Proceedings of the South Baltic Conference on
Dredged Materials in Dike Construction
Rostock, 10-12 April 2014
ISBN: 978-3-86009-409-9
www.dredgdikes.eu

INVESTIGATION ON WATER INFILTRATION AND WATER CONTENT CHANGES IN A LARGE-SCALE EXPERIMENTAL TEST DIKE

Rafał Ossowski[1], Zbigniew Sikora[2], Remigiusz Duszyński[3], Jacek Sawicki[4]

[1, 2, 3, 4] *Gdansk University of Technology, Narutowicza 11/12, 80-233 Gdansk, POLAND, ross@pg.gda.pl, zbig@pg.gda.pl, rdusz@pg.gda.pl*

Abstract. The paper presents result of series of experiments made within the DREDGDIKES project, performed on a test dike built from composite soil. The composite is produced by mixing fly ash (by-product of energetics) with dredged material (sand) taken from the mouth of The Vistula river. The test dike, located near Gdansk in Poland, was subjected to hydraulic load in several flooding time scenarios and the unsaturated unsteady flow was measured using moisture sensors. There are experimental results presented via evolution of moisture (degree of saturation) in the dike core is. The experiments are compared and final conclusions are presented.

Keywords: Dikes, Composite Soils, CCPs, Green Geotechnics, Unsaturated Flow

1. Introduction

An average observer can notice the increasing frequency of floods which have caused several serious disasters in Central and Eastern Europe in the past 20 years. To prevent flood disasters one has to gain the knowledge of possible failure mechanisms caused by floods. It is also needed for a reliability assessment of existing dikes (and its restoration) and for an optimal design of new dikes. The design process has to be closely linked to the proper analysis of construction material – both in micro-scale (e.g. microscopic investigation of bonding) and macro-scale (field and laboratory tests). Engineers have to investigate new materials for dike construction to find optimal solutions – in economical and mechanical sense.

The proposed study is strictly connected to composite soils: namely mixtures of sand with CCP (Coal Combustion Products) and the motivation for usage of these materials for dikes is linked with aforementioned aspects. From an economical point of view the composition of sand (e.g. dredged from the adjacent river) and CCP (e.g. fly-ash) is a cost-effective option. It allows to cut the transportation costs, moreover – it has also an environmental friendly aspect (lower CO2 emissions compared to natural binders such as cement and recycling of ashes instead of storing them in waste disposals). Considering mechanical properties: one can expect an increase of shear strength of such composite as a result of binding properties of ash as well as a decrease of permeability coefficient comparing to "pure" soil. It is necessary to perform series of laboratory tests to find an optimal mixture – composite soil to be used on construction site.

2. The test dike

The experimental dike section in the bank of the Vistula river has been constructed by Gdansk University of Technology as an experimental site, realized within the DREDGDIKES Project (www.dredgdikes.eu), in cooperation of partners from Germany and Poland. While in Poland the investigation is focused on sand-ash composites application in dike construction, the German partner institutions, under direction of Rostock University, are investigating ripened fine-grained organic dredged materials in combination with geosynthetics for flood protection constructions (Cantré, Saathoff 2013, Cantré et al. 2012, Saathoff 2003).

The test dike is a prototype dike model and the dike core is built of composite soil: river sand mixed with fly-ash (see Fig.1). To obtain an optimal mixture, a series of laboratory experiments were performed. There were different sand & ash ratios investigated and its mechanical and flow properties were studied.

The prototype dike, being 3 m high, was built on the bank of the Vistula in Trzcinisko, 20 km from the center of Gdansk. The clay layer was put on the ground level in order to make an impervious layer at the bottom and to avoid filtration under the dike.

Fig 1. The prototype dike near Gdansk, constructed from composite soil

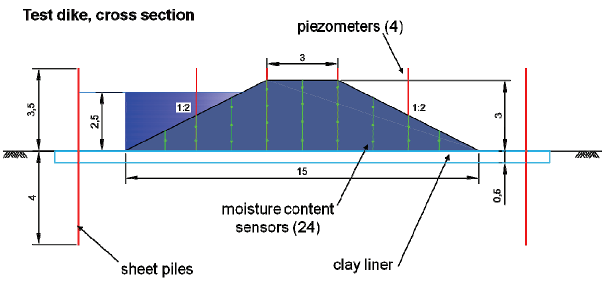


Fig 2. The experimental dike near Gdansk: cross-section with sensors placement

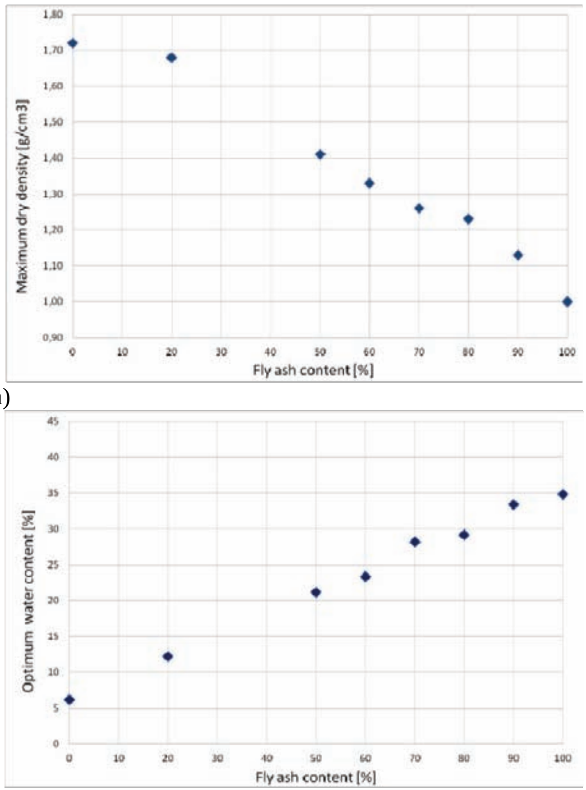
The dike has a separated (with sheet piling) section 5 m wide (see Fig. 1), to enable simulations of flood conditions with variable water levels. The dike instrumentation includes 4 water level gauges (piezometers) and 24 moisture sensors installed in the section center (see Fig. 2).

2.1 Construction material

The goal of the preliminary laboratory investigation was to choose the optimum ash - dredged sand mixture of a composite soil to be applied at the test site. The tests were performed to determine basic soil properties, soil strength and compressibility, compaction and permeability parameters. The tests were made on dredged sand and fly ash itself as well as on the mixtures with different fly ash content. The mixtures were prepared using volumetric ratios. In the first stage properties of ash and sand were investigated, (see Table 1). Mean specific gravity of dredged sand was determined to 2.67 g/cm3. Mean specific gravity of fly ash was estimated as 1.87 g/cm3, being in the range from 1.77 g/cm3 to 1.95 g/cm3.

Table 1. Granulometry and specific gravity of the fly ash and dredged material (Bałachowski & Sikora, 2013)

Parameter	Ash	Sand
Uniformity coefficient U	2.00	3.14
Curvature coefficient Cc	0.87	1.30
Mean grain diameter d_{50} [mm]	0.20	0.40
Specific gravity ρs [g/cm^3]	1.87	2.67



a)

b)

Fig 3. Ash content vs.
a – maximum dry density; b – optimum water content

There were also studied compaction properties in series of experiments. The tests were performed in Proctor apparatus for 1 dm^3 mould with three layers of materials compacted with 25 blows of the rammer. The optimum water content and the maximum dry density were determined for ash – sand mixtures in the range from 0 to 100% of the ash content with 10% step. The obtained compaction curves are rather flat and the maximum dry density is not well defined, as the materials are difficult to compact, (Sas et al., 2012). There was also a modification of the fly ash granulometry observed, caused by grain crushing, as described by Zabielska-Adamska (2008). The dry density decreases and optimum water content increases with increasing fly ash content (see Fig. 3).

To study the strength behaviour of the composite, the direct shear tests for the mixtures were made to estimate the internal friction angle and cohesion. All tests were made on reconstituted samples. For different mixtures the angle of internal friction varied between 28^o and 40^o, in general the angle decreases with increasing fly ash content. The measured cohesion is negligible for low fly ash content and slightly increases to several kN/m^2 for higher fly ash content (see details in Bałachowski & Sikora, 2013). After completing all series of experiments the mixture of ash-sand (70/30) was chosen for test dike construction, having optimal compaction properties and good effective strength parameters: angle of internal friction equal to 38^o and cohesion equal to 5 kN/m^2.

2.2 Environmental analysis

There are numerous concerns on environmental aspects of using ashes in soil constructions. The ecologists are suspicious to all CCPs, indicating high concentration of heavy metals and other toxic materials, increased radiation etc. In order to repel such a speculations, the European Coal Combustion Products Association (ECOBA) deputed a series of environmental analyses to get the REACH (Registration, Evaluation and Authorisation of Chemicals) certificate for ash-based products.

To address these issues within the DREDGDIKES project, several chemical analyses were made, both for components of composite soil and water filtration through the dike body. The samples of dredged sand and ash were tested on a chosen set of chemical properties closely related to environmental indicators and water purity indictors. Some results, related to heavy metal content in sand and ash, are presented in Table 2. Additionally, a sample of composite soil was taken from the test dike and placed in triaxial apparatus to obtain a leachate sample. The leachate was produced by saturating the probe and slow circulation of pure water through the sample. The value of acceptable content (occupational exposure limit) is presented in Table 3, as a reference. This reference value is mandatory for most strict requirements of soil subjected to environmental protection and drinkable water resources, and it is mostly fulfilled by a margin of safety for this material. Moreover one can observe much lower values of heavy metal concentration in leachate, compared to constituents; it confirms wide opinions of forming so-called ash matrix, as a result of developing cementation, which traps heavy metal molecules in skeleton, thus not allowing them to be freely dissolved.

2.3 Hydraulic properties

Another interesting indication for cementation is a series of hydraulic conductivity tests. Initially, the hydraulic conductivity of the optimum fly ash – dredged material mixture (70/30) was measured in constant head apparatus on a fresh sample reconstituted in laboratory. In this case the hydraulic conductivity of fresh mixture k_{10} was estimated to be close to $9.4 \cdot 10^{-5}$ m/s. Hydraulic conductivity was also measured on (70/30) mixture sample taken from the dike core. The test was performed during 3 weeks.

The values of hydraulic conductivity corrected for the temperature effect were decreasing with time, considered from the dike construction. Finally, the conductivity coefficient after 2 weeks of measurements had stabilized. The hydraulic conductivity corrected for temperature effect k_{10}, was estimated to be close to $1.3 \cdot 10^{-5}$ m/s. It is about 7 times lower than the one measured on the laboratory prepared (70/30) mixture. Future investigations will take into account tests on soil samples taken from the dike core in different time steps after construction.

3. The experiments

The described test dike was completed in autumn 2012 and instrumented in the end of 2012. First large-scale experiments started in spring of 2013. There were two lowland flood scenarios investigated, namely: a short flood wave (one-week experiment) and a long flood wave (two-weeks double peak experiment). The experiments were conducted in 2 repetitions each to observe the mechanic and hydraulic behaviour under cyclic saturation/desaturation process.

Figure 4 presents the hydraulic loading – water level in the upper basin for the mentioned two flood scenarios. One can observe the rather steep curve in the beginning of each scenario, which was caused by a small volume in the upper basin and resulting fast filling by medium-sized pump (increasing the water level in upper basin from 0 to 2.5m takes about 1 hour). Although in nature the uplift of water table takes more time, we consider this case to be more dangerous to the dike structure compared to slower filling (due to higher gradient of pressures inside dike core), therefore this fast-filling option was chosen to be simulated. The water was hold in the upper basin - slowly infiltrating the dike core – and subsequently:

- in a first (one-week) scenario, water was released from the upper basin after 6 days,
- in a second (two-weeks) scenario, we simulated a second flood peak and, finally, water was released from the upper basin after 13 days.

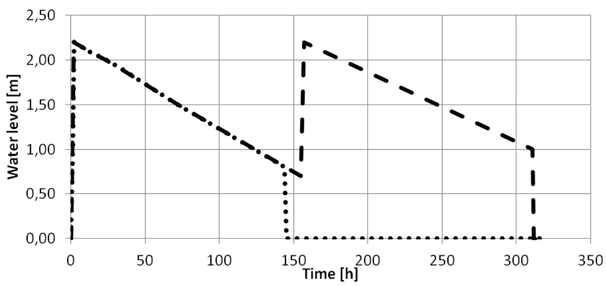


Fig 4. Flood wave shape: one-week experiment (dotted line) and two-week wave (dashed line)

Table 2. Results of the chemical analysis of composite soil

Analysis	Unit	Sand	Ash	Leachate water	Reference value
Lead (Pb)	[mgPb/kg]	16.0	23.0	<0.2	50.0
Cadmium (Cd)	[mgPb/kg]	<0.5	<0.5	<0.01	1.0
Copper (Cu)	[mgPb/kg]	<2.0	30.0	<0.05	30.0
Mercury (Hg)	[mgPb/kg]	0.0018	0.0140	0.0009	0.5
pH	[-]	7.98	8.90	7.52	-

The measurements of soil moisture were performed using dielectric moisture sensors EC-5. The sensors measure volumetric water content (VWC) in soil, in order to obtain geotechnical parameter, such as the degree of saturation (S_r), which is calculated by dividing VWC by the porosity n:

$$S_r = VWC/n \tag{1}$$

Despite controlling in the construction phase, it is impossible to have perfectly homogenous compaction in the dike core; as a result, a slight variation of porosity in the dike core is expected. The mean value of porosity in the dike was estimated to be n=0.4 and this value was used for S_r calculation in the general case. We were able to adjust the value of n for the lower moisture sensors when completely saturated by measuring maximum value of VWC.

The moisture development in the one-week flood scenario is presented below (Fig. 5, 6, 7, 8) in chosen time steps (artefacts due to linear interpolation between measurement points).

Although there is not much visual difference between pairs of graph, one can notice a little higher line of fully saturated region in the second experiment. Similar results were observed in two-week series of experiments. This effect gets more clear if the water levels in the piezometers are compared at the same time in subsequent experiments, (see Table 3).

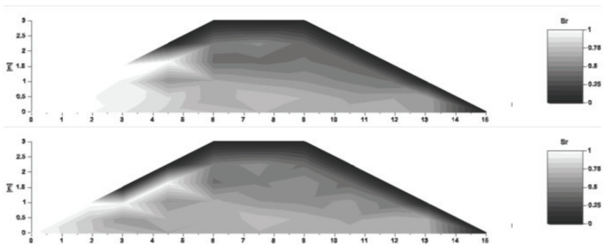


Fig 5. Maps of S_r at t=1h; experiment: No.1 (upper graph) and No.2 (lower graph)

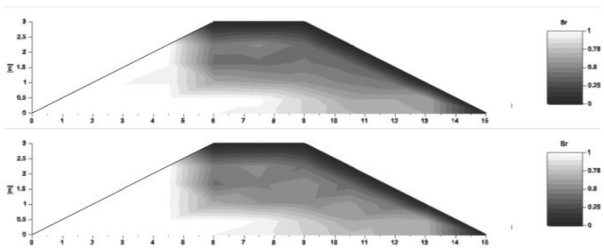


Fig 6. Maps of S_r at t=4h; experiment: No.1 (upper graph) and No.2 (lower graph)

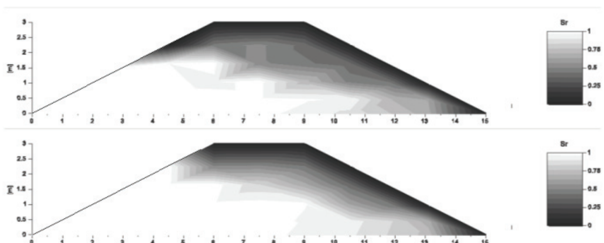


Fig 7. Maps of S_r at t=24h; experiment: No.1 (upper graph) and No.2 (lower graph)

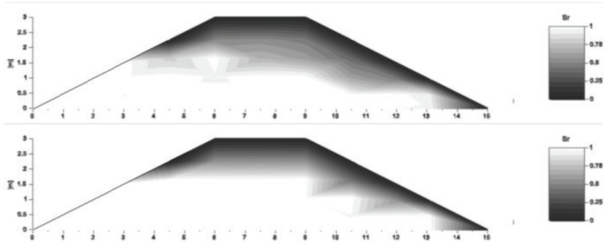


Fig 8. Maps of S_r at t=72h; experiment: No.1 (upper graph) and No.2 (lower graph)

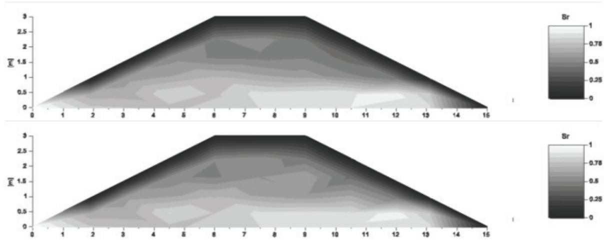


Fig 9. Maps of residual S_r at t=96h after water release in experiment: No.1 (upper graph) and No.2 (lower graph)

Table 3. Water levels measured in piezometers in subsequent experiments at given time

t=6h				
Exp. No	P1[m]	P2[m]	P3[m]	P4[m]
No1	2.11	0.48	0.15	0.00
No2	2.26	0.51	0.21	0.00
No3	2.15	0.48	0.21	0.00
t=36h				
Exp. No	P1[m]	P2[m]	P3[m]	P4[m]
No1	1.90	1.54	0.95	0.00
No2	2.10	1.77	1.19	0.18
No3	2.00	1.62	1.04	0.23

Table 3 shows the results of three experiments: two one-week series (No1 and No2) and experiment No3, a two-weeks wave, which had the same first phase characteristics as the previous two experiments (see Fig. 4). As we can see, there is not much difference after 6 hours between the three waves. The variations in the first piezometer (P1) are caused by a little higher water level in the upper basin at the beginning of experiment. There are however differences visible after 36 hours: In piezometer P3 clearly higher water levels in experiments No2 and No3 are observed. In experiment P4 an increase of water level is registered with each repetition of experiment. The reasons of such behaviour can be twofold:

- increasing residual moisture after each repetition (there were a break of 2 weeks between each experiment) - see comparison of residual moisture in experiments No1 and No2 on fig. 9,
- flushing out of small particles resulting in a increase of hydraulic conductivity of the dike core.

A clear answer will be possible after completing the whole programme of experiments after the second year of research.

4. Conclusions

1. The described research activity is an answer to current flood events in Poland, Germany and other European countries. The proposed approach can be considered as a part of "Green Geotechnics" paradigm (Sikora et al. 2012), which aims to promote environmentally friendly activities in the framework of geo-engineering. The Eco-aspect is understood here as a reduction in the amount of solid waste (reuse of fly ash), CO2 reduction (use of low-emission materials) and reducing energy consumption (use of materials available near the construction site.
2. The laboratory tests have shown that the CCPs have good mechanical parameters, comparable with mineral soils, e.g. silts and fine sands. Mixing the CCPs with mineral soil, such as dredged sand, fairly improves the parameters of such a composite, with strength developing in time due to cementation.
3. The laboratory investigations showed clearly that the composite soil, such as mixture of sand with ash, is a very promising engineering material, but not so simple in its physical behaviour. That is why constitutive modelling – in sense of skeleton mechanics, but more important: water – skeleton interaction should be carefully studied. Firstly, we need to verify the principle of effective stress in case of composite soil. There are several proposals of such formulas in general form, see Ossowski & Sikora (2004).
4. The experimental results at current stage give of research proved usability and excellent mechanical behaviour of the used composite material. The evolution of the water content inside the dike was presented in the paper, however at this stage no conclusions can be given regarding the influence of water table changes on the dike internal structure. Additional research has to clarify if the faster flow through the dike core in consecutive experiments is caused by increased hydraulic conductivity or if it is an effect of higher initial moisture.
5. Further research shall focus on unsaturated model parameters (e.g. van Genuchten (1980)) and cementation effects, which are important issues in mechanical behaviour of the described composite soils. Calibrated and verified models can be used to simulate various hydrological load scenarios on the dike, to confirm the stability of the dike.

Acknowledgments

The current research on application of soil-ash composites for dike construction in the DREDGDIKES project is part-financed by the European Union, South Baltic Programme (ERDF). The authors are grateful to all DREDGDIKES project partners and associated organizations for their continuous support.

References

Bałachowski, L; Sikora, Z. 2013. Mechanical properties of fly ash - dredged material mixtures on laboratory test, *Studia Geotechnica et Mechanica, Vol. XXXV, No. 3, 2013*.

Cantré, S., Saathoff, F., Große, A.-K., Nitschke, E. 2012. Dredged Materials in Dike Construction: First Results of the DredgDikes Large-Scale Field Tests in Rostock, *Proceedings of the 12th Baltic Sea Geotechnical Conference, pp. 281-285*

Cantré, S.; Saathoff, F. 2013. Investigation of dredged materials in combination with geosynthetics used in dike construction, *Proceedia Engineering, vol. 57, pp. 213-221*

Ossowski, R., Sikora, Z. 2004. Numeryczne modelowanie sondowania statycznego CPTU, Gdansk University of Technology, Gdansk (in Polish).

Saathoff, F., 2003. Geosynthetics in geotechnical and hydraulic engineering, in Smoltczyk (Ed.). Geotechnical Engineering Handbook, Berlin: Ernst&Sohn, pp. 507-597

Sas W., Szymański A., Malinowska E., Gabryś K. 2012. Geotechniczne uwarunkowania zastosowania materiałów antropogenicznych w budownictwie, *Inżynieria Morska i Geotechnika, 4, 376-380 (in Polish)*

Sikora, Z., Szczygielski, T. and Ossowski, R. 2012. Green Geotechnics in practice and theory. *Proceedings. 40th Conference Zakládání staveb – Foundations; ČGtS (Eds.), Brno, 184-191*

van Genuchten, M. 1980. A closed form equation for predicting the hydraulic conductivity of unsaturated soils, *Soil Science Society of America Journal. J., 44 (5), 892-898.*

Zabielska-Adamska, K. 2008. Laboratory compaction of fly ash and fly ash with cement additions, *Journal of Hazardous Materials, 151, 481-489.*