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Geotechnical Investigations during Construction of the Nuclear Power Plant at Żarnowiec

1. Introduction

Various types of geotechnical investigations have been carried out for several years on the site of the construction of the nuclear power plant at Żarnowiec, located about 70 km from Gdańsk (Fig. 1).

The investigations were conducted by specialized Polish and Russian enterprises, for example "Geoprojekt" Gdańsk and "LEOTAP" Leningrad in cooperation with the Department of Geotechnology of the Hydro-Engineering Faculty of Gdańsk Technical University. Recently, together with representatives of "TRACTEBEL" Power Engineering Division from Belgium additional series of measurements were carried out. In Fig. 1 the location of the Żarnowiec Nuclear Power Plant is presented, Fig. 2 shows the layout of the main constructions. The paper gives a short presentation of the investigations and selected results of field and laboratory research.

2. Objectives and Scope of Geotechnical Investigations

As with the construction of all non-typical objects, which this power plant certainly is the geotechnical investigations programme embraced the optimum range of research available to us to determine all possible parameters of the substratum and its reaction to anticipated combinations of forces. The site of the Żarnowiec Nuclear Power Plant is one of the few areas in Poland which have been investigated with respect to safe construction of nuclear power plants. The following tests of the substratum were carried out at Żarnowiec:

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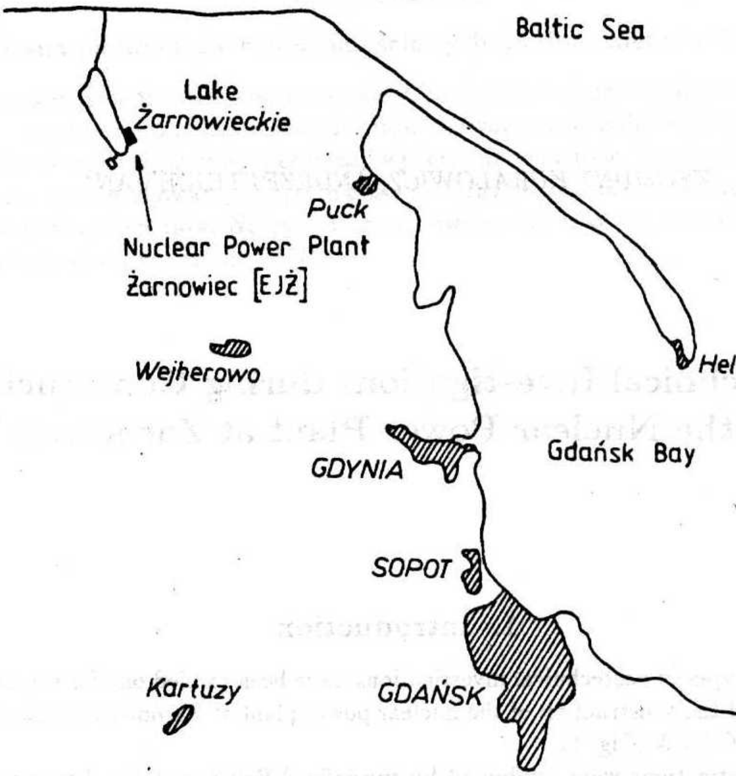

Fig. 1. Localization of Żarnowiec nuclear power plant

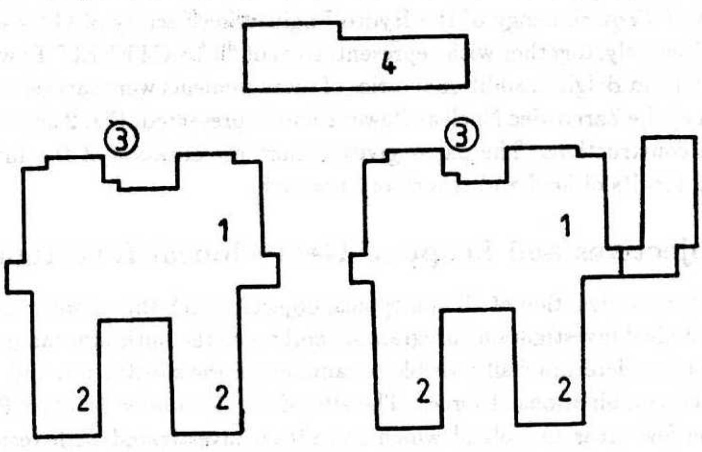

Fig. 2. Main building of the nuclear power plant
1) Reactor House Nos. 1 and 2, 2) Generators Nos. 1, 2, 3, 4, 465 MW each, 3) Ventilation shafts Nos. 1 and 2, 4) Waste deposits building

- basic deep pilot investigations,
- local deep investigations,
- local investigations of the near-surface layer,
- shallow and deep checking investigations.

Apart from these, hydrogeological and seismic measurements and investigations were carried out.

The following work was carried out at the Żarnowiec site under the geotechnical research programme:

- deep boring to 100.0 m below the surface of the terrain,
- tests with dynamic penetrometer to depth of 20.0 m,
- mechanical boring to depth of 20.0 m,
- controlled shallow sounding to depth of 3.0 m,
- measurements of soil reaction coefficient,
- test loading of soil from the bottom of the borehole,
- test loading of soil from the surface of the terrain,
- static sounding to depth of 20.0 m,
- loading test of piles.

Some preparations were made for installing various sensors in the soil, e.g. for temperature, pore pressure, soil pressure measurements.

3. Characteristics of Investigations Performed

3.1. Local Deep Borings

Local deep borings were made in virgin soil, starting at terrain levels before earth works began, that is the range of +12.43 m to 1.5 m above mean sea level, and reached to 20.0 m below MSL.

Analysis of samples taken from the deep bore indicated that in the direct vicinity of the Main Building fluvioglacial sediments of the latest oscillation and kame terraces were present. Most often, gravel, aggregate and sand with laminations of sandy loam and loam appear under the surface soil. Between −30.0 m MSL and −70.0 m MSL there is a layer of clay, under which gravel and aggregate are present (Fig. 3). Geotechnical parameters determined by "Geoprojekt" are given in Table 1. Basing on deep boring,

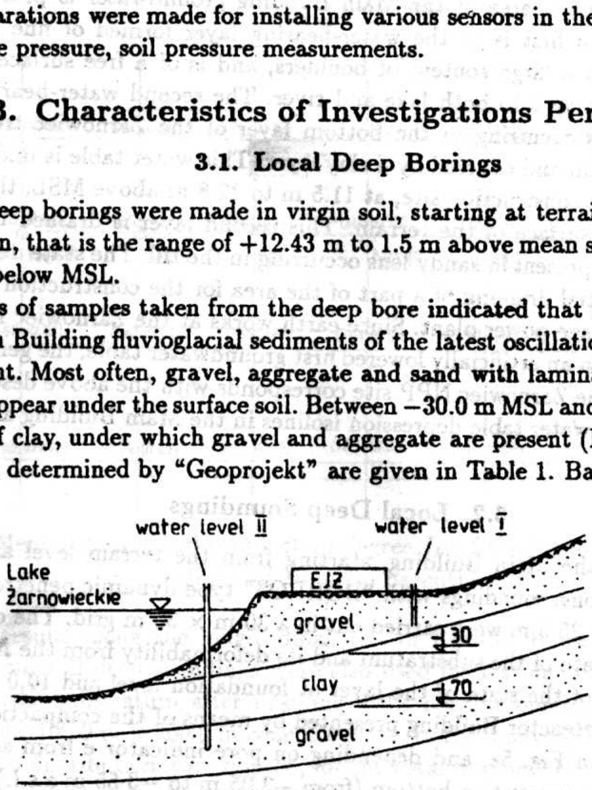

Fig. 3. Simplified soil and ground water conditions

Table 1

Type of soil	Humidity	Degree of compaction I_D/I_L	Material coefficient γ_m
Fine sand	Damp or saturated	0.27	
Fine sand silty sand	Damp or saturated	0.71	0.90
Mean and coarse sand	Damp or saturated	0.68	0.82
Gravel and aggregate		0.70	0.78
Clay	Hardplastic	0.15	
Clay	Plastic	0.35	

it was stated that in the area of the Main Building groundwater is present on two horizons of which the first is in the water-bearing layer formed of fine and coarse sand and gravel with a large content of boulders, and is of a free surface character. This water was draining into both lake and river. The second water-bearing layer is formed by sediments occurring in the bottom layer of the Żarnowiec trough, lying above postglacial loam and covered by a clay layer. This water table is under pressure and stabilizes, at the construction site, at 11.5 m to 12.8 m above MSL, that is 6.1 m to 6.5 m below the surface of the terrain. This second layer is drained by the lake. Groundwater is also present in sandy lens occurring in the till. The state described was observed during partial draining of a part of the area for the construction need of the nearby pumped-storage power plant. Since earth works at the Żarnowiec Power Plant site are carried out on an artificially lowered first groundwater table, the general picture of groundwater at the Żarnowiec NPP site corresponds with the above description. An example of the first water table depression isolines in the Main Building area is shown in Fig. 4.

3.2. Local Deep Soundings

In the area of the Main Building, starting from the terrain level and from the bottom of excavations, soundings with "BORROS" type dynamic penetrometer down to a depth of about 25.0 m were carried out in a 30 m × 30 m grid. The objective was to determine the state of the substratum and its deformability from the N_{20} indicator. Exemplary results of the state of the layer at foundation level and 10.0 m below the foundations of the Reactor Building presented by means of the compaction coefficient I_D are illustrated in Fig. 5a, and depending on pore indicator e from samples taken from just below the excavation bottom (from −3.05 m to −3.55 m a.s.l.) in Table 2.

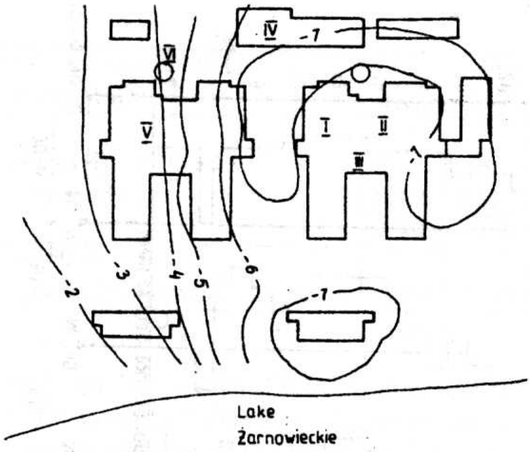

Fig. 4. Dewatering level around site building and locations of subsoil load tests (from I to VI)

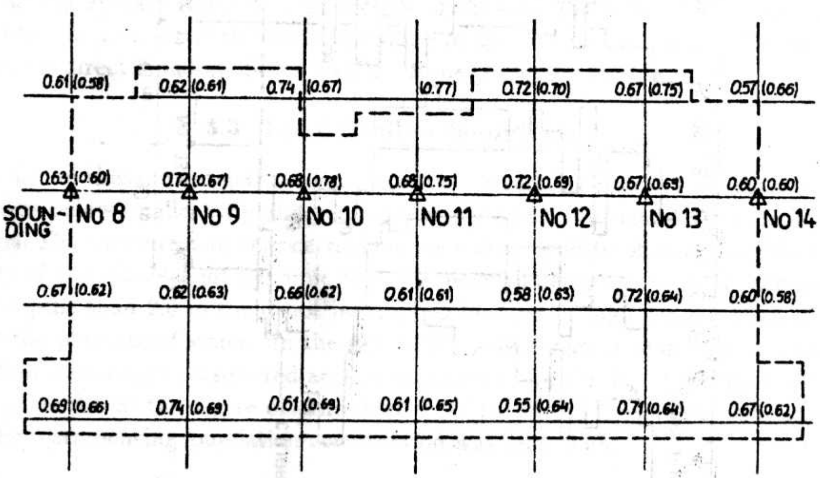

Fig. 5a. Mean values of soil compaction degree I_D of the foundation level and at a depth of 10 m (in parentheses)

The DPT results along the longitudinal axis of Reactor House No I, are shown in Fig. 5b. Results of deep soundings were also used for testing and comparing possible changes in the substratum after draining wells became operative in the immediate vicinity of the 100.0 m × 200.0 m concrete plate. In the analysis, the statistical method as for normal distribution was adopted, for the total number of impact required for full penetration of the rod down to 25.0 m. Comparisons showed that soundings performed earlier in and outsiede the building contour, in the belt with installed draining wells, differ. Results of soundings obtained before switching on the draining system and the

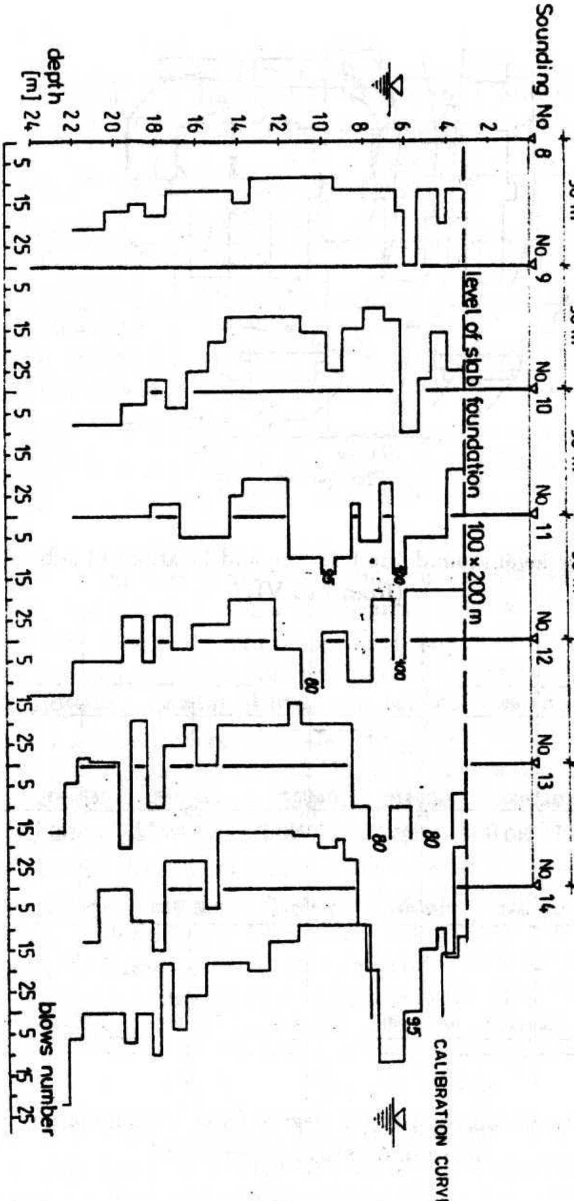

Fig. 5b. Sounding results of soil along chosen longitudinal axis of Reactor House foundation No. 1 (Borros type dynamic penetrometer)

Table 2

Type of soil taken from different depths relation to MSL	Mean value			
	e_{min}	e_n	e_{max}	I_D
−3.16 m Mean sand (+gravel) silty sand, aggregate clayey sandy loam	0.396	0.509	0.744	0.671
Aggregate	0.340	0.430	0.630	0.690
−3.50 m to −3.60 m Mean sand (+gravel) sandy loam fine sand	0.403	0.510	0.752	0.697

deep excavation were better. Test results of subsoil compaction near wells (mean values of blow number per penetration of Borros penetrometer) are presented in Fig. 6. In Fig. 7 the test results of subsoil soundings below the Ventilation shaft and in Fig. 8 below the Engine Room Building, in which generating sets on pile foundations are placed are shown.

Results indicated that in the Engine Room Building area the soil should be strengthened as the average degree of compaction of the soil was below that required, i.e < 0.9, while in vicinity of the shaft the value of the soil compaction coefficient was sufficient for direct founding. Some results will be presented further.

3.3. Local Shallow Soundings

The aim of these investigations was to provide a running check of the state of the substratum below smaller strip and pad foundations and fills around large foundations and walls. The measurements are carried out in a dense grid to observe possible heterogeneity of the fills. A light dynamic ITB ZW penetrometer was used. In virgin soil, greater depths than 2.0 m could not be reached because of high consolidation of the soil and the presence of stones. In the case of fills, the range of soundings was about 4.0 m. Test soundings in a selected area of excavations for the Reactor Building foundations showed that the degree of consolidation of the upper layer of the substratum, just before commencing foundation construction was $I_D > 0.68$.

3.4. Investigations of Soil Deformability

During deep soundings with the "Borros" sounder and during borings, samples were taken for laboratory testing. Among other things the aim of these tests was to determine the value of the deformability modulus. Results obtained by the Polish and Russian supervisors gave positive, though divergent values. For the mean value of the consolidation indicator $e = 0.54$, in accordance with the Soviet Standard SNiP II–15–74, the deformability modulus equal to 40.0 MPa was assumed, and in accordance with the Polish Standard PN–81/B–03020 170.0 MPa (according to different classification) was taken for $I_D = 0.66$. For this reason, several methods of test loadings were carried out following excavations for foundations of more important objects.

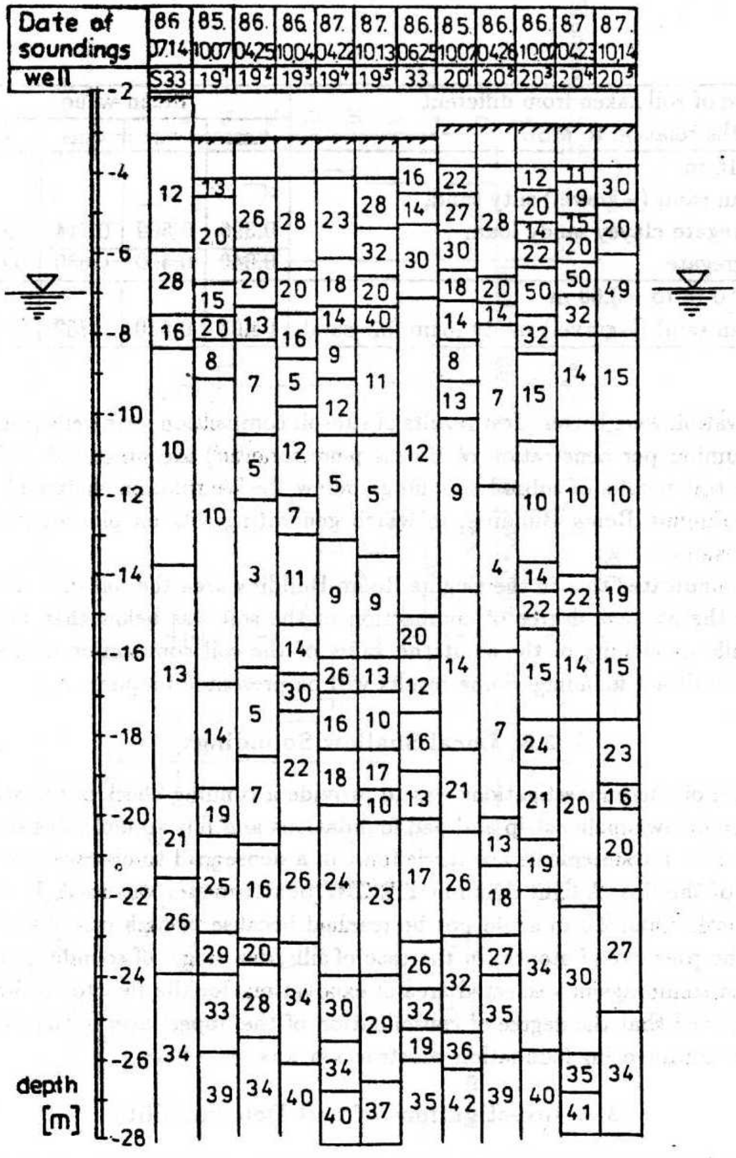

Fig. 6. Comparison of control tests by means of Borros penetrometer near filter wells Nos. S33, 19, 33 and 20 carried out for evaluation of long term dewatering influence on subsoil state

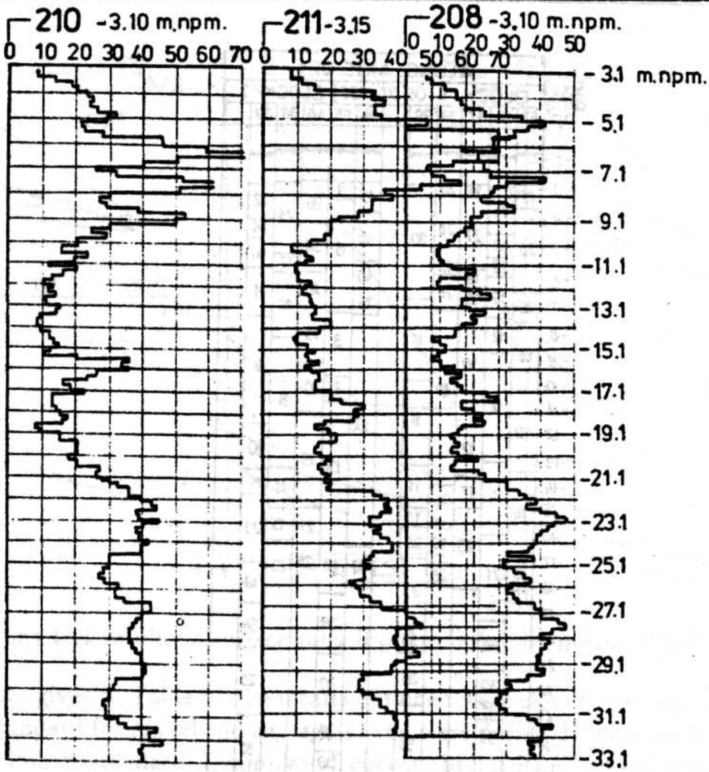

Fig. 7. Sounding results of soil under the Ventilation Shaft (foundation plate of 25 m diameter)

3.4.1. Testing of Substratum Deformability with VSS Plates

Measurements were carried out in one section before laying the subinsulating layer of Reactor House foundations, at 5 sites, using a 30 cm diameter steel plate. The test load range was between 0.0 and 0.25 MPa, and the following cycle was used: preliminary loading, unloading, repeated loading and complete unloading. Results are shown in Fig. 9. Results of soil compactibility obtained from this test were used to determine the value of soil reaction coefficient k in MPa/cm according Westergaard and OSŻD interpretation and simplified method. It was found that soil is characterized by:

$k = 0.53$ to 0.68 MPa/cm according to the Westergaard method,

$k = 1.26$ to 1.95 MPa/cm according to the OSŻD VSS method,

$k = 0.90$ to 1.39 MPa/cm according to the simplified method,

and that the determined k values correspond to requirements for the heavy loading class.

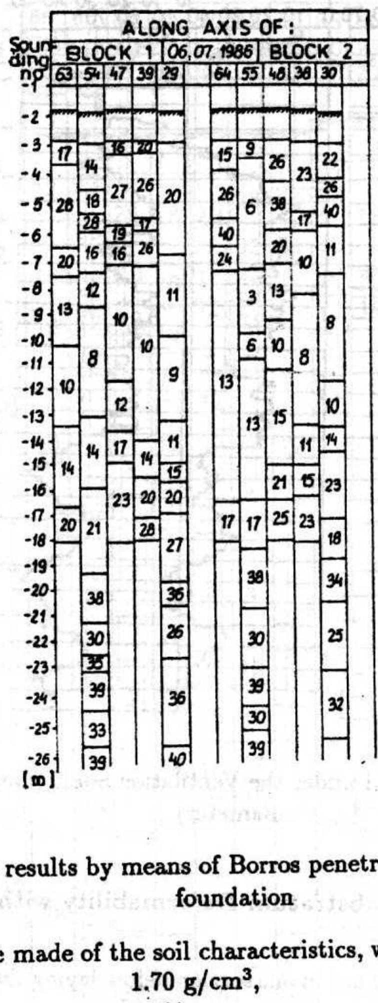

Fig. 8. Sounding test results by means of Borros penetrometer below Engine Room I foundation

Mention should be made of the soil characteristics, which were:

density	1.70 g/cm^3,
natural soil humidity	4.0%,
maximum density	1.90 g/cm^3,
optimum humidity	6.9%,
grain size variability (d_{60}/d_{10})	4.5.

3.4.2. Test Loading of Soil in Boreholes

To supplement previous data on soil deformability and decrease the divergence of the value of previously determined deformation moduli, basing on the results of soundings and evaluation of porosity index a test loading below the groundwater table was carried out in the boreholes in accordance with the Russian Standard GOST – 12374-66. The tests were performed at the bottom of the boreholes in a layer of gravel and aggregate (9.0 m below the surface of the terrain) using columns of pipes 35.6 cm in diameter with base surface 600 cm^2, in the range of loads of from 0.0 to 0.8 MPa.

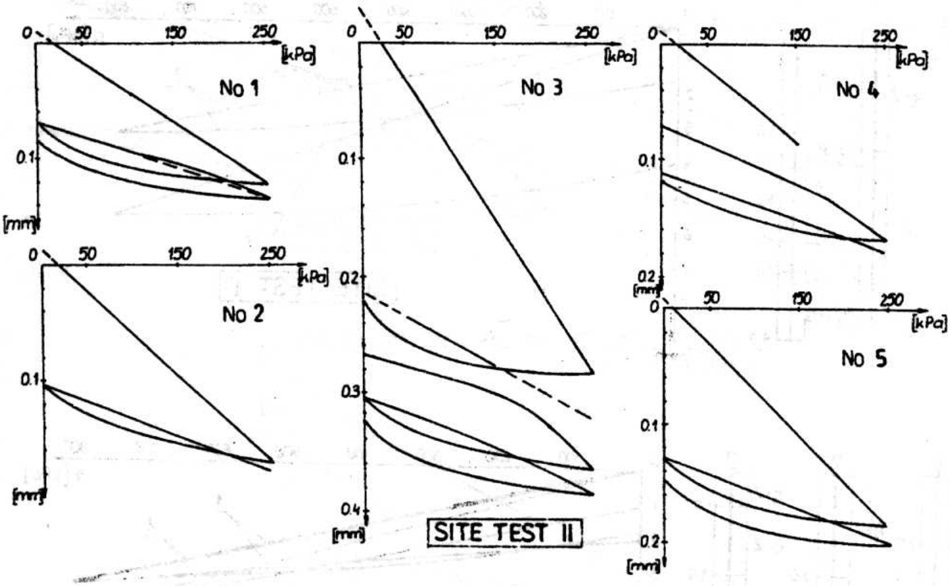

Fig. 9. Loading test results of surface subsoil deformation by means of VSS method

The results are given in Table 3. The results obtained were close to the values given in the Soviet Standard for gravel and aggregate, and were decidedly different from values given in the Polish Standard. Examples of curves obtained for soil deformability are shown in Fig. 10.

Table 3

Type of soil	Grain size indicator $U = d_{60}/d_{10}$	Modulus E_0 [MPa]
Gravel	18.1	60.07
Aggregate	8.1	39.15

3.4.3. Test Loading from Ground Surface

These tests were done on the fill within the belt between the Reactor House and Engine Room, on the virgin soil on which foundations for the Radioactive Waste Building were to be constructed, and in the excavation for foundations for Reactor House II and Ventilation Shaft II. In all, tests of soils with similar grain sizes were performed, 2 with a 0.25 m column and 14 with a column with a surface area of 0.50 m^2. A hydraulic set consisting of a servo-motor and hydraulic pomp, and a set of sensors of 0.01 mm accuracy were used. The tests were carried out in accordance with recommendations of the Polish Standard PN–74/B–04452. Table 4 gives a comparison of deformability moduli, and an exemplary test curve is shown in Fig. 11. Results of tests performed

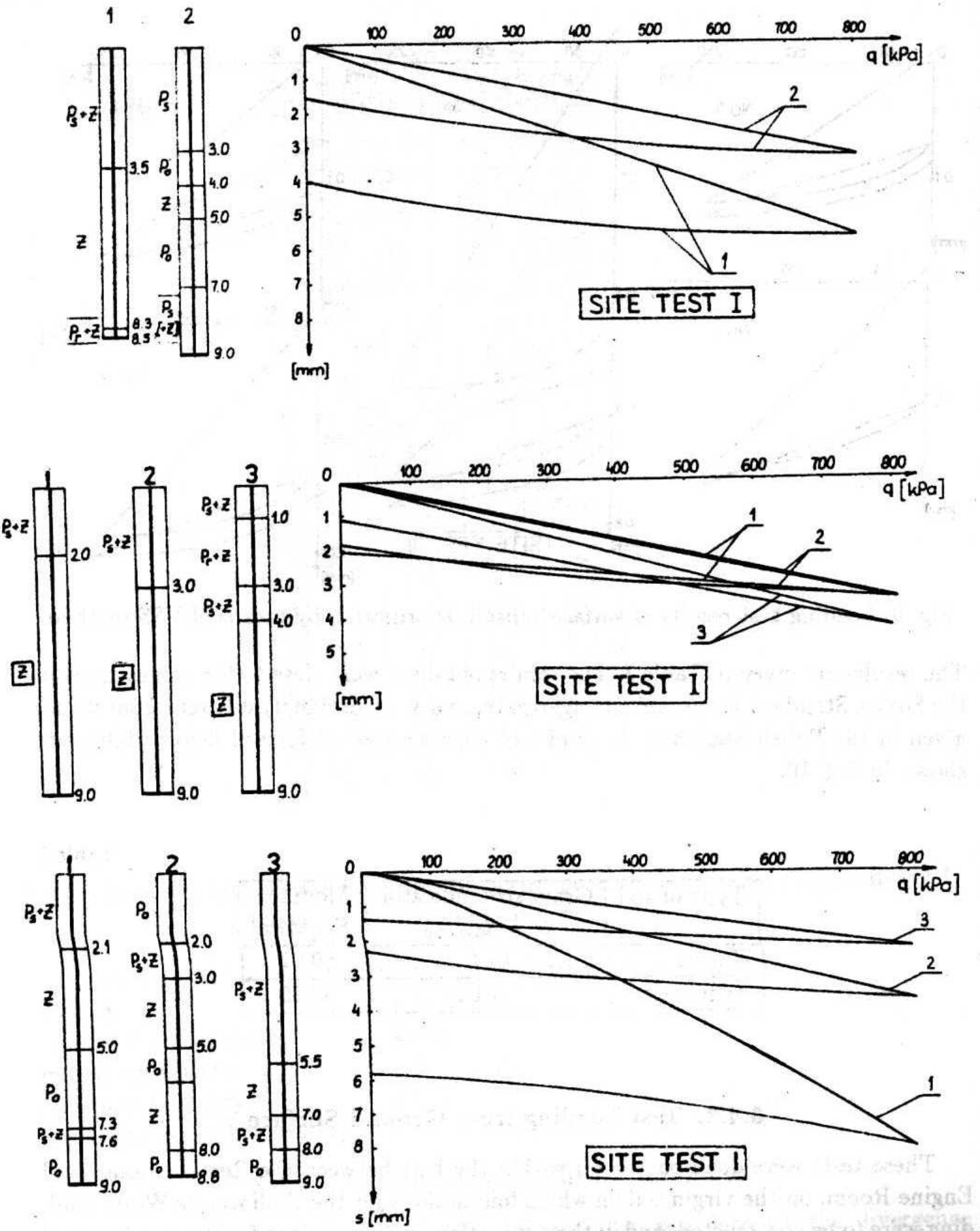

Fig. 10. Loading test results of subsoil deformations by means of columns in boreholes at a depth of 9 m

a) in sand, b) in gravel, c) in aggregate (sand and gravel)

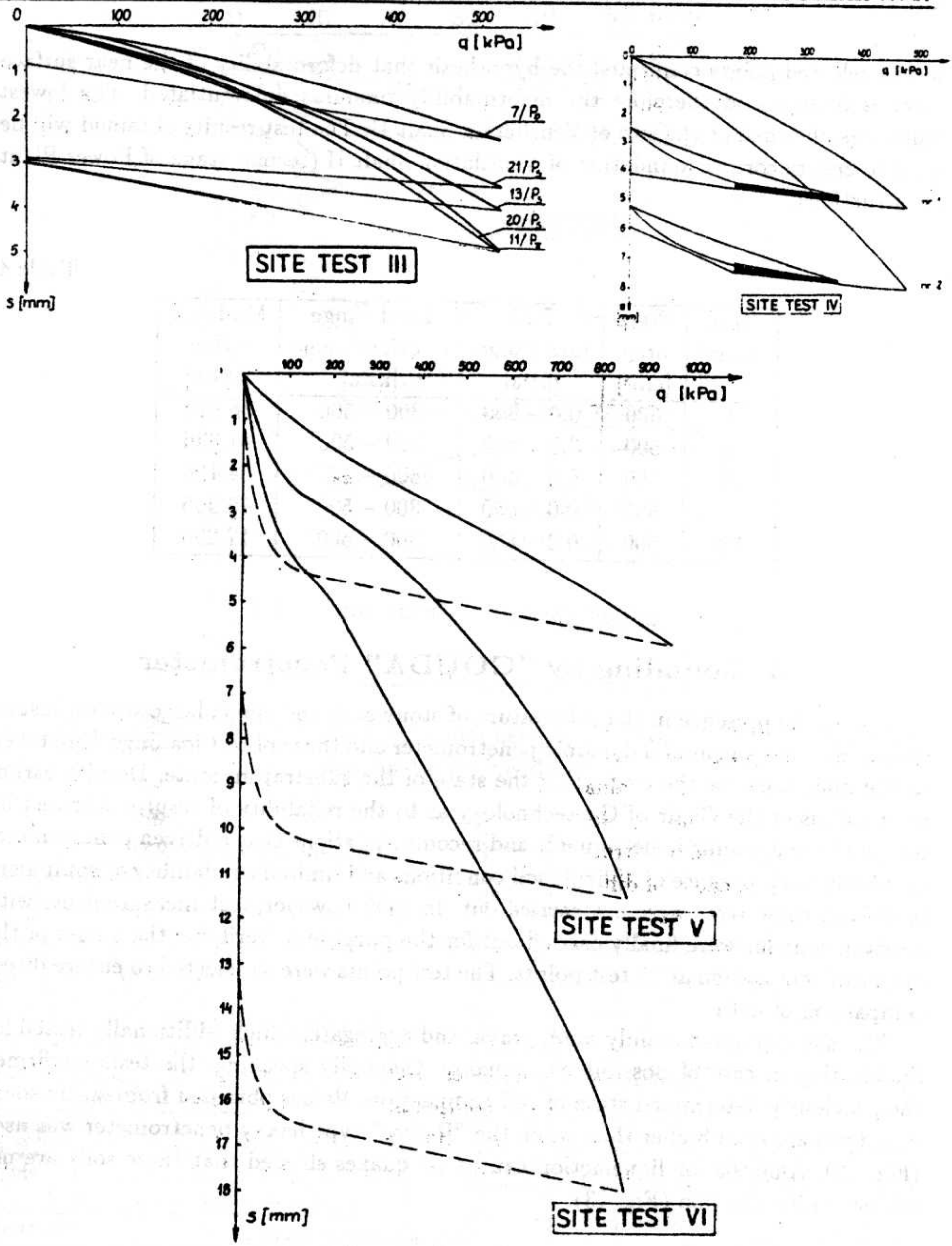

Fig. 11. Control loading test results of fill (site No. IV) and subsoil (site Nos. III, V and VI, see Fig. 4)

at the selected points confirmed the hypothesis that deformability of the near surface layer is diverse and therefore the deformability modulus differentiated. The lowest value was obtained at the site of Ventilation Shaft II. The test results obtained will be used to ensure correct foundation of Ventilation Shaft II (second stage of Power Plant construction).

Table 4

Test points	Plate area [cm²]	Full load range [kPa]	Load range in calculations [kPa]	Modulus value [MPa]
I	600	0.0 – 800	300 – 500	36.916
III	500	0.0 – 520	300 – 500	61.036
IV	250	0.0 – 480	300 – 480	34.166
V	500	0.0 – 850	300 – 500	79.335
VI	500	0.0 – 850	300 – 500	17.209

4. Sounding by "GOUDA" Penetrometer

Due to the presence in the substratum of stony soils and single large stones, results of soundings by means of a dynamic penetrometer and those of test loadings were taken as the main base for the evaluating the state of the substratum state. Despite earlier reservations of the Chair of Geotechnology as to the reliability of results obtained by means of the dynamic penetrometer and recommendations that a driven penetrometer should be used, because of difficult soil conditions and limited availability of equipment in Poland these tests were not carried out. In 1990 however, test measurements with a driven sounder were finally carried out for the purpose of verifying the values of the degree of compaction at 11 test points. The test points were so selected to ensure direct comparison of data.

The soil contained mainly sand, gravel and aggregate, which additionally tested for liquefaction in case of possible earthquakes. Generally speaking, the tests confirmed the previously determined state of soil compaction. Values obtained from static sounding tests are even higher than when the "Borros" type heavy penetrometer was used (Fig. 12). Analysis for liquefaction caused by quakes showed that these soils are not subject to liquefaction (Fig. 13).

5. Test Loading of Piles

When it was found that the substratum for generator set foundations required strengthening, the design provided for placing the sets on piles with a reinforced concrete plate 3.0 m thick on top. As a large plate for the Reactor Building had been built nearby, bored piles of 700 mm (Block No. 1, 70 piles) and 1220 mm (Block No. 2, 39 piles) and respective lengths of 18.0 m and 17.0 m were designed (Fig. 14). After the

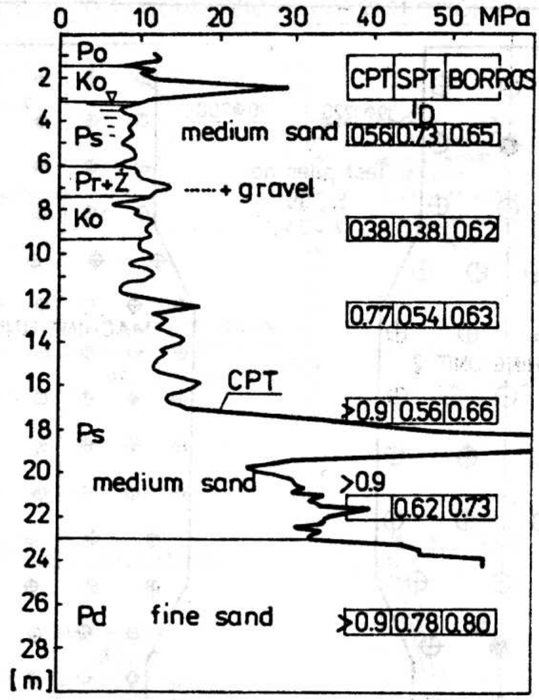

Fig. 12. Comparison of sounding test results between "Borros", SPT and CPT near Reactor House foundation

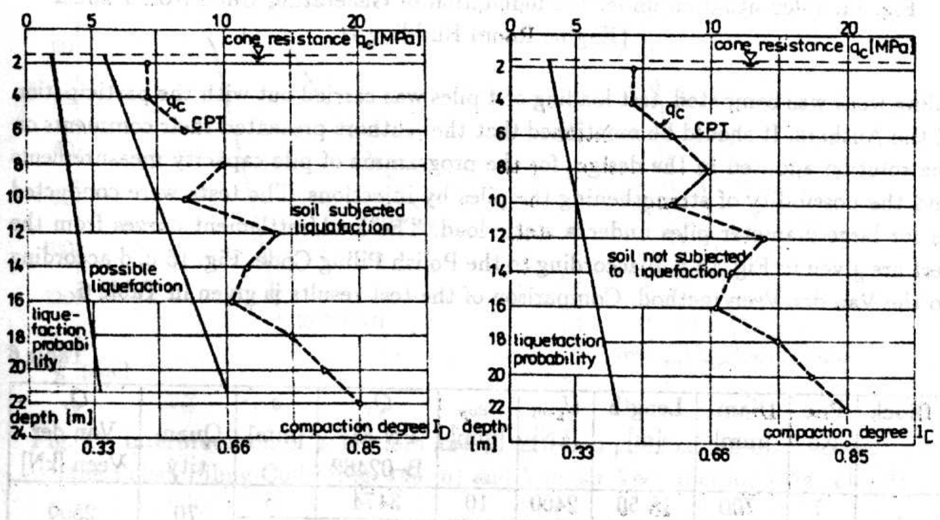

Fig. 13. Range of soil resistance under penetrometer cone q_c dependening on liquefaction of soil subjected to dynamic load

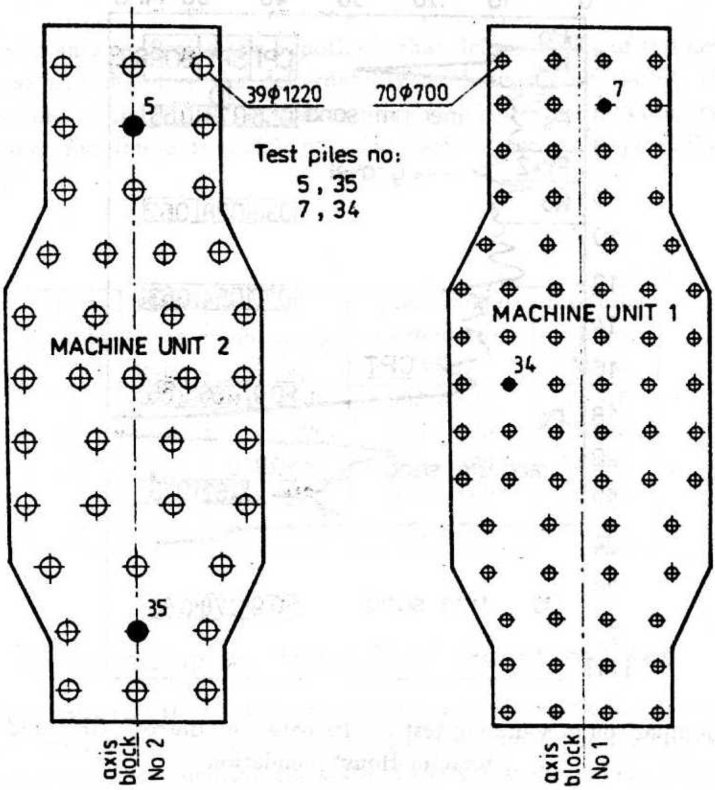

Fig. 14. Piles situation under the foundation of Generating Units Nos. 1 and 2 (Engine Room Building I)

piling work was competed, test loading of 4 piles was carried out with the participation of the Authors. It should be mentioned that the Authors presented their comments on the solution adopted in the design, for the programme of pile capacity measurements and the possibility of strengthening the piles by injections. The tests were conducted as for large-diameter piles under a static load. The load/settlement curves from the test are given in Fig. 15 a, b according to the Polish Piling Code, Fig. 15 c, d according to the Van der Veen method. Comparison of the test results is given in Table 6.

Table 6

Block	Pile No	Diam. [mm]	Length [m]	U_{proj} [kN]	s_{dop} [mm]	Q_r PN-81/ B-02482	s [mm]	Quan-tity	Q_r Van der Veen [kN]
1	7	700	18.50	2400	10	3474	8	70	2500
	34	700	18.40	2400	10	3600	10		
2	5	1220	17.20	3800	10	5065	10	39	3333
	35	1220	17.20	3800	10	4650	22		

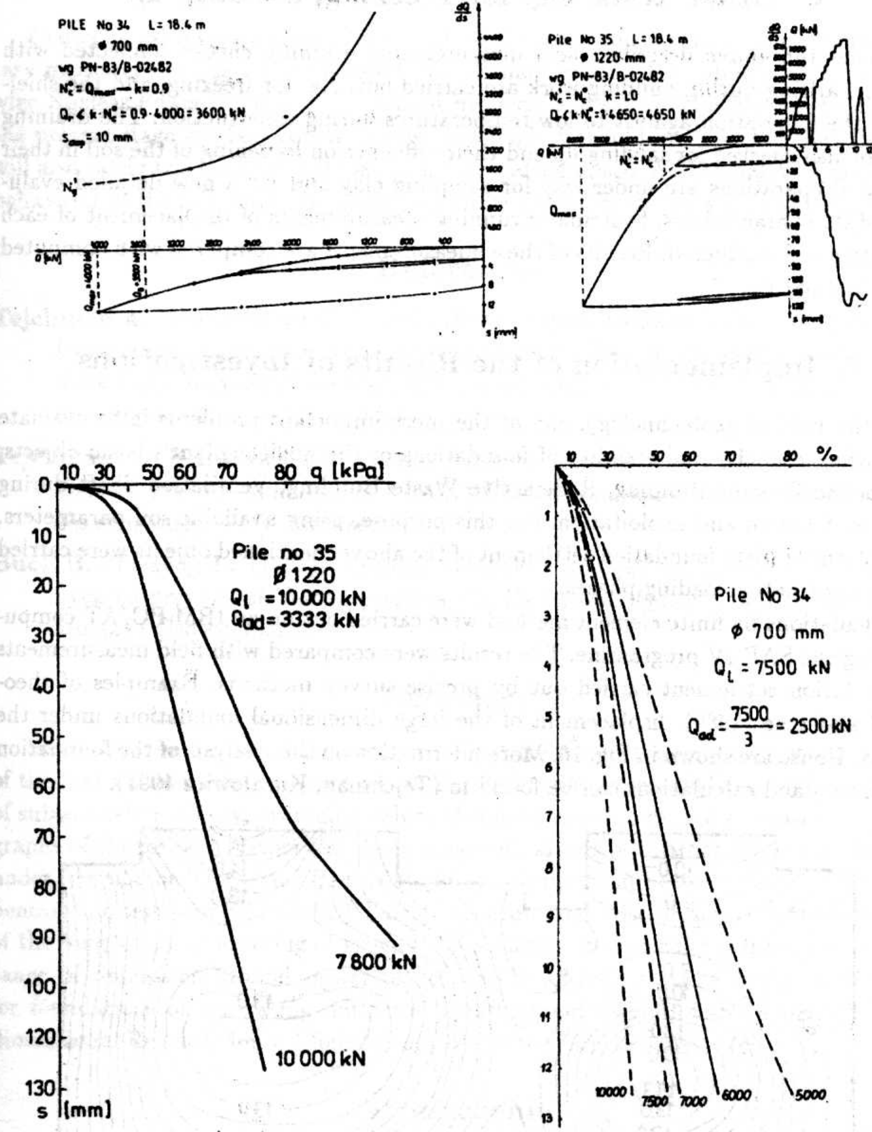

Fig. 15. Interpretation of ϕ 700 mm and ϕ 1220 mm pile loading tests according to the Polish Piling Code (Fig. 14a, b) and Van der Veen method (Fig. 14c, d)

6. Other Tests, e.g. for Freezing, Sanding up

Besides the above described field measurements, running checks connected with problems arising during building work are carried out, e.g. for freezing, and the shielding of the foundation against to low temperatures during construction. The draining wells are also checked for sanding up and their influence on loosening of the soil in their vicinity. Preparations are under way for sampling clay and for a new detailed evaluation of its characteristcs. Systematic running measurements of displacement of each foundation are conducted. Results of these measurements are compared with computed theoretical results.

7. Implementation of the Results of Investigations

In the field of geotechnology, one of the most important problems is to evaluate the bearing capacity and stability of foundations of the nuclear plant's basic objects, such as the Reactor Building, Radioactive Waste Building, Ventilation Shaft during their construction and exploitation. For this purpose, using available soil parameters, calculations of plate foundation settlement of the above mentioned objects were carried out for consecutive loading phases.

Calculations by finite element method were carried out on an IBM PC/AT computer using the SAP IV programme. The results were compared with field measurements of foundation settlement carried out by precise survey methods. Examples of theoretical and true (1989) displacement of the large dimensional foundations under the Reactor House are shown in Fig. 16. More information on the analysis of the foundation settlements and calculations can be found in (Tejchman, Kuralowicz 1991).

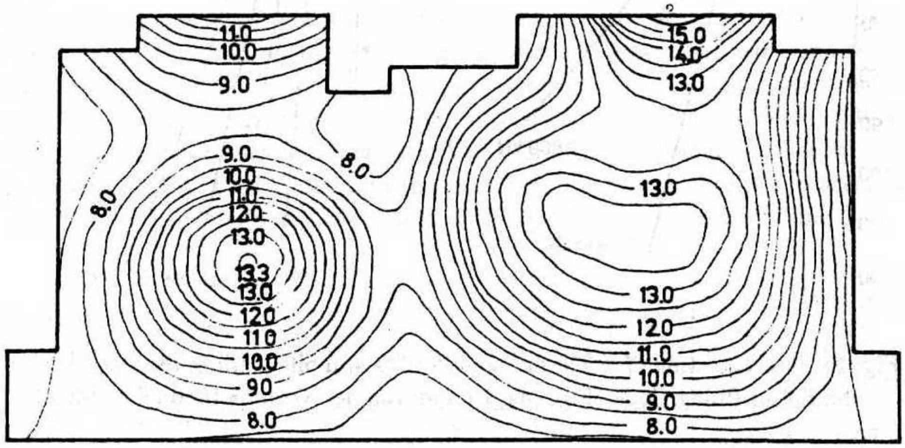

Fig. 16. Calculated settlement values of the main plate foundation under Reactor House No. I

8. Conclusions

Geotechnical investigations carried out so far, continuous control and supplementary measurements, as well as computational analyses show that objects of the Żarnowiec Nuclear Power Plant have been built properly and safely. This of course concerns the present stage of plant constructions. Although it should be expected that the soil will also safely transmit the full load in the operating phase. Additional analysis of the behaviour of the soil under dynamic load under the generator sets is required.

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Summary

Some of the results of geotechnical investigations conducted on the construction site of the first Polish nuclear power plant at Żarnowiec are presented. They embrace those of subsoil deformability, averaging values of soil compaction degree I_D with exemplary graphs of Borros penetration test along longitudinal axis of Reactor House foundation, under Ventilation Shaft and Engine Building. Comparison between results of Borros penetration tests and SPT and CPT results is presented. Also presented is the influence of the long standing lowering of ground-water surface on subsoil condition and on the range of depression around power plant. Results of load tests of bored piles made for foundations of generating units and measurement results of settlement of large-dimensional Reactor House I foundations settlement are also presented.

Streszczenie

Badania geotechniczne w czasie budowy elektrowni jądrowej w Żarnowcu

W artykule przedstawiono niektóre ważniejsze wyniki badań geotechnicznych przeprowadzonych na terenie budowy pierwszej w Polsce elektrowni jądrowej w Żarnowcu oddalonej około 70 km od Gdańska. Zamieszczono m.in. rezultaty badań odkształcalności podłoża gruntowego, uśrednione wartości stopnia zagęszczania I_D wraz z przykładowymi wykresami sondowań sondą dynamiczną Borros w podłużnej osi fundamentu Budynku Reaktorowni, Komina Wentylacyjnego i Budynku Maszynowni. Porównano

wyniki sondowań na poletkach doświadczalnych w rejonie budowy elektrowni sondą dynamiczną Borros, z wynikami sondowań sondą SPT i CPT. Ukazano wpływ długoletniego odwodnienia na stan podłoża i zasięg leja depresji wokół elektrowni oraz wyniki próbnych obciążeń pali wierconych wykonanych pod fundamenty Turbozespołów. Ponadto zamieszczono wyniki pomiarów osiadania wielkogabarytowego fundamentu Budynku Reaktorowni I.