GEOTECHNICAL CONDITIONS OF INDUSTRIAL WASTE LANDFILL CONSTRUCTION FOR U.S. STEEL SERBIA

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ABSTRACT. U.S. Steel Serbia Company, produces about 1 150 000 tons of industrial waste every year, and almost a half of it (500 000 t) is reused or recycled, either within the same company or outside of it. The rest of the industrial waste is permanently disposed. The latter includes disposing of the solid industrial waste – steel slag, and also a sludge from the substation for industrial waste water treatment. In this regard U. S. Steel Serbia Company has started with the construction of the first certificated substation for the industrial waste management in the Republic of Serbia, in 2011. The facility also includes the industrial waste landfill body with two independent cells: smaller – for the disposal of hazardous industrial waste and bigger – for non-hazardous industrial waste. The total available volume is approximately 4 685 000 m^3, 235 000 m^3 of which is for industrial hazardous waste and 4 450 000 m^3 for non-hazardous waste. Considering that in one part the height of the landfill should reach 50 m, it was necessary to analyse an important geotechnical factors for the proper evaluation of industrial waste permanent storage. Therefore, the most important geotechnical problems which are analysed for the construction of the landfill and the other waste management facilities within U.S. Steel Serbia Company are presented in this paper and they are: conditions of the landfill body design for the hazardous and non-hazardous industrial waste – stability analysis, the landfill settlement with the analysis of the landfill impact on the terrain and surrounding objects, excavation and preparation of the substrate for the landfill body, construction conditions of the associated facilities and the arrangement of the terrain with the traffic roads construction.

Keywords: industrial waste landfill, slag, stability, settlement.

INTRODUCTION

U.S. Steel Serbia Company, produces about 1 150 000 tons of industrial waste every year, and almost a half of it (500 000 t) is reused or recycled, either within the same company or outside of it. The rest of the industrial waste is permanently disposed. The latter includes disposing of the solid industrial waste – slag, and also a sludge from the substation for industrial waste water treatment. In this regard U. S. Steel Serbia Company has started with the construction of the first certificated substation for the industrial waste management in the Republic of Serbia. The aim of this facility is permanently disposing of eleven types of the industrial waste in rational and safe way. Based on the volumes of waste in year 2008, the estimated volumes of waste which would be disposed annually are shown in Table 1.

Tabl. 1 Annual quantity of waste to be landfilled

Types waste	Classificat.	Solid/ Sludge	Volume (m^3)
BF lump slag	nHZW	Solid	130681
Convertor slag	nHZW	Solid	100754
Mixer slag	nHZW	Solid	65605
BF sludge	HZW	Sludge	9565
Neutralization sludge	HZW	Sludge	7630
Refractory waste	HZW	Solid	1888
Steel turnings	nHZW	Solid	40
Roll shop machinery waste	nHZW	Solid	11
Tandem mill sludge	HZW	Sludge	411
Filter cake	HZW	Sludge	855
Tin mill sludge	HZW	Sludge	6
Total			317446

Designed period of exploitation of the landfill is 10 years, but the cells for hazardous and non-hazardous waste would be filled in phases, on 5 years. The total available volume of the landfill is approximately 4 685 000 m^3, of which 235 000 m^3 is for industrial hazardous waste and 4 450 000 m^3 for non-hazardous waste. With amount of waste that will be disposed, it should be provided to dispose 900.000 m^3 of the BF lump slag which is currently located on the site (Table 2).

The industrial waste landfill body consists of two independent cells: smaller – for the disposal of hazardous industrial waste and bigger – for non-hazardous industrial waste (Figure 1).

The PUO facility has the following functional units: the landfill body; manipulative-service plateau (on which are located all auxiliary facilities necessary for the performance of all planned activities during the work of the landfill complex); internal traffic roads (they connect all objects and facilities); system of protective boundary channels (with it the rainfall water from the surrounding catchment areas and from the landfill body are drained in the shaft for the recirculation).

Tabl. 2 Volumes to be disposed from 1 year till 10 years

Type of cell	Present waste (m^3)	Yearly production for landfilling (m^3)	Years	Total capacity needed (m^3)
nHZW-solid	900000	297091	1 - 5	2385455
HZW – solid	0	1888		9440
HZW - sludge	0	18467		92335
nHZW-solid	0	297091	6 - 10	1485455
HZW – solid	0	1888		9440
HZW - sludge	0	18467		92335
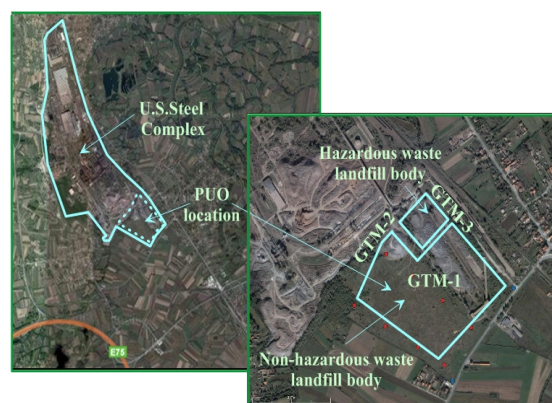
Fig. 1 PUO location within US Steel complex with the zones of geotechnical models

GEOTECHNICAL CHARACTERISTICS OF THE LOCATIONS

Geotechnical characteristics of the natural terrain

The waste management facilities – PUO are located southeast of the steel factory US Steel Serbia complexes, in the southeast part of the city Smederevo between the river Ralja and the local asphalt road

Ralja-Vranovo. It occupies an area of about 37 ha, on the terrain that belongs to a typical alluvial lowland part of the right coast of the river Danube, with elevations in the range of 85 to 87 m. At this location, in several phases, terrain and laboratory geotechnical investigations were performed, during the years of 2009 and 2010 (Geomehanika, 2010). From the terrain investigations, in total it was carried out: 15 exploratory borehole depth of 10 to 35 m, in 4 of them standard penetration tests – SPT were performed, 15 static penetration tests – CPT, two wells in which the piezometer construction was built, 3 exploration pits and one test field.

The terrain and laboratory researches were used to define the geological structure of the exploration field in which the following lithological members were isolated: the humus layer (variable thickness from 0.3 to 1.2 m); embankment (it was formed in northeast part of the location from the industrial waste – slag, thickness up to 2.5 m); dusty materials (they form overlain and within this package three relatively similar lithological members were isolated); sands (within them, based on compaction, two zones were isolated: more and less compacted zones and they appear at depths under 11 m with respect to the surface of the terrain); gravel (the deepest layer that was determined in the exploratory borehole IB-6 up to a maximum drilling depth of 35 m). A constant level of groundwater at a depth of about 12 m with respect to the surface of the terrain was determined by the explorations, and since the maximum depth of the excavation for the forming of the landfill body is 8.5 m, the groundwater didn't have a greater influence on the formation of the landfill base.

Geomechanical laboratory tests included the tests of natural materials at a total of 89 soil samples (on 71 samples identification-classification data were determined only, on 15 samples beside the determination of identification-classification data the strength and deformability tests were performed and on 3 samples from the exploratory pits Proctor and CBR test were performed). The results of the basic physical and mechanical parameters for the isolated lithological environments are presented in Table 3.

Tabl. 3 Adopted values of physical and mechanical properties

| Lithological environment	t/t_{sat} (kN/m³)	φ' (°)	c' (kN/m²)	$M_{v100-200}$ (MN/m²)	q_c (MN/m²)
Silty materials- ML, CL	19/20.5	19-24	3-26	3.6-8.5	2.2-4.0 4.0-8.0
Sands and silty sands- SP,SC,SM	19.5/20	25-30	0-2	-	20-30
Gravel and silty gravel- SP, GP	21	-	-	-	> 30.0

Geotechnical characteristics of the landfill material

There is still no international accepted standard procedure for sampling and testing of the industrial waste. The reason for this is the extreme heterogeneity of the waste (in composition, size and shape of the fractions, the different characteristics of the certain waste types). Furthermore, the mineralogical composition of the industrial waste is different from the soil. Therefore, the tests are generally performed on artificially prepared samples, taking into account the moisture content, compaction, content percentage and shape of waste particles. Appearance of the industrial waste – slag, which will be disposed on the landfill for non-hazardous waste is shown in Figure 2.

Fig. 2 Appearance of non-hazardous waste (slag) which will be disposed on the landfill

Geotechnical laboratory tests on samples of the landfill material of which will be formed the landfill body (hazardous and non-hazardous industrial waste), were perfomed on 5 samples. The test results of the grain size distribution for different types of waste are presented on Figure 3.
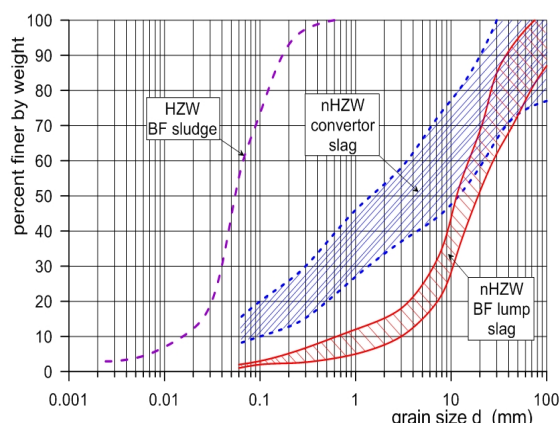
Fig. 3 Grain size distribution curves for different types of waste

Regardless of the fact that the industrial waste is significantly different from the soil, for determining the mechanical properties, techniques that are used are those ones developed for the soil. So, for determining the shear strength linear Coulomb-Mohr-Terzaghi fracture criterion is still used the most, defined in terms of angle of internal friction φ' and cohesion c'. In practice, the most commonly used two methods to determine the shear strength parameters are: laboratory tests (direct shear test and triaxial compression test) and feedback analysis and monitoring of the defined slides or of unstable slopes in landfills. From laboratory tests, the most commonly used is direct shear test, primarily due to the simpler sample preparations, which are generally larger dimensions. In Table 4 values of the most important physical-mechanical characteristics of the industrial waste - slag, obtained through geomechanical laboratory tests are presented.

Tabl. 4 Adopted values of physical and mechanical properties of slag

Type of steel slag	t/t_{sat} (kN/m³)	φ' (°)	c' (kN/m²)	E_{ref} (MN/m²)
BF lump slag	15/15.5	36-54	0-4	20
Convertor slag	16.5/18	29-34	0-3	20
BF sludge	17/18	24-29	3-8	7.5

When it comes to shear strength, it should be mentioned that this is a material that is well graded and in which dominate non-rounded particles with rough surfaces. Therefore, these materials manifest good frictional properties. Based on some literature data, angle of internal friction of slag from blast furnaces varies φ'= 40 - 50º (Noureldin and McDaniel, 1990).

Laboratory analysis showed that the slag can be used in the construction of traffic roads (for the base and bearing layers), because the CBR values ranged between 21.2-30.2% and that at the optimum moisture content w_{opt}=6.6-11.1%, dry unit weight ranges t_{dmax}=16.4-18.9 kN/m³ (Figure 4).

According to some literature data, it can be seen that the slag has a lot of good physical and mechanical properties: G_s = 3.2 - 3.6; t_d = 16 - 19.2 kN/m³; absorption of water up to 3%; Los Angeles - wear from 20 - 25%; hardness between 6 and 7 and the California bearing ratio (CBR) can be over 100% (Yildirim and Prezzo, 2009).
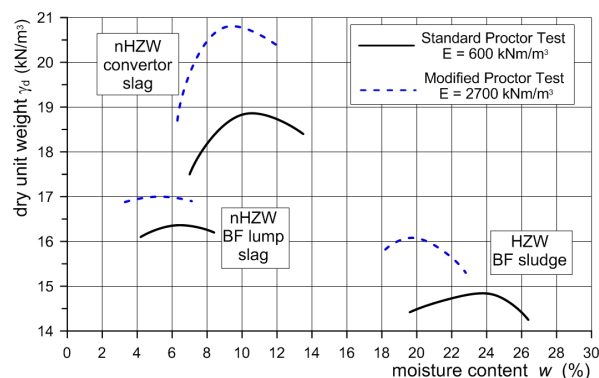
Fig. 4 Comparison of standard Proctor test and modified Proctor test for different types of slag

DEFINING OF THE GEOTECHNICAL MODELS

Based on the results of terrain and laboratory tests, geotechnical models for the terrain are defined, which were necessary for the geostatic analysis. Due to the surface of the exploration area, and the position of the associated structures, including the cells of the landfill, three geotechnical models were defined (Rakic and Vojnovic, 2010).

GTM-1 - geotechnical model of the terrain which relates to geostatic calculations of the landfill body (the central part of the site which occupies the largest area of the terrain - Figure 5), GTM-2 - geotechnical model of the terrain in the zone of associated facilities (reservoir for tin sludge, weighbridge, tank for recirculation of seepage and atmospheric water, car wash facility, office building - northwest part of the location Figure 6). GTM-3 – is the geotechnical model of the terrain in the zone of the depot for storing of temporary waste (north-eastern part of the location).
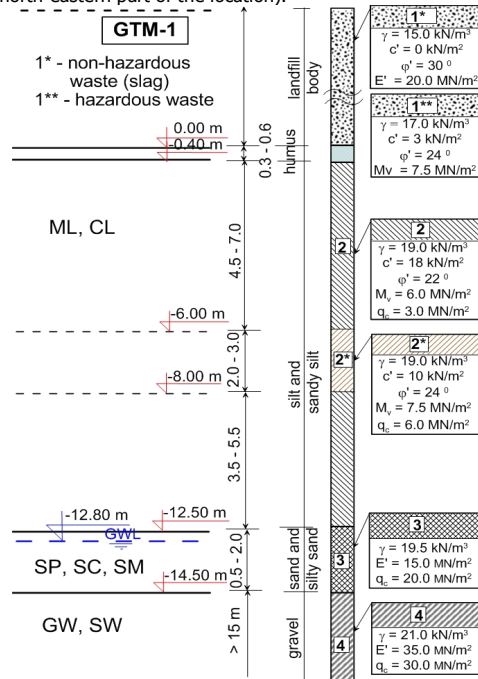

Fig. 5 Adopted geotechnical models of the terrain in the zone of the landfill bodies for hazardous and non-hazardous waste
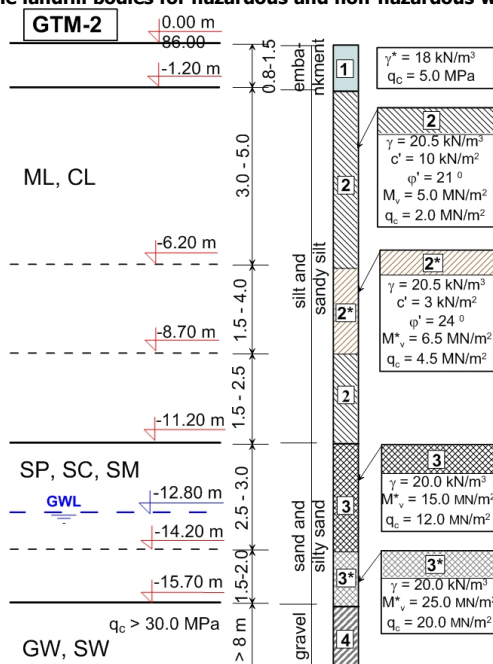

Fig. 6 Adopted geotechnical models of the terrain in the zone of associated facilities

GEOTEHNICAL CONDITIONS FOR THE CONSTRUCTION OF THE LANDFILL

Regulated industrial waste landfills, can be defined as: "an engineering construction (filled, embedded or partially embedded structure), which was built and equipped for continuous, controlled, organized and safe disposal of industrial waste." It builds on the previously prepared and protected natural terrain by impermeable barrier system, in which the waste is transported, planned filled and compacted, if it is necessary, it is covered with suitable protective system (Rakic, 2011). Regulations in this area are changing constantly, because the construction of a modern waste landfill includes solving a series of problems such as: ecological, economical, hydrological, infrastructural, technological, constructional, geological and certainly geotechnical problems.

The most important geotechnical problems that are usually analysed, mainly are related to vertical and horizontal displacement. This primarily refers to the load capacity test of a base, settlement of a base and waste within the landfill, slope stability of the landfill, waste interaction with natural or geosynthetic materials that are used as protective systems and tightness of protective layers in the base and on the surface (Rakic, 2011). In this regard, geotechnical analyses that have been carried out at this location, were related to:
- Formation of a landfill body of hazardous and non-hazardous waste (stability analysis);
- Landfill settlement with the analysis of the influence on the terrain and surrounding objects;
- Excavation and preparation of the base for the landfill body;
- Construction terms for the associated facilities;
- Landscaping and construction of the traffic roads.

In all filled geotechnical objects, one of the major problems that must be solved is certainly the slope stability. That is why preventive measures are taken to stabilize slopes of landfills and the most common are: choice of slope angle for the required factor of safety, the tape of disposal of industrial waste, setting up security systems in the base, the reinforcement of slopes, placement of surface protection systems etc. It should be noted that the shaping of the landfill body is conditioned by time and that the shear stresses in the zone of slopes change in time (Rakic, 2011).
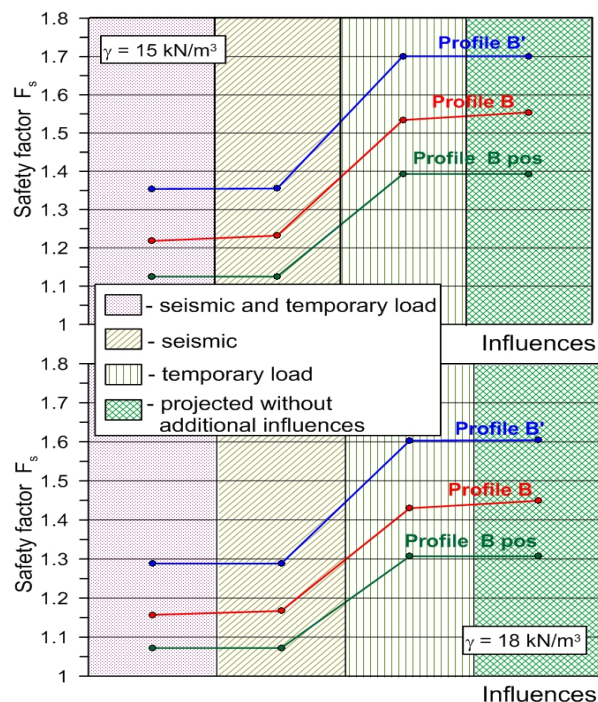
The stability analyses were performed for the characteristic profiles of the landfill (include both cell - for non-hazardous and hazardous waste) with the projected slopes of 1:3 inclination, but at a certain height berms were projected with width of 6 m. In both cases, the analyses were performed for the cases of landfill saturation in the excavation up to the level of 86 m. Although, in practice, such extreme conditions are not expected, it was started from the fact that the results will be on the side of safety. Other impacts that were involved in slope stability analysis are: dead load in the form of the mass of the landfill embankment (different volume weights were used: t = 15 kN/m³ for disposed industrial waste in the moment of disposing; t = 18 kN/m³ after completed degree of degradation and most of the consolidation; t = 17 kN/m³ for disposed material of hazardous waste); temporary load in the form of seismic impacts, temporary load which refers to the movement of transport vehicles at the landfill berms (dumper with a maximum weight of 120 t). All stability analyses were performed using the software package SLIDE, using Bishop, Spencer and Janbu methods. In these analyses the shear strength parameters obtained in the laboratory tests by the direct shear apparatus on samples of waste materials were used (for hazardous waste: $\varphi' = 24^0$ and cohesion c' = 3 kN/m², for non-hazardous waste – slag $\varphi' = 32^0$ and cohesion c' = 0 kN/m²).

For the characteristic profiles on Figure 7 just some of the results of stability analysis by the Janbu method were presented (the lowest values of F_s were obtained by this method) in terms of the impact factor. From the presented results it can be seen that the slope stability of the landfill is confirmed, according to pre-defined criteria in relation to the minimum value of the safety factor, as follows: Fs$_{min}$ = 1.05 - when all the influences are included in the analysis and Fs$_{min}$ = 1.3 – when only the dead load of the disposed material weight is taken into account in the stability analysis (Figure 8). In Figure 8 it can also be seen that the seismic influences are significant in terms of slope stability, and on the contrary the temporary load from dampers influences very little on the slope stability of the landfill.
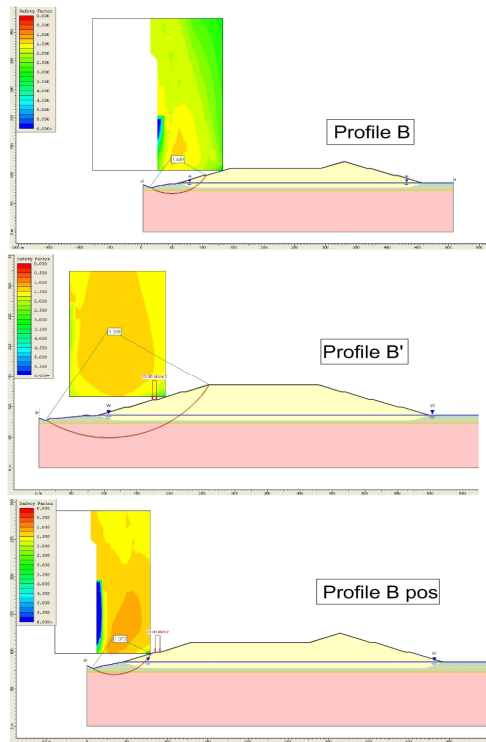
Fig. 7 Characteristic profiles of non-hazardous waste landfill on which the slope stability analyses were performed

**Fig. 8 Results of the stability analysis of the landfill slopes for the characteristic profiles**

In addition, based on the performed analyses, it was concluded that a significant impact on the slope stability of the landfill, has a small distance of the river Ralja river bed (Figure 9).
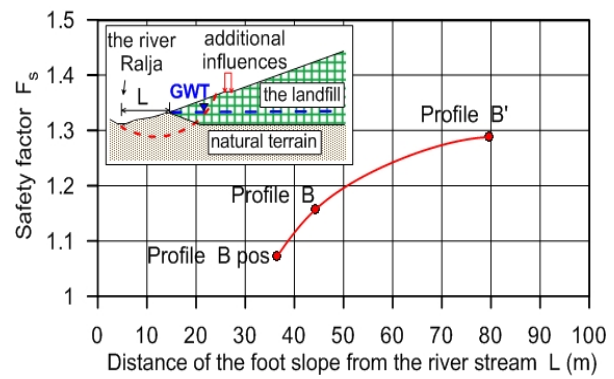

Fig. 9 The effect of the distance of the river Ralja on the landfill body slope stability

The settlement of the landfill body can cause negative consequences during its use, but in the period after its closure also. The mechanism of industrial waste landfill settlement depends on many factors and it is not conditioned only mechanically, but it is also the result of a complex and interactive effects of fracture fragments in waste (different types of slag are dominant), time decomposition of waste fragments, mechanical creep and others. Furthermore, in some cases, settlements caused by surface deformation were expressed. Impermissible settlements can have very negative consequences on the safety systems. This is particularly manifested in the appearance of joints in the base protective layers, malfunctioning of the drainage systems, cracking and splitting of the final cover layers, the influence on the adjacent facilities etc. In most of these cases, the biggest problem is the differential settlements.

For these reasons, the adequate analyses of settlement calculations were performed on the characteristic cross sections of the landfill. The analyses were performed using the software package PLAXIS 8, applying the finite element method. Since there is a plan to build the auxiliary facilities in the zone of the landfill bodies on the north and east side, the model was analysed which also included the part of the terrain outside the landfill body at a distance of approximately quadruple of the excavation depth made for the landfill body (about 40 m) to the left and right of the excavation. For all profiles the three typical cases were analysed: simulation of the excavation for the landfill body; I phase of waste deposition for a period of 5 years and II (final) stage of waste deposition for a period of 10 years. For all three cases, data were obtained about the stress state and deformations in the landfill body and its base - the natural terrain, at specific time intervals (5 and 10 years). On figures 10 and 11 the characteristic numerical models are presented with the position of nodes in which the settlement was calculated and also the settlement results for two characteristic profiles of the landfill for the period after completion of the landfill forming for 10 years.
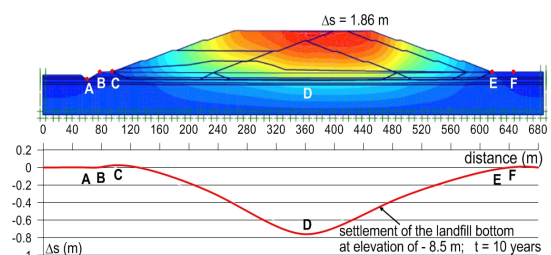
Fig. 10 Numerical model with the characteristic points of the settlement calculation for the profile b-b
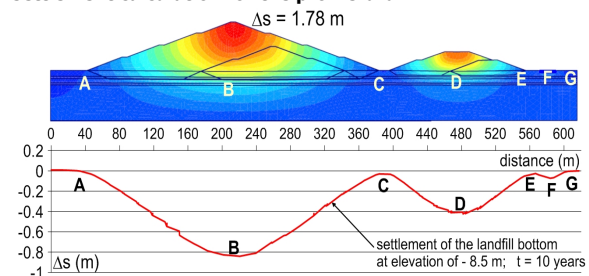
Fig. 11 Numerical model with the characteristic points of the settlement calculation for the profile a-a

The results showed that the maximum deformations occur at the landfill surface and in its highest part (Δs = 1.78 - 1.86 m, Figures 10 and 11). However, in order to predict the influence of the settlement on the base protective systems (protective film and drainage systems), the settlement values were analysed on the elevation of the excavation. The maximum differential settlement between points A and B was about 1.27 m, which in comparison to the distance between these points of 181 m presents a negligible value of potential foil elongation (less than 0.5 cm). Besides the analysis of vertical displacements the horizontal displacements were analysed too, in order to define the influence of the landfill construction to the river Ralja and associated facilities. The results showed that the construction of the landfill will have very small influence on the riverbed of the river Ralja, since the displacements in the horizontal direction were between 3 and 5 cm.

As for the excavation and the preparation of the base of the landfill body, the stability of the natural terrain for maximum dig depth of 8.5 m was analysed. At the same time, the influence of the riverbed of the river Ralja on the stability of the excavation slopes for the characteristic profiles. The stability of the excavation for the projected slope of 1 : 3 was confirmed by these analyses, considering that the minimum values of the safety factor were between F_s = 1.394 (including the impact of the seismic and the temporary loads) to F_s = 2.142 (slope excavation in the projected state with no additional influences).

In addition, the specific recommendations for the substrate preparation and for the construction of the protective lining system were given which consists of: compacted clay liner (CCL) thickness of 0.5 m; geosynthetic clay liner (GCL – "bentonite mat") thickness of 5-6 mm; geomembrane - HDPE foil minimum thickness of 2.5 mm and gravel drainage layer thickness of 0.5 m. For all the elements of the system the general geotechnical characteristics are given and considering that the compacted clay lining and drainage layer are constructed from natural materials, hereafter only general recommendations relating to these materials are given. The basic recommendation of the compacted clay liner, refers to the water permeability coefficient, whose value should be less than 10-9 m/s. It is well known that the maximum dry unit weight is achieved at the optimum moisture content, but this moisture does not give the minimum water permeability, which in clays is usually achieved with the moisture content higher than the optimal for about 3-7%. Besides the low values of the filtration coefficient, clay should satisfy the following requirements: to contain at least 40-50% of the fine fraction (<0.074 mm) of silt and clay, to contain clay fraction (<0.002 mm) in the range of 18 - 25%, the value of yield strength should be between 25 and 30% (soil with a higher yield strength is more sensitive to cracking); the plasticity index should be I_p = 10 - 20% (otherwise it becomes sticky and difficult to handle; the maximum content of gavel fraction should be 10% with no larger grains than 75 mm.

In the geotechnical analyses which relate to the landfill associated facilities construction, the analysis of the ultimate bearing capacity of the base and the foundation settlement of some objects was performed. The geostatic analyses were performed by the geotechnical models GTM and GTM-2-3. The several methods were used for the case of a shallow foundation system that can be classified into two groups: the so-called static methods - based on the

values of shear strength parameters, and methods based on the results of the CPT test.

The general geotechnical recommendations which relate to the terrain organization and on the construction of the traffic roads included: preparation of the subsoil, the use of natural materials from the excavation for the landfill body, the use of industrial waste - slag for the traffic road base; recommendations related to the general conditions of filling. In this, the results of laboratory and terrain results (field test) were used that were performed on samples of converter slag, blast furnace slag and hazardous waste so called (sludge and "filter cake").

CONCLUSIONS

The disposal of industrial waste in a regulated landfill site includes a very long period of time (usually ten years or more) so the landfill volume can exceed several million cubic meters of industrial waste materials. Considering this, the landfill body changes its physical and mechanical properties in time, which can lead to endangering the protective system (unequal and differential settlements) as well as the certain technological systems such as the facilities for recirculation or evacuation of seepage water, and in some cases comes to the appearance of instability. For these reasons the geotechnical aspects, primarily stability, bearing capacity and settlement prediction of the landfill material should not be ignored in the design of industrial waste landfills.

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