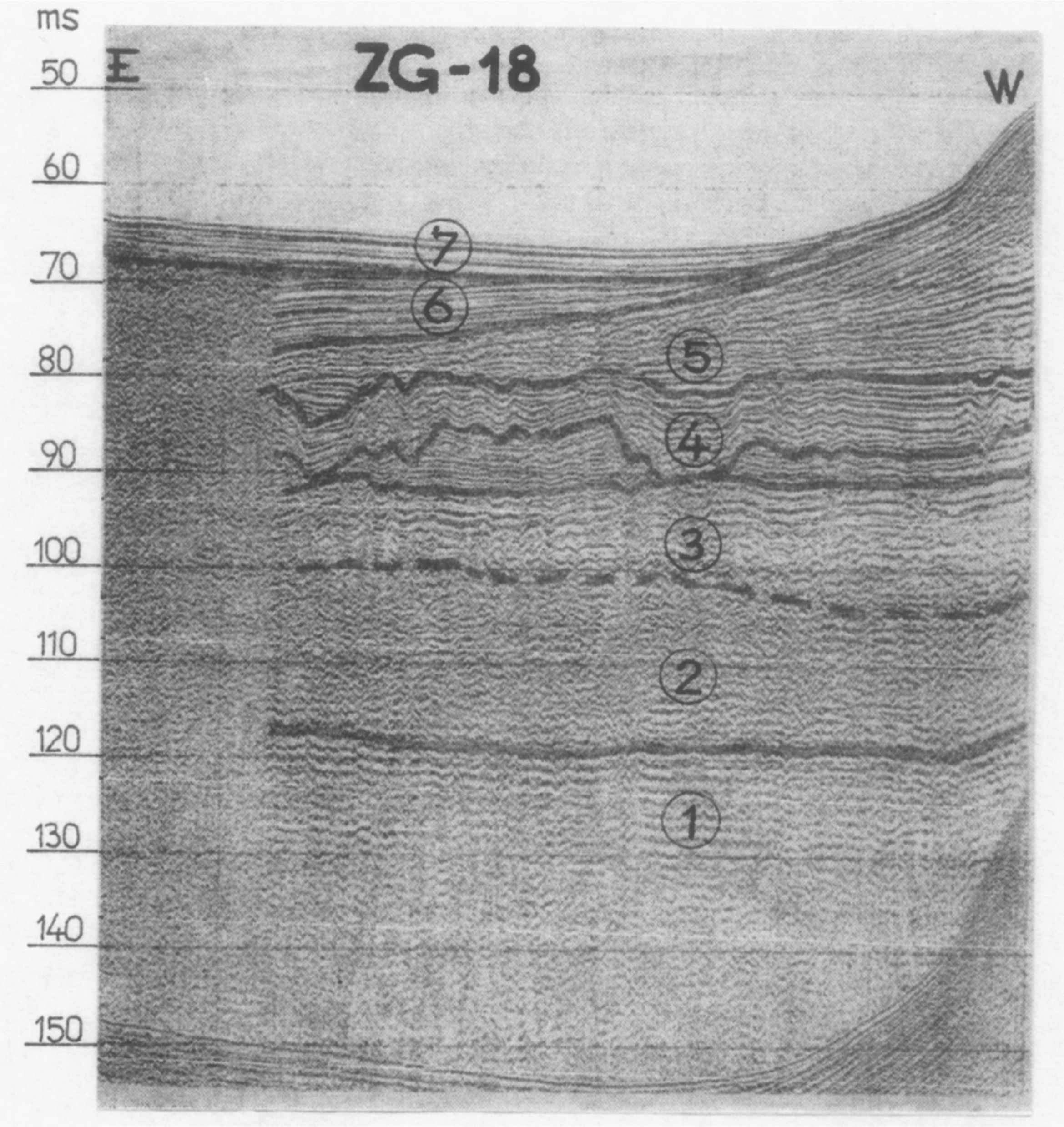


Figure 9. Overview map of the distribution and location of collected 2D seismic data within the Gulf of Gdańsk and Gdańsk Basin [1] 1ZG54-drilling core.



Two-way travel time depth (milliseconds) to ms. 1—Cretaceous deposits; 2—Vistula Glaciation tills of the Pleistocene; 3—Palaeodelta fluvial sends of the late Pleistocene; 4—late Pleistocene varve clays; 5—Hel Spit dystal parts of deposits of the Holocene; 6—Baltic different stages limnic and marine sediments of the early Holocene; 7—Littorina and Post-Littorina clays, silts and sands of the middle and late Holocene.

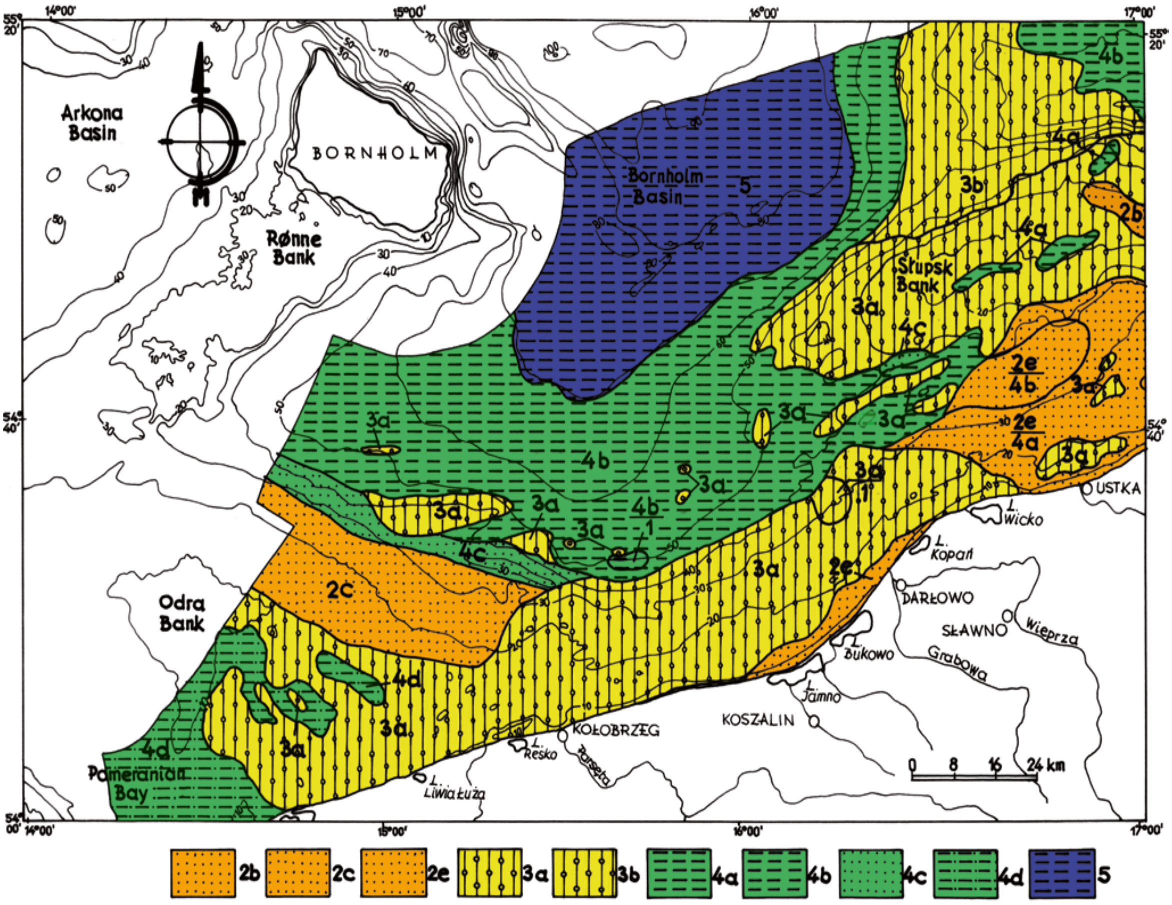
Figure 10. Seismo-acoustic cross-section in the area of the underwater slope of the Hel Spit. Seismic source—Boomer. Materials of the former Department of Geomorphology and Marine Geology of the Institute of Meteorology and Water Management in Gdynia [27].

5. Results

5.1. Analysis of geotechnical conditions on the area of the Polish Baltic Sea

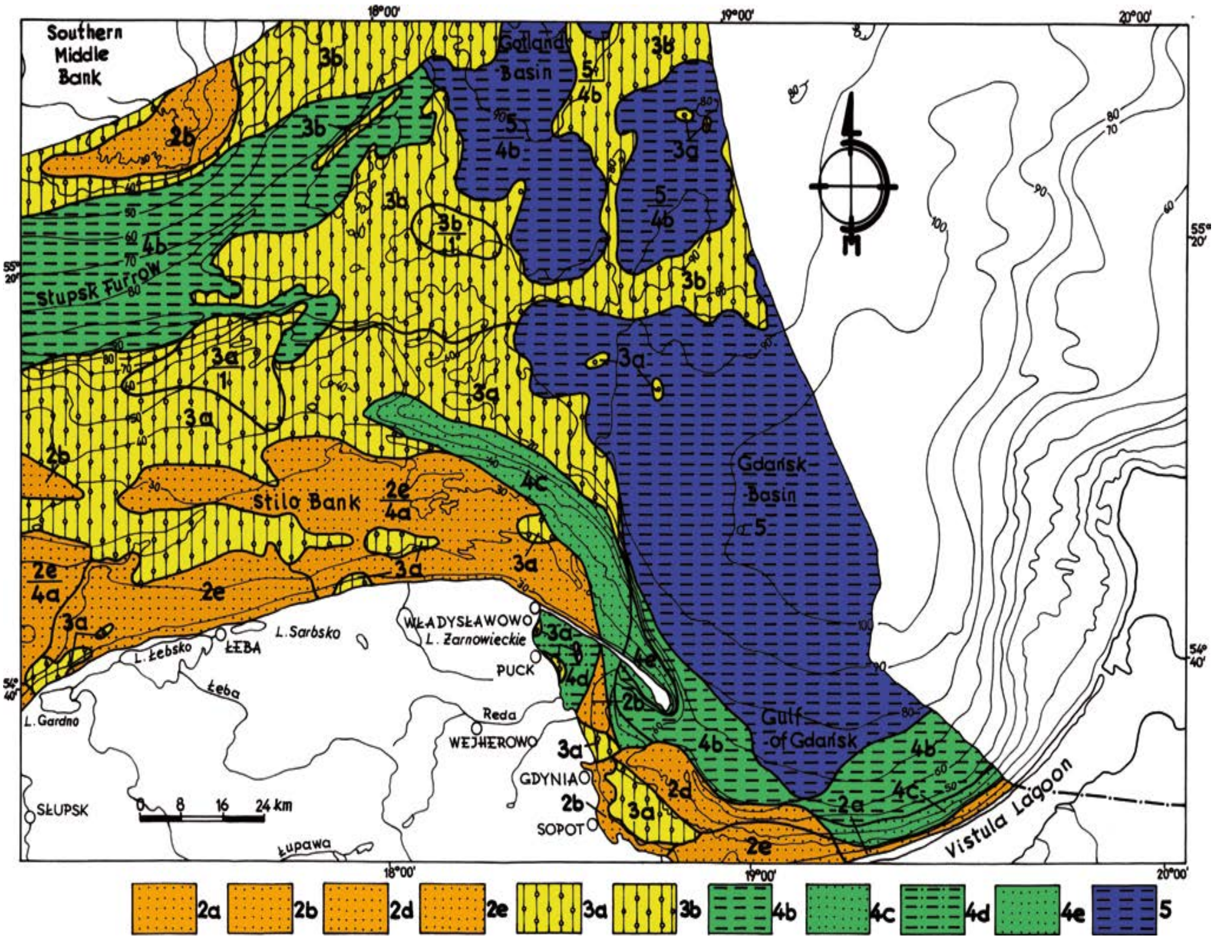
The author has previously elaborated and published geotechnical characteristics related to the Polish Baltic sea-bottom, the substrate at a depth of 10 and 20 m below the seabed [1,28–30]. For comparison with the obtained results related to the geotechnical conditions that prevail at a depth of 30 m below the seabed, geotechnical maps made for the higher levels of the Baltic sea-bottom (Figures 11–18) are also presented here. On the basis of these maps, spatial analysis of various geotechnical types of the deposits and rocks occurring on the area of the Polish Baltic Sea was possible. Figures 11 and 12 show the geotechnical conditions that occur at the bottom of the Polish Baltic Sea. Different geotechnical types of the seabed sediments can be distinguished here. It should be noted that very favourable soils for marine constructions do not occur on the analyzed seabed. This type of soil is often found directly on the sea-bottom of the northern and north-eastern parts of the Baltic Sea. The soils of this type are considered to be a *very favourable sea-bottom for marine constructions* and geotechnically the best fragment of the Baltic sea-bottom (unit no. 1). This type consists of rocky soils with very high values of compression strength of over 1MPa [1,28–30].

The share of *very favourable soil substrate for marine conditions* increases here, showing very high values of geotechnical parameters, that is Rc considered here as a characteristic indicator of the resistance for vertical pressure on the soil substrate. For example, the Rc index for a substrate built of igneous rocks has a value over 200 MPa. In addition, rocky soils in comparison with unconsolidated soils have also better values of other parameters such as specific gravity, Poisson’s ratio or Yang’s module. Of course, rocky soils have also their negative properties, e.g. high ability to the erosion processes of soft limestones or mudstones, metamorphic rocks with clearly marked slate textures and high sloping of layers, or considerable thickness of the weathered layer. But generally in terms of strength as a soil substrate they have much better geotechnical parameters than unconsolidated soils.



It should be added that the rocky soils not occurring in the Polish part on the Baltic seabad. 2b—Late Pleistocene glacio-fluvial gravelly-sandy deposits; 2c—Late Pleistocene fluvial gravelly-sandy deposits; 2e—Littorina and Post-Littorina gravels and sands of the middle and late Holocene; 2e/4a—Littorina and Post-Littorina gravels and sands of the middle and late Holocene on ice-marginal lacustrine silts and clays of the late Pleistocene; 2e/4b—Littorina and Post-Littorina gravels and sands of the middle and late Holocene on different stages of the Baltic silts and clays of the late Pleistocene and early Holocene; 3a—Pleistocene Wartanian Glaciation tills or older glaciations; 3a/1—Pleistocene Wartanian Glaciation tills or older glaciations on Cretaceous rocky soils; 3b—Pleistocene Vistula Glaciation subaquatic glacial tills; 4a—Late Pleistocene ice-marginal lacustrine silts and clays; 4b—Late Pleistocene and early Holocene different stages of the Baltic silts and clays; 4b/1—Late Pleistocene and early Holocene different stages of the Baltic silts and clays on Cretaceous rocky soils; 4c—Late Pleistocene Baltic Ice Lake aeolian sandy deposits; 4d—Early Holocene mudy deposits and silty sands of lacustrine origin; 5—Middle and late Holocene Littorina and Post-Littorina clayey, silty, mudy deposits and organic muds.

Figure 11. Soil types at the sea-bottom in the western part of the Polish Baltic [1,28].



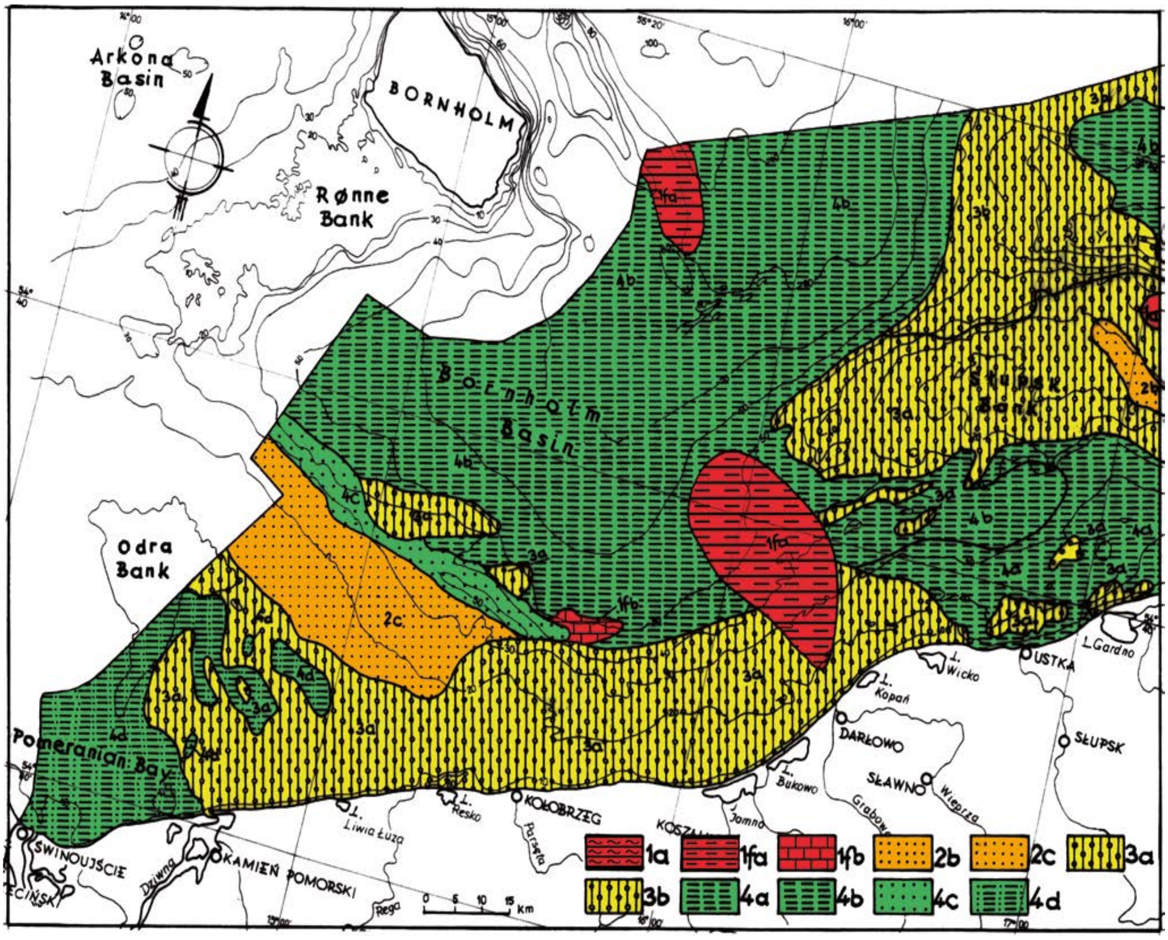
It should be added that the rocky soils not occuring in the Polish part on the Baltic seabad. 2a—Pleistocene Eemian marine gravels and sands; 2b—Late Pleistocene glacio-fluvial gravels and sands; 2d—Late Pleistocene fluvial gravels and sands; 2e—Middle and late Holocene Littorina and Post-Littorina marine gravels and sands; 2e/4a—Middle and late Holocene Littorina and Post-Littorina marine gravels and sands on late Pleistocene ice-marginal lake silty-clayey deposits 3a—Pleistocene Wartanian Glaciation glacial tills or older glaciations; 3a/1—Pleistocene Wartanian Glaciation glacial tills or older glaciations on Silurian rocks; 3b—Pleistocene Vistula Glaciation subaquatic glacial tills 3b/1—Pleistocene Vistula Glaciation subaquatic glacial tills on Silurian rocks; 4b—Late Pleistocene and early Holocene Baltic silts and clays of different stages; 4c—Late Pleistocene Baltic Ice Lake aeolian sands; 4d—Early Holocene lacustrine muds and silty sands; 4e—Late Holocene marine and aeolian sands; 5—Middle and late Holocene Littorina and Post-Littorina clays, silts, muds and organic muds; 5/4b—Middle and late Holocene Littorina and Post-Littorina clays, silts, muds and organic muds on late Pleistocene and early Holocene silty-clayey deposits of different stages of the Baltic.

Figure 12. Soil types at the sea-bottom in the eastern part of the Polish Baltic [1,28].

However, a *favourable sea-bottom for marine constructions* can be distinguished here (Figures 11 and 12). There are seabed soils (unit no. 2) that reach high values (Table 1, [28], See Supplementary) of shear strength τf (300–1000 kPa). In this case, the oedometric original bulk modulus Mo ranges from 80–200 MPa [1,28]. A distinction should be made here between non-cohesive soils of different origins and ages (Figures 11 and 12). *Sufficient sea-bottom for marine* *constructions* include soils (unit no. 3) reaching average values (Table 1) of shear strength τf (100–300 kPa), and the oedometric original bulk modulus Mo ranging from 40–80 MPa [1,28]. This includes cohesive soils like glacial tills from the Vistula Glaciation and the Wartanian Glaciation. Sometimes the till of older glaciations may occur. *Unfavourable sea-bottom for marine constructions* consists of seabed soils (unit 4) that have low values (Table 1) of shear strength τf (50–100 kPa). The oedometric original bulk modulus Mo ranges from 5 to 15 MPa. A distinction should be made here between cohesive and non-cohesive deposits represented by glacio-lacustrine, aeolian, glacio-marine and lacustrine soils, belonging to the late Pleistocene and early Holocene (Figures 11 and 12). *Very unfavourable sea-bottom for marine constructions* is seabed soils (Unit 5) that reach very low values (Table 1) of shear strength τf (less than 50 kPa). The oedometric original bulk modulus Mo reaches a values lower than 5 MPa [1,28]. These include marine cohesive deposits formed during the middle and late Holocene, and which have a very bad geotechnical parameters (Table 1). These soils consist of muds, clay and organic silts formed during the Mastogloii Sea, Littorina Sea, Limnaea Sea and Mya Sea. The spatial analysis of the western part of the Polish Baltic seabed showed that the largest surface is occupied by soils of unit number 3 as *sufficient sea-bottom for marine constructions*. This unit is represented by glacial tills of the Wartanian Glaciation. The second largest area is the surface associated with the unit number 4 as *unfavorable sea-bottom for marine constructions.* There are soils in the form of a cohesive and non-cohesive deposits represented by glacio-lacustrine, aeolian, glacio-marine and lacustrine soils, belonging to the late Pleistocene and early Holocene (Figure 11). However, the area associated with the soils of unit number 5 as a very unfavourable sea-bottom for marine constructions is located in the region of the Bornholm Basin (Figure 11).

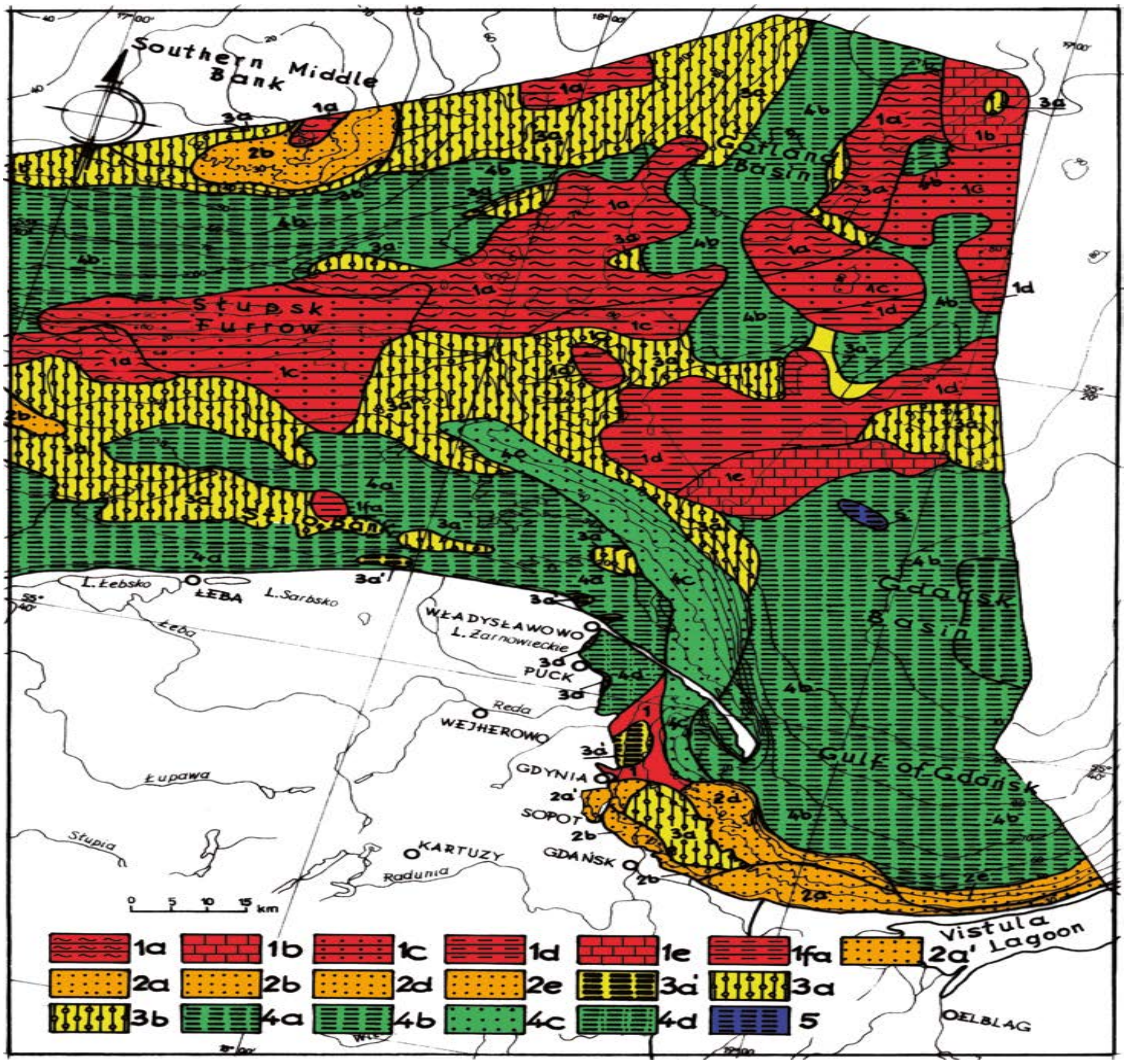
Similarly to the western part of the Polish Baltic Sea, the eastern part consists primarily of unit 3 deposits, which constitute *sufficient substrate for marine constructions*. These include glacial tills of the Wartanian Glaciation (Figure 12) and in the northern part of the Vistula Glaciation. The second largest area is covered with soils associated with the unit number 5 as *very unfavorable sea-bottom for marine constructions*, where include marine cohesive deposits formed during the middle and late Holocene. These soils consist of muds, clay and organic silts formed during the Mastogloii Sea, Littorina Sea, Limnaea Sea and Mya Sea (Figure 12). Near the sea shore there is an area belonging to unit number 2 as favourable sea-bottom for marine constructions. One can distinguish non-cohesive deposits represented by sands and gravels with high geotechnical parameters (Table 1) formed during the Mastogloia Sea, Littorina Sea and Post-Littorina period (Figure 12).

It should be noted that geotechnical conditions at a depth of 10 m below the seabed are also diverse (Figures 13 and 14). In the western part of the Polish Baltic, outcrops of Silurian and Cretaceous rocks appear in the analyzed soil substrate. This substrate as a *very favourable for marine constructions* has very high values of geotechnical parameters (Table 2, [29], See Supplementary). The Silurian outcrops are built from clayey shales but the Cretaceous outcrops from siltstones, claystones and limestones (Figure 13). The largest surface of the western part of the Polish Baltic is covered by substrate that is *unfavorable for marine constructions*, represented by glacio-lacustrine, aeolian, glacio-marine and lacustrine soils, belonging to the late Pleistocene and early Holocene (Figure 13). A fairly large surface here is *sufficient substrate for marine constructions* consisting of glacial tills of the Wartanian Glaciation (Figure 13).



1a—Silurian clayey shales; 1fa—Cretaceous siltstones and claystones; 1fb—Cretaceous limestones; 2b—Late Pleistocene glacio-fluvial gravels and sands; 2c—Late Pleistocene fluvial gravelly-sandy deposits; 3a—Pleistocene Wartanian Glaciation tills; 3b—Pleistocene Vistula Glaciation subaquatic glacial tills; 4a—Late Pleistocene ice-marginal lake silts and clays; 4b—Late Pleistocene and early Holocene Baltic silts and clays of different stages; 4c—Late Pleistocene Baltic Ice Lake aeolian sands; 4d—Early Holocene lacustrine muds and silty sands.

Figure 13. Soil substrate in the western part of the Polish Baltic at a depth of 10 m below sea-bottom [1,29].

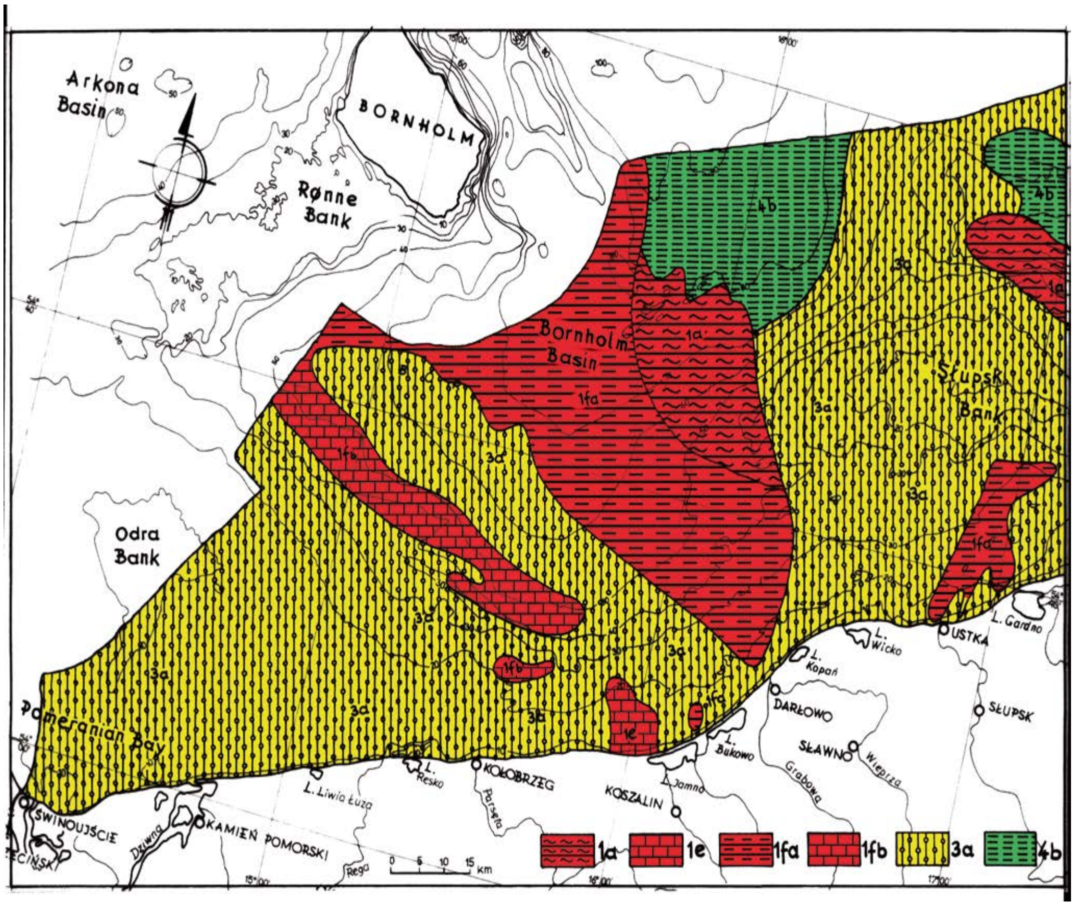


1a—Silurian clayey shales;1b—Devonian limestones; 1c—Permian sandstones; 1d—Triassic siltstones and claystones; 1e—Jurassic limestones; 1fa—Cretaceous siltstones and claystones; *2a'*—Neogene sands; 2a—Pleistocene Eemian marine gravelly-sandy deposits; 2b—Late Pleistocene glacio-fluvial gravels and sands; 2d—Late Pleistocene and early Holocene fluvial gravelly-sandy deposits; 2e—Middle and late Holocene Littorina and Post-Littorina marine gravels and sands; 3a' —Neogene silts and clays; 3a—Pleistocene Wartanian Glaciation tills; 3b—Pleistocene Vistula Glaciation subaquatic glacial tills; 4a—Late Pleistocene silty-clayey deposits; 4b—Late Pleistocene and early Holocene Baltic different stages silts and clays; 4c—Late Pleistocene Baltic Ice Lake aeolian sands; 4d—Early Holocene lacustrine muds and silty sands; 5—Middle and late Holocene Littorina and Post-Littorina clays, silts, muds and organic muds.

Figure 14. Soil substrate in the eastern part of the Polish Baltic at a depth of 10 m below sea-bottom [1,29].

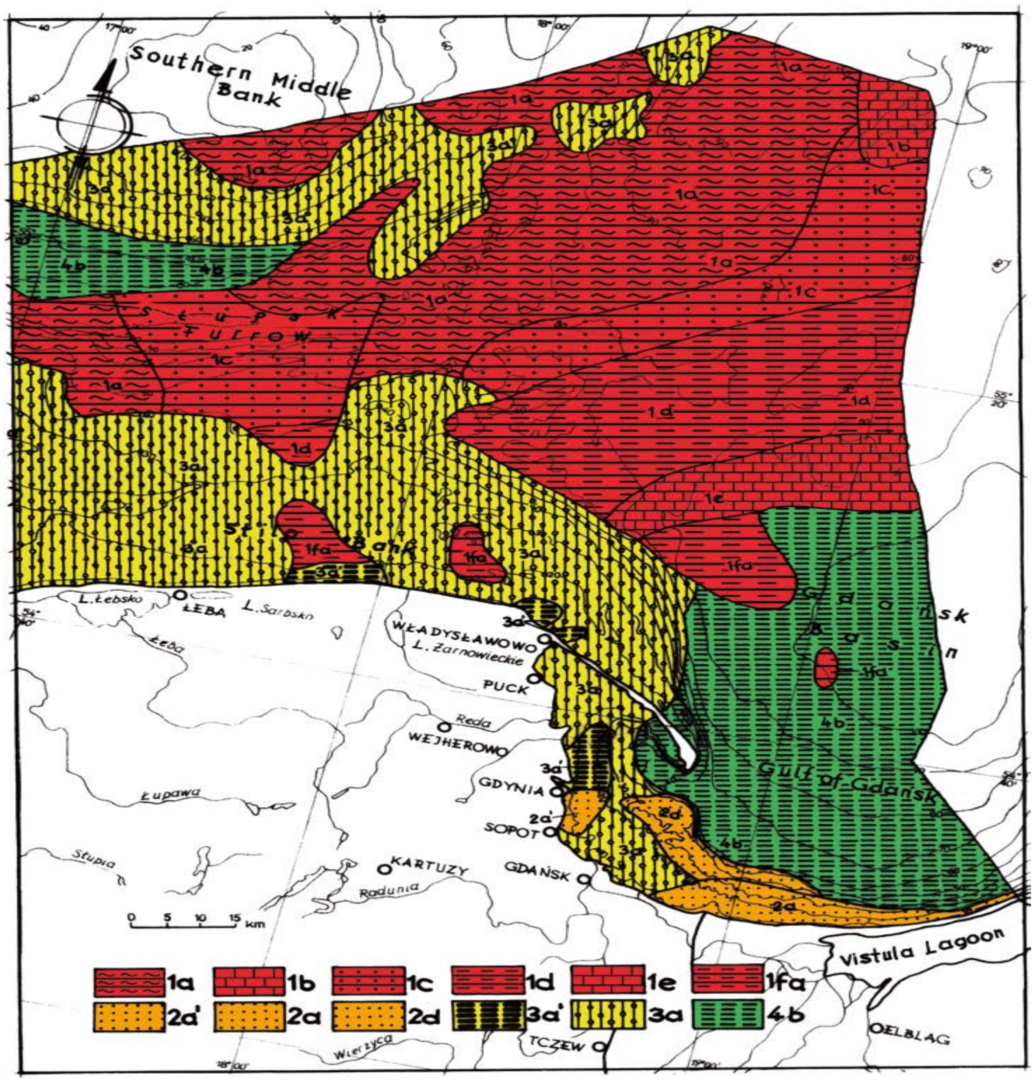
On the other hand, in the eastern part of the Polish Baltic, *very favourable substrate for marine constructions* constitutes a significant share in the occupied area (Figure 14). There are outcrops of Silurian clayey shales, Devonian limestones, Permian sandstones, Triassic siltstones and claystones, Jurassic limestones and Cretaceous siltstones and claystones (Figure 14). A large surface is *unfavourable substrate for marine constructions* with low geotechnical parameters (Table 2), which is represented by glacio-lacustrine, aeolian, glacio-marine and lacustrine soils, belonging to the late Pleistocene and early Holocene (Figure 14).

It can be observed that the soil substrate at a depth of 20 m below the seabed differs from the one previously described (Figures 15 and 16). There are outcrops of Silurian clayey shales, Jurassic limestones, Cretaceous siltstones, claystones and limestones (Figure 15). A very large area constitutes *sufficent substrate for marine constructions*, composed of glacial tills of the Wartanian Glaciation and in the northern part of the glacial tills of the Vistula Glaciation (Figure 15). In the eastern part of the Polish Baltic, *very favorite substrate for marine constructions* definitely prevails. There are outcrops of Silurian shales, Devonian limestones, Permian sandstones, Triassic siltstones and claystones, Jurassic limestones and Cretaceous siltstones and claystones (Figure 16). The *sufficent substrate for marine constructions*, which is built from glacial tills of the Wartanian Glaciation, still has a significant share (Figure 16). It can be observed that both in the western and eastern part of the Polish Baltic a *very unfavourable substrate for marine constructions* is absent (Figure 16).



1a—Silurian clayey slates; 1e—Jurassic limestones; 1fa—Cretaceous siltstones and claystones; 1fb—Createaceous limestones; 3a—Pleistocene Wartanian Glaciation tills; 4b—Late Pleistocene and early Holocene Baltic different stages silts and clays.

Figure 15. Soil substrate in the western part of the Polish Baltic at a depth of 20 m below sea-bottom [1,30].



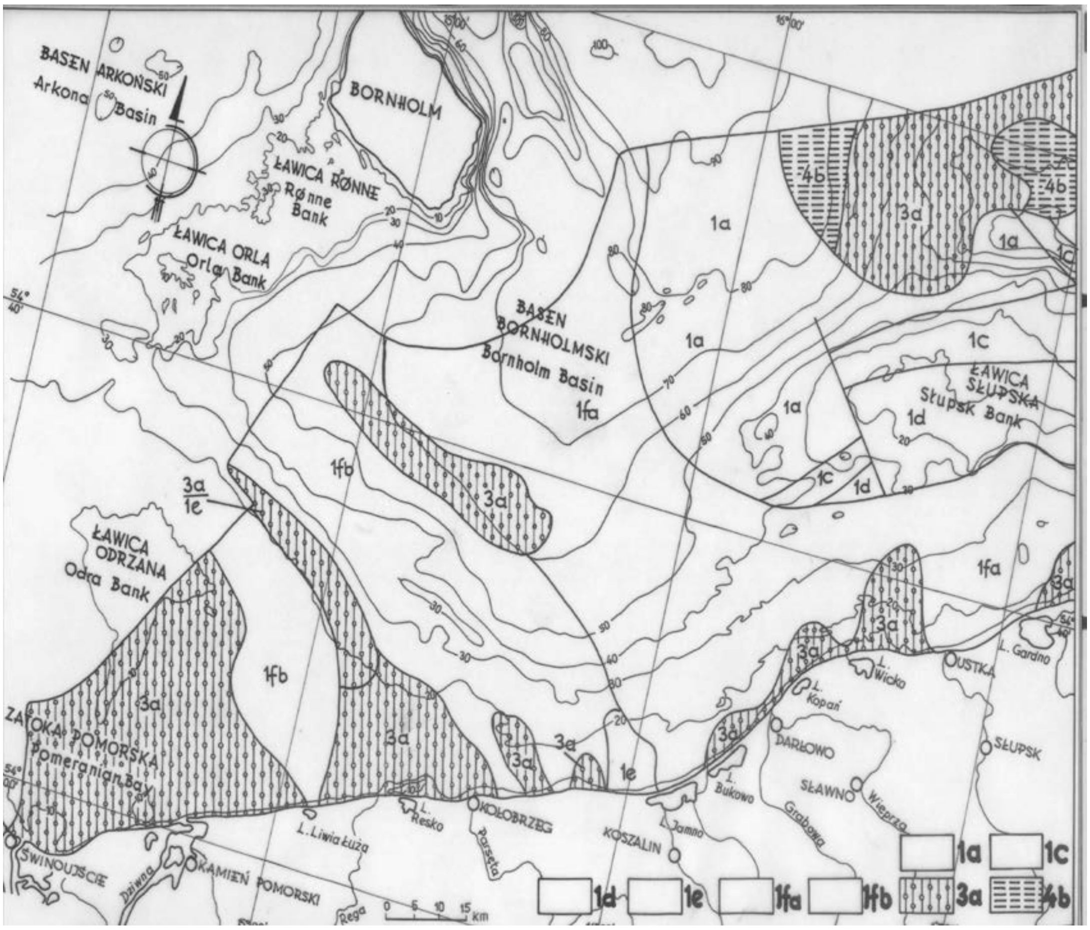
1a—Silurian clayey slates;1b—Devonian limestones; 1c—Permian sandstones; 1d—Triassic siltstones and claystones; 1e—Jurassic limestones; 1fa—Cretaceous siltstones and claystones; 2a'—Neogene sands; 2a—Pleistocene Eemian marine gravels and sands; 2d—Late Pleistocene and early Holocene fluvial gravelly-sandy deposits; 3a'—Neogene silts and clays; 3a—Pleistocene Wartanian Glaciation tills; 4b—Late Pleistocene and early Holocene Baltic different stages silts and clays.

Figure 16. Soil substrate in the eastern part of the Polish Baltic at a depth of 20 m below sea-bottom [1,30].

5.2. Geotechnical characteristics of the soil substrate at a depth of 30 m below sea-bottom

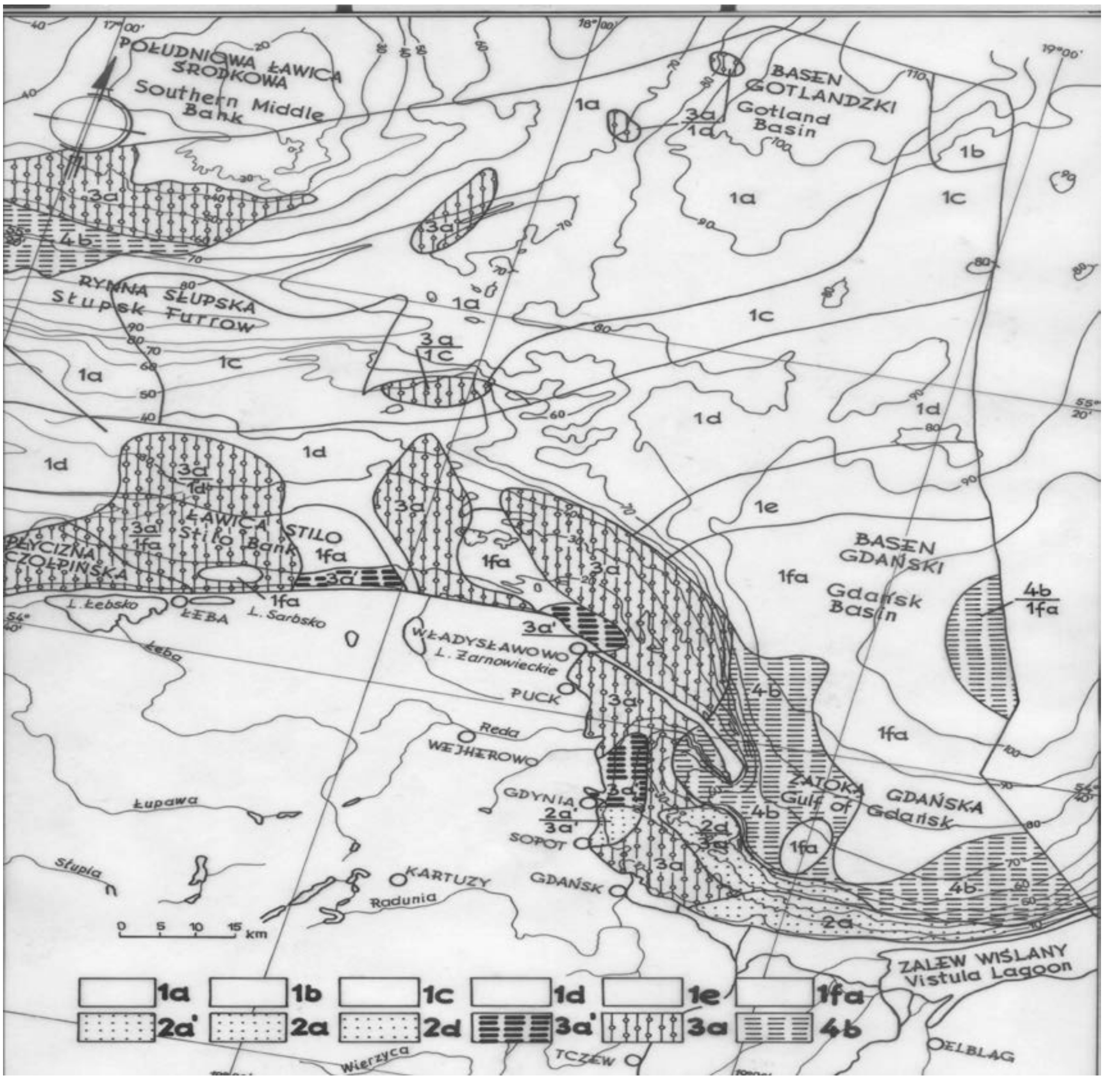
Seismic analysis of the geological and geotechnical conditions of the substrate situated at a depth of 30 m below the seabad contributed to the separation of the following geotechnical types (units) presented below:

Very favourable soil substrate for marine constructions, as already mentioned, rocky soils (Table 4, See Supplementary) with very high values of compression strength R_c (> 1 MPa) should also be included here (unit no. 1). In the western fragment of the Polish Baltic, the area of rocky soils in comparison with the soils occurring at a depth of 20 m below the seabed has increased even more—over 100% (Figures 15 and 17). West of Słupsk Bank, at a depth of 30 m below the sea-bottom, the area of Silurian clayey shales (sub-unit 1a) increased even more in comparison with the previous situation (Figures 15 and 17). To the south of the Silurian shale occurrence, significant areas of Permian sandstones and Triassic siltstones and claystones (Figure 17) are revealed at a depth of 30 m below the sea-bottom. The rocky outcrops of the Jurassic near the Jamno Lake (sub-unit 1e) represented by limestones. At Darłowo towards Bornholm there is a very large Cretaceous outcrop area (sub-unit 1fa) of medium compression strength siltstones of 20–40 MPa [31] and claystones, and at some points it has increased even further in sandstones (Figure 17). At the height of Kołobrzeg between the isobath 20 and 50 m and opposite the Liwia Łuża Lake the area of outcrops of Cretaceous rocks of considerable thickness (sub-unit 1fb), probably are built of limestones [32], which compression strength (Table 4) ranges from 10 to 100 MPa also significantly increased. The area of outcrops made of Cretaceous rocks is also increased at the level of Ustka (Figures 15 and 17) is built of siltstones and claystones (sub-unit 1fa) with compression strength (Table 4) from 20–60 MPa.



1a—Silurian clayey slates; 1c—Permian sandstones; 1d—Triassic siltstones and claystones; 1e—Jurassic limestones; 1fa—Cretaceous siltstones and claystones; 1fb—Cretaceous limestones; 3a—Pleistocene Wartanian Glaciation tills; 4b—Late Pleistocene and early Holocene Baltic different stages silts and clays.

Figure 17. Soil substrate in the western part of the Polish Baltic Sea at a depth of 30 m below sea-bottom.

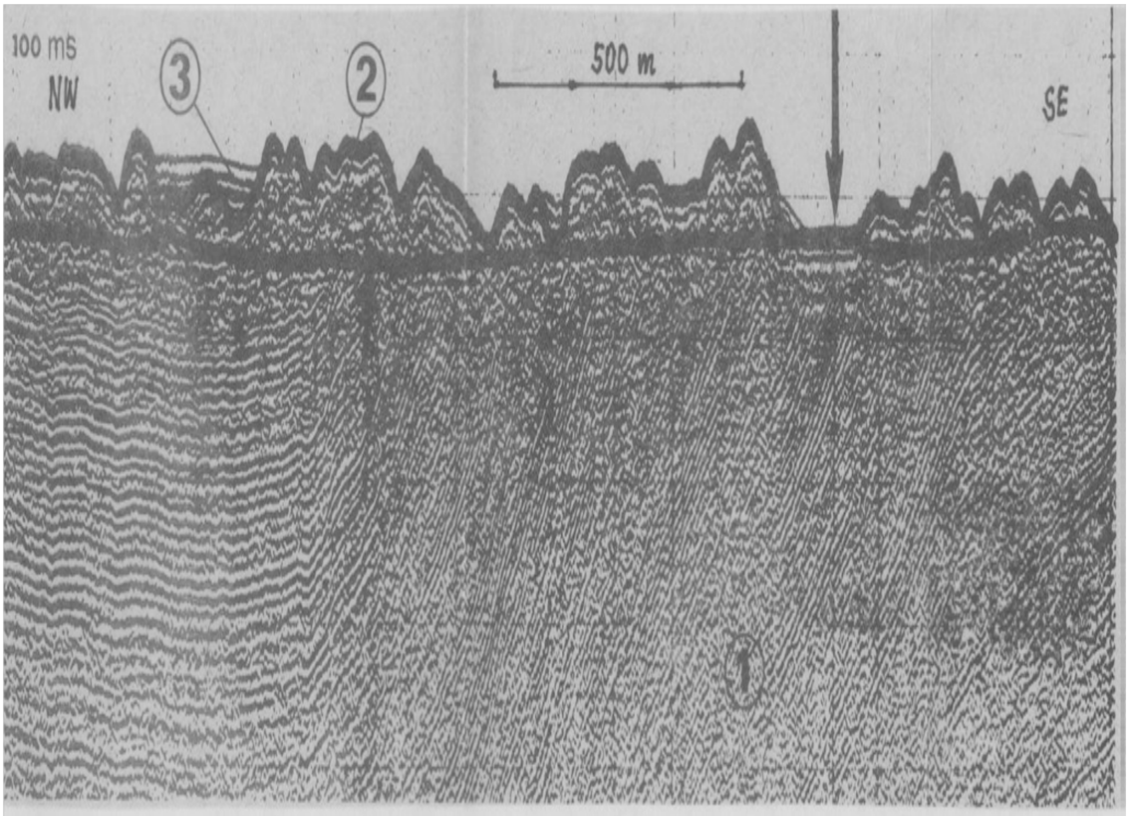


1a—Silurian clayey shales; 1b—Devonian limestones; 1c—Permian sandstones; 1d—Triassic siltstones and claystones; 1e—Jurassic limestones; 1fa—Cretaceous siltstones and claystones; 2a’ —Neogen fluvial sands; 2a—Pleistocene marine sands and gravels; 2d—Late Pleistocene and early Holocene fluvial sand and gravels; 3a’—Neogene silts and clays; 3a—Pleistocene Wartanian Glaciation tills; 4b—Late Pleistocene and early Holocene Baltic different stages silts and clays.

Figure 18. Soil substrate in the eastern part of the Polish Baltic at a depth of 30 m below sea-bottom.

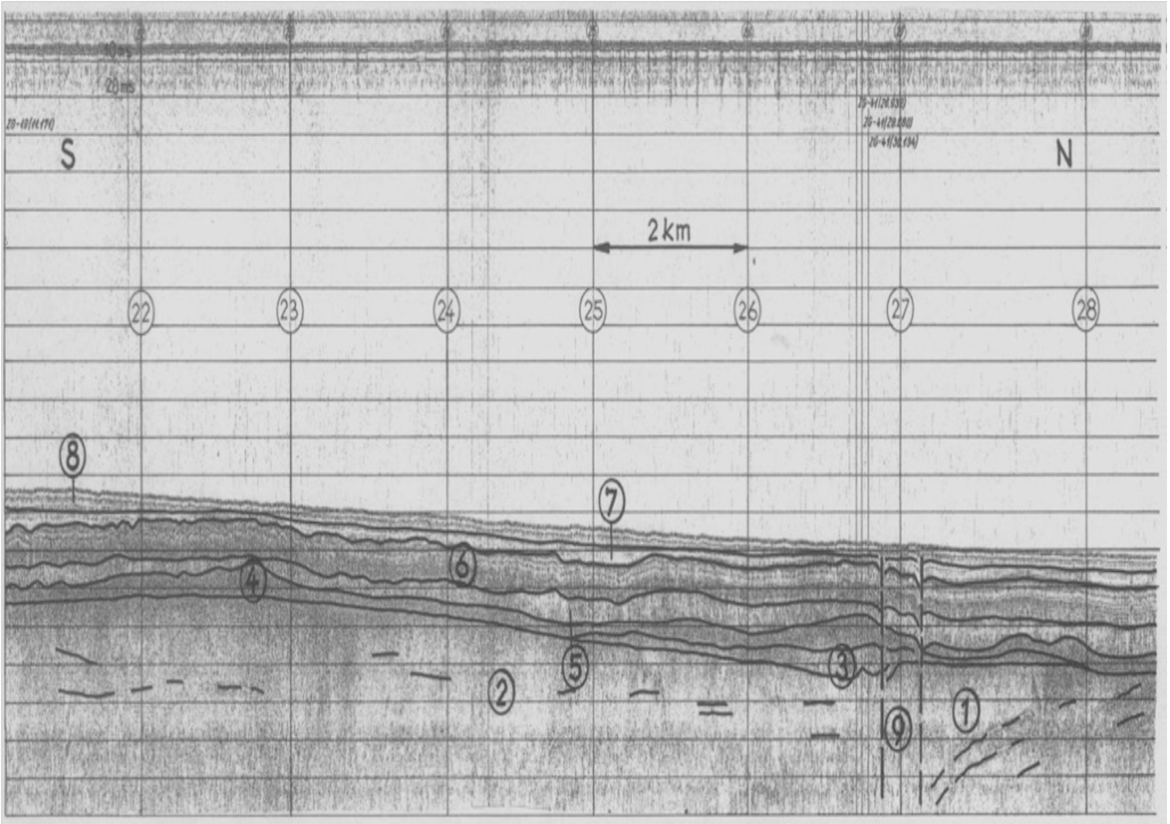
Compared to the sediments at the depth of 20 m below the sea-bottom, the area of the thicker Silurian clayey shales (sub-unit 1a), which occurs in many places in the eastern fragment of the Polish Baltic (Figure 18), in the southern fragment of the Gotland Basin, in the bridge area between the Gotland Basin and the Słupsk Furrow and in the southern part of the South Central Bank and the area to the east of it, has also increased significantly. The Silurian rock substrate is well represented in the seismo-acoustic cross-section (Figure 19) in the Słupsk Furrow area, where the folding structures of these rocks can be observed [33]. On the other hand, the surface of outcrops of Devonian rock (sub-unit 1b), which are represented by limestones of significant thicknesses, did not change in the south-eastern part of the Gotland Basin (Figures 16 and 18). These rocks have quite significant values of compression strength (Table 4). The analyzed area of outcrops of Permian rocks (sub-unit 1c), which are created from sandstones of small thickness (below 50 m), has been slightly enlarged. Rocks of this type (Table 4) have quite significant values of compression strength from 15 to 150 MPa.

In the bridge area between the Słupsk Furrow and the Gdańsk Basin there are Triassic outcrops (sub-unit 1d), which are built from siltstones and claystones of considerable thickness. Compared to the substrate, at a depth of 20 m below the sea-bottom (Figures 16 and 18) it appears at the height of the Żarnowieckie Lake and Łebsko Lake—a significant area of outcrops of these rocks. Southwards towards the Gdańsk Basin, the area of the outcrops of the Jurassic rocks (sub-unit 1e) represented by limestones and marls with not very large thicknesses only slightly increased. The seismo-acoustic cross-section made in the northern part of the Gdańsk Basin (Figure 20) shows the geological structure of the area with the contact zone of the rocks of the Jurassic and the Cretaceous with the tectonic fault marked there [1]. At a depth of 30 m below the sea-bottom, the Cretaceous outcrop area covering the area of the Gdańsk Basin and the Gulf of Gdańsk increases very significantly (Figures 16 and 18). The outcrops of Cretaceous rocks (sub-unit 1fa) are built from siltstones and claystones, sometimes carbonate and silica rocks of large thicknesses.



Two-way travel time depth (milliseconds) to ms. 1—Silurian clayey shales; 2—Pleistocene plastic clays; 3—Holocene semi-liquid muds.

Figure 19. Seismo-acoustic profile of the Słupsk Furrow area. Seismic source-Boomer. Materials of the former Department of Geomorphology and Marine Geology of the Institute of Meteorology and Water Management in Gdynia [33].



Two-way travel time depth (milliseconds) to ms. 1—Upper Jurassic siltstones; 2—Upper Createaceous-Campanian clayey marls; 3—Pleistocene lower glacial tills; 4—Pleistocene upper glacial tills; 5—Late Pleistocene glacio-lacustrine clays; 6—Late Pleistocene Baltic Ice Lake varved clays; 7—Early Holocene Yoldia Sea and Ancylus Lake clayey-silty deposits; 8—Middle and late Holocene Littorina and Post-Littorina silts and organic muds; 9—tectonic faults.

Figure 20. Seismo-acoustic cross-section through the Gdańsk Basin. Seismic source—Boomer. Materials of the former Department of Geomorphology and Marine Geology of the Institute of Meteorology and Water Management in Gdynia [1].

Favourable soil substrate for marine constructions similarly as in the previous situation, where the soil substrate located at the depth of 20 m below the sea-bottom, unconsolidated deposits (unit 2) represented by un-cohesive soils of Neogene, Pleistocene and Holocene age of fluvial and marine genesis, which reach (Table 4) high values of shear strength τf (300–1000 kPa). In the western part of the Polish Baltic Sea there are no such soils in the analyzed substrate (Figure 17). In the eastern fragment of the Polish Baltic (Figure 18), the soil substrate that is *favourable for marine constructions* is represented by Neogene's fluvial sands of low thickness (sub-unit 2a'), marine sands and gravels from the Eemian Interglacial (sub-unit 2a) and good geotechnical parameters (Table 4) located opposite the Vistula delta. Subsequent division (sub-unit 2d) is represented by fluvial gravels and sands of the Vistula paleodelta occurring at the level of Gdynia and Sopot (Figure 18) of low thickness (< 5 m), which overlie the Wartanian Glaciation tills.

Sufficient soil substrate for marine constructions similarly as at the depth of 20 m below the seabed are unconsolidated deposits (unit no. 3) built with cohesive soils of Neogene and Pleistocene age, lacustrine and glacial origins, which have (Table 4) quite high values of shear strength τf (100–

300 kPa). In the western fragment of the Polish Baltic, at a depth of 30 m below the sea-bottom, similarly as at the depth of 20 m, significant areas located opposite Kamień Pomorski and Świnoujście (Figure 17) are associated with the Wartanian Glaciation tills (sub-unit 3a). The glaciogenic sediments of this type have been found to a depth of 30 m in the area of Słupsk Bank [34]. At the discussed level, the soils also occur at the Resko Lake (Figure 17) height and north-west of this place, they have a small thickness, in places where they overlie the limestone of the Jurassic (sub-unit 3a/1e). In the coastal zone, to the isobath of 20 m (sometimes crossing it) from Kołobrzeg to the level of the Gardno Lake the Wartanian Glaciation tills occur in the form of patches (Figure 17). To the east of the Bornholm Basin, the area of the glacial tills in question is slightly reduced.

In the eastern fragment of the Polish Baltic, lacustrine silts and clays of Neogene age (subunit 3a') located near Karwia, Władysławowo and Kępa Oksywska (Figure 18) are still sufficient for marine constructions. In the proximity of Gotland Deep the Wartanian glacial tills occur in form of patches of a low thickness and overlie the Silurian clayey shales (sub-unit 3a/1a). The largest areas of this division occur north of the Słupsk Furrow and at the level of the Żarnowieckie Lake to the Hel Peninsula. At the level of Łeba, the glacial tills of this glaciation (Figure 18) have a small thickness and lie in the south on the siltstones and claystones of Cretaceous (sub-unit 3a/1fa) and more to the north on the siltstones and claystones of Triassic (sub-unit 3a/1d). Glacial tills of this glacial stage are also found in the Gdańsk region.

Unfavourable soil substrate for marine constructions similarly like at the depth of 20 m below the sea-bottom consist of unconsolidated deposits (unit no. 4) represented only by cohesive deposits of the late Pleistocene and early Holocene age of glacio-marine and lacustrine genesis, which have low values of shear strength τf (50–100 kPa). In the western part of the Polish Baltic, the clays and silts (sub-unit 4b) of the Baltic Ice Lake, the Yoldia Sea and Ancylus Lake created in the late Pleistocene and early Holocene occur. These deposits occur only in fragments of the north-eastern part of the Bornholm Basin and the north-western slope of the Słupsk Furrow (Figure 17). In the eastern fragment of the Polish Baltic, the silts and clays of the Baltic Ice Lake, the Yoldia Sea and the Ancylus Lake of the late Pleistocene and the early Holocene (sub-unit 4b), which occur in a small area of the northern slope of the Słupsk Furrow, are also unfavourable soils for constructions. The area of occurrence of these geological units in the terrain of the Gdańsk Basin and the Gulf of Gdańsk (Figure 18), which is limited only to the western parts of these areas, has decreased very significantly. On the other hand, the described outcrops located slightly to the east of the 100 m isobath have a small thickness and are located on siltstones and claystones of Cretaceous (sub-unit 4b/1fa). However, it should be noted that such soils in both the western and eastern parts of the Polish Baltic do not occur.

4. Conclusions

Seismo-acoustic surveys are very important method of geotechnical recognition of the seabed, due to their large coverage and the accuracy that allows to determine the limits of the soil occurring there, characterized by certain physical and mechanical properties. Determination of the seismic velocity in a given substrate gives insight into the volumetric density being a significant geotechnical parameter of the analyzed soils. Furthermore seismo-acoustic surveys of the seabed allow determination the thickness of the analysed geological strata, which constitutes a basis for design and development of selected marine constructions. The seismo-acoustic surveys of seabed are also of great importance for the detection of tectonic faults especially those where contemporary displacements of geological layers may pose a hazard the foundations of existing marine constructions. The seismo-acoustic, engineering-geological surveys which were carried out in the Polish sector of the Baltic Sea have provided a basis for the geotechnical classification of the seabed (Figures 11 and 12) and recognition of geotechnical conditions occurring at the depths of 10 m, 20 m and 30 m below the seabed (Figures 13–18). These results may be of great value for offshore design and construction of exploration and production platforms, oil and gas pipelines or windfarms.

On the basis of seismic surveys, detailed analyses of the Baltic geological maps in the scale 1:200,000, results of numerous engineering-geological and geotechnical research of northern Poland or the Polish Baltic coast and selected sea-bottom fragments, the following geotechnical types of the Polish Baltic seabed have been specified:

Very favourable soil substrate for marine constructions consist of the best geotechnical soils (unit 1), which are represented by consolidated soils (Tables 2–4, See Supplementary) with very high values of compression strength R_c (> 1 MPa). On the bottom of the Polish Baltic there are no such areas. At the level of 10 m below the sea-bottom, one should list (Figures 13 and 14) Silurian clayey shales (1a), Devonian limestones, Permian sandstones (1c), Triassic siltstones and claystones (1d), Jurassic limestones (1e), Cretaceous siltstones and claystones (1fa) and limestones (1fb). The sediments listed above have considerable thicknesses. At the level of 20 m below the sea-bottom, the same rocky soils with very high compression strength values (Table 3) and even more spreading than before (Figures 15 and 16) also have significant thicknesses. It should be noted that at the level of 30 m below the sea-bottom, the area of outcrops of rocky soils has significantly increased. In the area of the western fragment of the Polish Baltic additional Permian sandstone and Triassic siltstone and claystone outcrop (Figure 17).

Favourable soil substrate for marine constructions (Unit 2) in the area of the seabed is represented by unconsolidated and non-cohesive soil (Figures 11 and 12) of glaciofluvial, fluvial and marine genesis, created in Pleistocene and Holocene age. They have high values (Table 1) of shear strength τf (300–1000 kPa) and high values of oedometric original bulk modulus Mo (80–200 MPa). At a level of 10 m below the sea-bottom (Figures 13 and 14) there are sandy Neogene deposits (2a’), sands and gravels of the Eemian Interglacial (2a), sands and gravels of various origins (2b–e), of late Pleistocene, early, middle and late Holocene age. The thickness of the soil varies from 5 to more than 10 m. At a level of 20 m below the sea-bottom, only some non-cohesive soils (Figures 15 and 16) represented by Neogene sands (2a’), sandy-gravelly deposits of the Eemian Interglacial (2a), late Pleistocene and early Holocene sands and gravel (2d) with a thickness of between 5 and 10 m are found. At a level of 30 m below the sea-bottom only a few types of non-cohesive soils (Figures 17 and 18) built with sandy-gravelly deposits of the Eemian Interglacial (2a), sandy-gravelly deposits of late Pleistocene and early Holocene of the Vistula paleodelta (2d) of low thickness are found.

Sufficient soil substrate for marine constructions in the area of the seabed (unit no. 3) is represented by unconsolidated deposits such as cohesive soils (Figures 11 and 12), of Pleistocene age, and glacial origin, which have quite high values (Table 1) of shear strength τf (100–300 kPa) and quite high values of oedometric original bulk modulus Mo (40–80 MPa). At a level of 10 m below the sea-bottom (Figures 13 and 14), Neogene silts and clays (3a’), Wartanian glacial tills (3a) have a thickness of 20 to 40 m, and in case of Vistula glacial deposits only 5 m should be mentioned. At a level of 20 m below the sea-bottom, only (Figures 15 and 16) Neogene silt and clay (3a’) and

Wartanian glacial till (3a) with a thickness of 10–30 m are found. At a depth of 30 m below the seabed, only (Figures 17 and 18) Neogene silt and clay (3a') and Wartanian glacial till (3a) occur.

Unfavourable soil substrate for marine constructions in the area of the seabed (unit no. 4) is represented by unconsolidated cohesive and non-cohesive soils (Figures 11 and 12), ice marginal lake, aeolian, glacio-marine and lacustrine origins, created in the late Pleistocene and early Holocene, have (Table 1) small values of shear strength τf (50–100 kPa) and small values of oedometric original bulk modulus Mo (5–40 MPa). At a level of 10 m below the sea-bottom (Figures 13 and 14) late Pleistocene silt and clay (4a), late Pleistocene and early Holocene silt and clay (4b), late Pleistocene sands (4c), early Holocene silt and sand (4d) with a thickness of 5–10 m are found. At a level of 20 m below the sea-bottom (Figures 15 and 16) only silt and clay of late Pleistocene and early Holocene (4b) with a thickness of approximately 5 m are found. At a level of 30 m below the sea-bottom (Figures 17 and 18) only late Pleistocene and early Holocene silts and clays (4b) which are formed during the Baltic Ice Lake, Yoldia Sea and the Ancylus Lake period occur. In the area of the Gdańsk Basin, in the zone of the 100 m isobaths (Figure 18), the soils have a small thickness (<5 m) and overlie the clastic rocks of the upper Cretaceous.

Very unfavourable soil substrate for marine constructions (unit no. 5) is represented by unconsolidated deposits of middle and late Holocene cohesive soils (Figures 11 and 12) have a very low (Table 1) shear strength τf (<50 kPa) and very low values of the oedometric original bulk modulus Mo (<5 MPa). At a level of 10 m below the sea-bottom (Figures 13 and 14), clay, silt and organic mud from the middle and late Holocene (5) occur. They occur only in the eastern fragment of the Polish Baltic (Figure 14) and reach a thickness of up to 5 m. At a level of 20 m and 30 m below the sea-bottom, the following soil substrate do not occurs.

Conflict of interest

All authors declare no conflicts of interest in this paper.

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