Peat Consolidation with Bottom Ash
- Theory and Practice

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ABSTRACT:

In the Zachodniopomorskie Province (Poland) many reclamation and macro-levelling processes have been carried out in the last 12 years, with the use of nearly two million tons of fly ash. The area intended for levelling is located on the eastern side of Nad Odrą Street in Szczecin, between the Skolwin Paper Factory and Szczecin Steelworks. The existing ordinate of the ground ranged from 0.4 m in the western part to 1.5 – 2.0 m above sea level in the southern part. The geotechnical division of the substrate soil is the following: layer I– peat, (weaker), layer Ia – peat (stronger), layer II– organic mud (weaker), layer IIa – organic mud (stronger). Any industrial development of Odra river areas is possible only by preparation of the ground, which can be cheaper when fly ash is used. Nad Odrą Street due to the possible assigning of the land for industrial purposes, it is designed to fill the levelled ground with fly ash and slag mixture while keeping to the following conditions: filling gradually of the natural ground depression with fly ash and slag mixture in separately compacted layers, next forming of the ground surface (covering layer) and finally preparation of the ground for future industrial development. According to the design assumptions, mainly fly ash and slag mixture from Dolna Odra Power Plant in Nowe Czarnowo are to be used for levelling works. Water conditions are related to the geologic structure of substrate and water level in the adjacent channels and the Odra river. The basic water-bearing strata are river sand and glacial-water sand underlying the organic strata. The ash and slag mixture has been placed since August 2004 in 0.5 m thick layers, except for the first bottom layer that was up to 2.0 m thick.

Based on the analysis of the test results reached in December 2004, it appears that in the test points, upon incorporation of fly ash and slag mixture and improvement of the ground with a layer of 2 – 3 m, the organic soil got partially consolidated within the short period of 4 months. The limit pressure $p_l$ grew by approx. 7 – 35%, while the growth of the pressure meter modulus value ($E_M$) reaches 10 – 16%. Compressible organic soils are characterised with a long period of full consolidation. Completion of the process of consolidation will not occur earlier than after several tens of years.
1. Introduction

The economical growth being at present in Poland makes that the area with the weak soils are allocated with the architecture more and more frequently. There are lakelands and river valleys among these, where there are organic soils with the different derivations, very often with the great thickness [13]. The areas with the organic basis take ca. 5% of the land of Poland. The main part of these are peats, taking the area of ca. 2 million ha [6]. From the engineering-geological point of view, peats are the weak soils and differ fundamentally from the mineral soils. The organical basis is very susceptible with any changes of state of pressure and even very low loads make considerable deformation of the soil. The high susceptibility of peats is mainly influenced by their derivation and related structural construction.

Polish power plants produce every year about 15 mln tonnes of coal combustion products (CCPs). The main application it is mining, next road construction, reclamation and levelling.

In the Zachodniopomorskie Province (Poland) many reclamation and macro-levelling processes have been carried out in the last 12 years, with the use of nearly two million tons of fly ash.

Any industrial development of Odra river areas is possible only by preparation of the ground, which can be cheaper and more efficient, when fly ash is used.

The area intended for levelling is located on the eastern side of Nad Odra Street in Szczecin, between the Skolwin Paper Factory and Szczecin Steelworks.

The existing ordinate of the ground ranged from 0.4 m in the western part to 1.5 – 2.0 m above sea level in the southern part.

Major part of the ground surface was degraded by people, namely by deposition of various post-construction materials.

Picture 1. Levelling and research area
The objective of this research was to determine the consolidation rate of organic soil (peat and aggradate mud) and simulation of consolidation in the future, whereas in Poland there is no experience with organic soil consolidation with fly ash and slag mixture.

2. Materials

According to the design assumptions, mainly fly ash and slag mixture from Dolna Odra Power Plant in Nowe Czarnowo has been used for levelling works. The material is the fly ash and slag mixture, classification code 10 01 80. The mix is not considered to be hazardous waste within the meaning of the Regulation of the Minister of the Environment of 27th September 2001 on Wastes Catalogue (Journal of Laws No. 112, item 1206).

In order to cover the ground after levelling, there will be used a mixture of peat and local material – the existing output from water course dredging stored in the refill yard. In some of the places, ground waters are monitored with piezometers. In most cases when ashes are used, making of piezometric tests or monitoring of changes in water quality are not required. In no event release of detrimental substances has been found. For many years now, ashes have been used on a massive scale in Poland in geotechnical works, such as ground reclamation or macro-levelling. No cases of water pollution are known as a result of washing out of substances from ashes.

3. Theory of consolidation.

The skeleton of the organic soils is built with weak particles, that considerable deform themselves even under the light load. Under the taken load the structure of the skeleton changes and the particles get closer to each other, reducing at the same time the pore volume and force out the water, air and gas, that are the product of organical substances decomposition. Additionally, the part of the weak soil particles is destroyed during the structural damages [12]. Described conditions influence the considerable values of settlement and low durability of the organic soil. The most rational and common method of hardening the organic soils, including peats, is the initial consolidation. The researches spent with the settlement and consolidation of the organic soils have proven it is non-linear process and the deformation process is more complicated, that in the mineral soils case.

The classical models, describing the settlement and consolidation of the mineral soils are Terzaghi’s model and Biot’s model. Both are based on the elasticity theory and are used in case of mineral soils’ consolidation. Using mentioned models for the describing of consolidation of the organic soils is very complicated and doesn’t bring desired results [8].

There was elaborated the theory about settlement of the organic soil in the 1960. The authors, Gibson and Lo, have introduced the conception of the secondary soil compressibility. The secondary soil compressibilities are very important for the organic soils. They are the result of long lasting structural deformation of the soil and happen...
with no lateral deformation, after finishing primary settlements, when the water pressure in the soil pore are almost equal zero [12]. By Gibson’s and Lo’s theory, the practical dependence for defining the settlement values are following:

- for the short time periods:

\[
s = \frac{2}{\pi} \sqrt{c_k t a \Delta \sigma'} \left[ 1 + \frac{1}{3} \frac{\lambda}{a} t + c_k \left( \frac{\lambda^2 t^2}{a^2} \right) \right]
\]  

(1)

- for the long time periods, when the pore pressure growths are disappearing [12]:

\[
s = h \Delta \sigma' \left[ a + b \left( 1 - \exp \left( -\frac{\lambda}{b} t \right) \right) \right]
\]  

(2)

- \(a\) – primary soil compressibility factor, [1/kPa]
- \(b\) – secondary soil compressibility, [1/kPa]
- \(c_k\) – consolidation factor, [m²/s]
- \(h\) – soil thickness, [m]
- \(s\) – soil settlement, [m]
- \(t\) – time, [s]
- \(\lambda\) - parameter dependent of the viscosity of soil skeleton,
- \(\sigma'\) – effective stress, [kPa].

Today the empirical equations are formulated, for the calculating verification of the settlement and consolidation of the organic soils. Using the equations is possible to calculate the settlement of the basis, resulted by the additional loading.

There have been proposed the following equation of the soil consolidation degree in the Swedish Geotechnical Institute:

\[ U = I - A \exp(-Bt) \]

(3)

- \(A\) – const,
- \(B\) – the function of peat thickness, natural humidity \(w_n\) and load \(\sigma\),
- \(t\) – time, [s].

There was differential equation used for calculating the peat consolidation [9]:

\[
\frac{\partial u}{\partial t} = \frac{M}{\gamma_w} \frac{\partial}{\partial z} \left( k \frac{\partial u}{\partial z} \right)
\]

(4)

- \(u\) – water pressure in soil pores, [kPa]
- \(t\) – time, [s]
- \(M\) – soil consolidation module
- $k$ – filtration factor [m/s],
- $\gamma_w$ – water weight density, [kN/m$^3$]
- $z$ – depth, [m].

Carlsten [3, 9] has obtained following equation of the consolidation degree, for the peat of the thickness $H=2\div4$ m, natural humidity $w_n = 800\div1500\%$, and load $\sigma < 50$ kPa:

$$U = 1 - 0.6 \exp \left( \frac{0.52 w_n^{0.75} t}{H^2 \sigma^{0.5}} \right)$$

(5)

Den Haan [2] has proposed the dependence, describing the relationship stress – settlement, based on the self-made researches:

$$1 - \frac{s}{a h_0} = \left( \frac{\sigma - \text{const}}{\text{const}} \right)^m$$

(6)

- $a$ – compressibility parameter,
- $h_0$ – soil thickness, [mm]
- $s$ – settlement
- $\sigma$ – stress [kPa].

The dependence (7) very well describes the relationship between the porosity indicator and the load only for the great values of $\sigma$.

There are researches performed in Department of Geotechnical Engineering of Technical University of Szczecin since 1986, concerning the empirical model of the organic soil. There has been researched the influence of the consolidation on the change the organic soils filtration factor and the change of the deformation module. There has been measured the consolidation time, including the changes of soil parameters.

The peats are the very heterogeneous soils, so Meyer [8,9,10] has proposed the empirical model for the practical determining of the settlement, that the equation is following:

$$s(t, \sigma) = s_{\infty}(\sigma) \cdot [1 - \exp(-D \cdot t^p - \alpha \cdot t)]$$

(7)

- $s$ – soil settlement, [m]
- $s_{\infty}$ – soil settlement after the time $t \to \infty$, [m]
- $t$ – time, [s]
- $D, p, \alpha$ - equation parameters,
- $\sigma$ - stress, [kPa].
\( D, p \) and \( \alpha \) are described based on the curve of the peat sample settlement curve. Many researches have proven, that curves described by the equation (7) mostly approximate the peat samples settlement curves, obtained in the laboratory [1, 7].

4. Layers

The geotechnical division of the substrate soil (and the current average pressuremeter test values for the separated layers) is the following:

– layer I – peat (weaker) of the characteristic values of the pressuremeter test parameters equal to: the limit pressure \( p_l = 101 \text{ kPa} \) and the pressuremeter modulus \( E_M = 692 \text{ kPa} \) (2 measurements have been assumed for the calculations according to the “A” method);

– layer Ia – peat (stronger) of the values of the pressuremeter test parameters equal to: the limit pressure \( p_l = 149 \text{ kPa} \) and the pressuremeter modulus \( E_M = 693 \text{ kPa} \) (1 measurement);

– layer II – organic mud (weaker) of the characteristic values of the pressuremeter test parameters equal to: \( p_l = 130 \text{ kPa} \) and \( E_M = 779 \text{ kPa} \) (2 measurements);

– layer IIa – organic mud (stronger) of the average values of the pressuremeter test parameters equal to: \( p_l = 153 \text{ kPa} \) and \( E_M = 861 \text{ kPa} \) (3 measurements).
Picture 2. Example profile in August 2004 [5]
Picture 2. Profile lines and testing points [5]
5. Hydrogeological conditions.

Water conditions are related to the geologic structure of substrate and water level in the adjacent channels and the Odra river. The basic water-bearing strata are river sand and glacial-water sand underlying the organic strata. The fly ash and slag mixture has been placed since August 2004 in 0.5 m thick layers, except for the first bottom layer that was up to 2.0 m thick.

![Photo 2. First layers of fly ash and slag mixture (Ekotech)](image)

The structures located on the south-west side of the discussed area cause inflow of polluted surface waters to the area intended for levelling. Solely storm waters shall inflow into the area planned for levelling. Water conditions are strictly related to the geologic structure of the substrate and water level in the adjacent channels and the Odra river. Ground water of free table present in the heavily soaked peat stabilises in reference to the surface 0.05 – 0.10 m above (ordinate +0.24 – +0.64 m above sea level). The basic water-bearing strata are river sand and glacial-water sand underlying the organic strata. Ground water of perched table is present therein, close to the ordinate of 0.0 m above sea level. In order to reduce the possibility to pollute water, disposing into the ground, both during levelling and thereafter, during the area developing after levelling, of any substances that might affect the composition of ground water must be forbidden.
Based on other papers on the utilisation of ashes from power plants, it may be assumed that releasing of compounds present in CCP (coal combustion products) in trace quantities is minimal due to several reasons:

- The concentration of water-soluble substances depends on the type of combusted coal and amounts to approx. 2-3% of the total mass. The main water-soluble substances are hydroxides and calcium, magnesium, potassium and sodium sulphates – they represent roughly 98% of all leached substances. Among minerals, first of all calcite, melanterite, gypsum, glauberite, kalinite and sodium bicarbonate are washed out.
- From ashes and slag the most common wash out components are those of sulphur, calcium, magnesium, potassium and sodium. Among microelements, the easiest soluble are boron and cadmium.

The fly ash and slag mixture is incorporated in solid state (about 30% moisture content), which practically eliminates washing out of compounds. The results of water extract tests reflect a considerably lower content of characteristic impurities than required by the standards for water fit for human consumption. Additionally, it must be underlined that the above requirements have been presented in the light of potable water standards, namely very strict ones and inadequate to the discussed matter, where we would rather talk about wastes discharge to waters.

In the light of the requirements set for wastes discharged to surface waters or to ground, the impurities rate in water extracts are by far lower than the ones determined in Enclosure 2 to the Regulation of the Minister of the Environment of 29th November 2002 on Conditions for Wastes Discharged to Waters or Ground (Journal of Laws No. 212, item 1799).


Nad Odrą Street due to the possible assigning of the land for industrial purposes, it is designed to fill the levelled ground with fly ash and slag mixture while keeping to the following conditions:

- filling of the natural ground depression with fly ash and slag mixture in separately compacted layers, ground levelling shall be executed gradually.
- forming of the ground surface (covering layer)
- preparation of the ground for future industrial development.

Ground levelling has been executed gradually. The general direction of the progressing face of the levelling works shall be from south-west (from the existing access way) towards west. For the levelling works a technical stage of works has been planned covering for the works related to the required forming of the ground surface and covering of the levelled area. Removal of surface depression in the area to be levelled will be made with bulldozers and construction equipment.

The final stage of levelling shall be covering of the newly formed ground surface with 10 cm thick cover layer.
The designed ground ordinates shall range from 2.0 m to 6.0 m above sea level. Final ordinates shall range from 1.5 m to 5.5 m above sea level. The area of the ground to be levelled shall be about 96 000 – 97 000 m². The planned period of levelling works is 10 years. Taking into account the planned compression rate, the quantity of ash and slag mixture necessary for the ground levelling shall reach the maximum of 900 000 m³, i.e. about 1 260 000 tons, broken down into following stages:

– stage I, 2004 – 2007, plot no. 2/4, part of plot no. 2/7 600 000 tons,
– stage II, 2008 – 2010, part of plot no. 2/7 500 000 tons,
– stage III, 2011 – 2014, part of plot no. 2/7 100 000 tons.

Filling of the natural ground depression must be carried out from the lowest part of the ground, up to the particular ordinates (acc. to the cross-sectional drawings), until the final ordinates will be reached. The mixture shall be compacted up to the compaction index of $I_d = 0.50$.

The designed ground ordinates shall range from 2.0 m to 6.0 m above sea level, which will then be reduced after compression to the final ordinate of 1.5 m to 5.5 m above sea level.

The upper layer must be covered with a 10 cm top layer made of a mixture of peat and the local material – the existing output from water course dredging stored in the refill yard.
7. Compression.

The objective of this paper was to determine the consolidation rate of organic soil (peat and aggradate mud) underlying the plots nos. 2/4 and 2/7 at Nad Odrą Street in Szczecin. The measurements were made with the Ménard pressuremeter. In September 2004 the first stage of tests was made in six test points. Three of them are, however, located in the area that has been excluded from the fly ash and slag mixture improvement (forest) and one (no. 13b) is located on the verge of the mixture improved area. Therefore, the assessment of the consolidation progress has actually been carried solely for two test points – nos. 22 and 34. A layer of 3.1 m and 2.5 m of fly ash and slag mixture, respectively, has been applied. The determined current condition of the organic soil will form a reference material for further analyses and assessment of the consolidation progress of the soil under the load of the subsequent layers of fly ash and slag mixture incorporated.

During the works on site made on 6th December 2004 two mechanical boreholes of φ 60 mm down to the depth of 11.6 – 11.7 m below ground level (total 23.3 m bored), based on which 9 pressuremeter tests were made. The works on site were made under standing geological supervision of the authorised technician, who had also set out the test points based on the orthogonal method in reference to fixed points in the ground. The pits were levelled to the state benchmark set out on a wall of the building no. 3 at Nad Odrą Street (benchmark ordinate no. 013 H = 8.555 m above sea level in the Amsterdam reference system).

For comparative assessment mainly the pressuremeter tests results made in the same test points nos. 22 and 34 (in August, i.e. before fly ash and slag mixture incorporation and in December 2004, after incorporation and improvement with mixture) have been taken into account. However, in further analysis also the other archival pressuremeter test results included in the listed archival documents nos. 5751a and 5794 for approximate generalisations.

The current pressuremeter test results were analysed, as well as the archival ones based on the archival documentation no. 5794, for two test points – nos. 22 i 34. Thus, the analysis refers to the profiles before the beginning of the macro-levelling works (August 2004) and after incorporation of the fly ash and slag mixture and improvement of the ground (current tests in December 2004).

Beside of the points nos. 22 and 34 the other archival pressuremeter test points from the archival documents nos. 5751a and 5794 have been marked on the Documentation Map. The archival tests points may be used for generalised comparative analyses in this paper, as well as on the further stages of the research.

In the substrate of the researched ground four geotechnical layers have been separated in the organic soil subject to the tests, according to the PN-81/B-03020 standard, analogically to the archival document no. 5794. Both in the peat and in the aggradate mud two geotechnical layers each have been separated, according to the simple criterion of “weaker” and “stronger” soil.

The average values of the geotechnical parameters of the separated soil in layers I, Ia, II and IIa have been determined with the so called “A” method, according to the PN-81/B-03020 standard and based on the current and archival pressuremeter tests (separately).

Based on the pressuremeter tests results the previous condition (consolidation rate) of organic soil was determined, that will form the “background” for further analyses.
and assessment of the consolidation progress of the soil under the load of the subsequent layers of fly ash and slag mixture.

The applied “in situ” test method enabling the assessment of the mechanical performance of the organic soil was the Ménard pressuremeter test. Therefore, the geotechnical division criteria were the pressuremeter parameters: limit pressure $p_l$ and modulus $E_M$, that enabled the determination of the load capacity and compressibility of the soil.

Attention must be paid to the slightly different values of the pressuremeter modulus $E_M$ to the limit pressure $p_l$ ratio for peat and aggradate mud. For peat the values range from 4.6 to 6.9, while for aggradate mud – from 4.7 to 7.1. The average values are $E_M/p_l = 6.1$ and $E_M/p_l = 5.3$, respectively. Therefore, the pressuremeter moduli for mud are relatively slightly lower than for peat. This partially results from the structure of the peat “improved” with the non-decayed parts of plants, and partially from the difficulty in maintaining the intact structure of borehole walls made by hand in the aggradate mud.

Table 1 and Table 2 below presents the average values of the limit pressure ($p_l$), the pressuremeter modulus ($E_M$) and the consolidation rate (comparative analysis for test points no. 22 and 34).

### Table 1 [5] – point 22

<table>
<thead>
<tr>
<th>Borehole number</th>
<th>Depth (m)</th>
<th>Pressuremeter test parameters</th>
<th>Geotechnical layer no.</th>
<th>Type of soil</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>pressuremeter modulus $E_M$ (kPa)</td>
<td>limit load capacity $p_l$ (kPa)</td>
<td>$E_M/p_l$ ratio</td>
</tr>
<tr>
<td>22</td>
<td>4,0</td>
<td>598</td>
<td>86</td>
<td>6,9</td>
</tr>
<tr>
<td></td>
<td>5,0</td>
<td>786</td>
<td>116</td>
<td>6,8</td>
</tr>
<tr>
<td></td>
<td>6,0</td>
<td>893</td>
<td>126</td>
<td>7,1</td>
</tr>
<tr>
<td></td>
<td>7,5</td>
<td>666</td>
<td>134</td>
<td>5,0</td>
</tr>
<tr>
<td></td>
<td>10,0</td>
<td>760</td>
<td>160</td>
<td>4,7</td>
</tr>
</tbody>
</table>

### Table 2 [5] – point 34

<table>
<thead>
<tr>
<th>Borehole number</th>
<th>Depth (m)</th>
<th>Pressuremeter test parameters</th>
<th>Geotechnical layer no.</th>
<th>Type of soil</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>pressuremeter modulus $E_M$ (kPa)</td>
<td>limit load capacity $p_l$ (kPa)</td>
<td>$E_M/p_l$ ratio</td>
</tr>
<tr>
<td>34</td>
<td>3,0</td>
<td>604</td>
<td>81</td>
<td>7,5</td>
</tr>
<tr>
<td></td>
<td>4,5</td>
<td>599</td>
<td>131</td>
<td>4,6</td>
</tr>
<tr>
<td></td>
<td>6,0</td>
<td>721</td>
<td>178</td>
<td>4,0</td>
</tr>
<tr>
<td></td>
<td>8,0</td>
<td>730</td>
<td>168</td>
<td>4,3</td>
</tr>
</tbody>
</table>

Table 1 and Table 2 below presents the average values of the limit pressure ($p_l$), the pressuremeter modulus ($E_M$) and the consolidation rate (comparative analysis for test points no. 22 and 34).
According to the provisions of the opinion on ground and water conditions the peat compression shall result in reducing water permeability of organic soils, as well as
forcing out of interstitial water to the top. The processes shall prevent the possible infiltration of storm water that will percolate through the embankment body deeper into the substrate. The possible components washed out from the layer of mixture should not endanger underground waters.

It may be assumed that CCP application in the reclamation process shall not affect the quality of surface and ground waters. Quite the opposite: the research carried out in the areas reclaimed with the use of fly ash and slag mixture have proven explicitly that the quality of waters is improved to a major extent and this is mainly in areas that have been previously degraded, such as dumping grounds and municipal sewage discharge grounds or other degraded grounds. Should it be questionable that fly ash and slag mixture improve water quality in reclaimed areas, irrefutable is the fact that after removal of the influence of factors that are clearly harmful to the environment in the particular area and after the area reclamation with combustion by-products, among others, the condition of surface and ground waters came back to standard. This confirms both the self-improvement capacity of the natural environment and the fact that coal combustion by-products are neutral to the environment and do not pose a threat to it.
Picture 5. Ménard pressuremeter test in point 22 (December 2004, No. 5794a Geoproject).[5]
8. Conclusions.

Based on the analysis of the test results presented in the table, it appears that in the test points nos. 22 and 34 (columns 3 and 4 compared to columns 5 and 6), the organic soil consolidated after substrate improvement with fly ash and slag mixture. The limit pressure $p_i$ grew by approx. 7 – 35%, while the growth of the pressuremeter modulus value ($E_M$) reaches 10 – 16%. The most visible growth in the load capacity of the soil (i.e. by approx. 35%) was present in the head layer of peat, which is obvious, as this resulted directly from the ballast of the fly ash and slag mixture.

Generally, it may be said that upon incorporation of fly ash and slag and improvement of the ground with a layer of 2 – 3 m, the organic soil got partially consolidated within the short period of 4 months. Attention must be drawn to the fact, that compressible organic soils (peat, aggradate mud) are characterised with a long period of full consolidation. Completion of the process of consolidation will not occur earlier than after several tens of years under no pressure.

Literature:


4. Enclosure 2 to the Regulation of the Minister of the Environment of 29th November 2002 on Conditions for Wastes Discharged to Waters or Ground (Journal of Laws No. 212, item 1799). (in Polish)

5. EKOTECH Inżynieria Popiołów (Research test made by Geological Enterprise GEOPROJEKT Szczecin)


14. PN-81/B-03020 Grunty budowlane - Posadowienie bezpośrednie budowli (obligatory polish legislation for soil and foundation)

15. Regulation of the Minister of the Environment of 27\textsuperscript{th} September 2001 on Wastes Catalogue (Journal of Laws No. 112, item 1206). (in polish)