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The impact of Ljubljana's municipal waste landfill on ground and groundwater

L'impact de la décharge municipale sur les sols de fondation et sur l'eau souterraine

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ABSTRACT

The municipal waste landfill Barje (Ljubljana, Slovenia) is located in the northern edge of the Ljubljana Marshland, which is one of the deepest marshlands in Europe. The foundation ground consists about a 35 m thick layer of highly compressible soils, under which there are several separate gravel aquifers. The Upper aquifer is connected to the alluvial aquifer, which is also the main source of the drinking water for Ljubljana. Due to the consolidation in some parts of the landfill, settlements have already reached the height of 2 m or more. To improve the efficiency of bottom lining system, in 2000 a system of preparing the sub grade below the landfill was introduced with artificial sealing of the bottom with prior preloading. Since 1998 in the area of the landfill a vast geotechnical and hydrogeological monitoring system has been under construction. The 6 year time monitoring has showed extremely non-uniform settlements of soil, which is the consequence of the lenticular, heterogeneous geological composition. The ground water exhibits a clear influence of reduction conditions as a consequence of reduced soil permeability due to consolidation, due to the fact that large surfaces are covered by wastes, and due to impacts of seepage waters from the old part of the landfill. In the direct vicinity of the landfill the contents of chemical elements, such as Fe, Mn, NO_2,NH_4, As and others, are increased, which is typical of oxidation-reduction processes. Other parameters do not give evidence of spreading in the horizontal direction outside the landfill area. The findings of monitoring show that oxidation-reduction processes are the most important impact that the landfill exhibits to the subsoil, which means that in the future the main interventions will have to be based on the technology that allows control of these processes.

RÉSUMÉ

La décharge municipale de Ljubljana en Slovénie se trouve au bord du marais de Ljubljana, l'un des plus profonds d'Europe. Une couche de sols compressibles de 35 m d'épaisseur repose sur différentes couches aquifères non correspondantes. La première couche aquifère est reliée à la couche alluviale et représente la source la plus importante d'alimentation en eau pour la ville. Du fait de la consolidation, dans certaines zones, de la base, les tassements dépassent déjà 2 m. Dans le but d'améliorer l'efficacité du système d'étanchéité et de drainage, une nouvelle méthode de préparation de fond imperméable subissant une surcharge a été mise au point en 2000. Pendant les 6 dernières années, des observations géotechniques et hydrogéologiques ont été effectuées. On peut constater que des tassements non uniformes se sont déroulés à cause de l'hétérogénéité géologique du sol de fondation. Dans l'eau souterraine, on observe, sous l'effet de la consolidation, l' influence de conditions réductrices dues à la diminution de la perméabilité du sous-sol, l'influence de l'extension importante de la décharge et l'influence des eaux d'écoulement qui proviennent de l'ancien emplacement de la décharge. Dans le voisinage immédiat, la teneur en éléments chimiques, tels qu'en Fe, Mn, NO_2, NH_4, As etc, a augmenté, ce qui est caractéristique des processus d'oxydoréduction. Les autres paramètres ne mettent pas en évidence une propagation dans un sens horizontal en dehors de la zone d'enfouissement. Les conclusions de l'observation montrent que les processus d'oxydoréduction ont le plus d'impact, ce qui signifie qu'à l'avenir les interventions majeures devront se fonder sur une technologie qui permet de contrôler ces processus.

1 INTRODUCTION

The Landfill Barje is the main waste deposit of Ljubljana, the capital of Slovenia (375,000 inhabitants) and the largest landfill of municipal waste in Slovenia. At the location covering about 80 ha the waste deposits came into operation first soon after 1950, and they included municipal, hospital and industrial wastes. The soil, once considered to be impermeable and suitable for waste deposits, is from the geological and hydrogeological standpoint actually very unsuitable and from the standpoint of contemporary Slovenian regulations even inappropriate for the construction of such structures. The landfill is located in a flood plain, at an about 140 m thick layer of quaternary sediments with extremely complex geological and hydrogeological composition. The groundwater can be found 0.5 – 1.0 m below the surface. The upper part of highly compressible soil is about 35 m thick. Below the upper layer of soft soils there are several aquifers, separated among each other with clayey layers. These aquifers are connected in the horizontal direction directly or indirectly with alluvial aquifer of the Ljubljana Field, the main source of drinking water for Ljubljana. Any breakthrough of pollution into Upper aquifer would mean direct risk of spreading the pollution towards the drinking water wells.

2 HISTORY OF LANDFILLING

Considering the manner how the landfill Barje was formed and filled, it can be divided into two parts: the old, northern part, where the depositing finished in 1986 and which is today intended to fairs and sports events, and the new parts, which came into operation after 1987. In the area of the old part the wastes were spread over natural ground surface and into shallow depressions, filled with water, which remained after excavation of clay. The height of the old deposit is 7 – 9 m at the surface of about 40 ha.

In the phase of planning the new part of the landfill, between 1983 and 1985 geotechnical tests were carried out. The analyses showed that for the planned magnitude of load (200 kPa) settlements of 150 –210 cm could be expected to develop in about 30 years. In the initial stages of design the results of geotechnical research were not taken into account. Only in 1990, after the landfill had began to sink into soft sub grade and after the seepage water surface in the newly constructed landfill had increased, several geotechnical principles of construction were assumed in the planning of the new landfill.

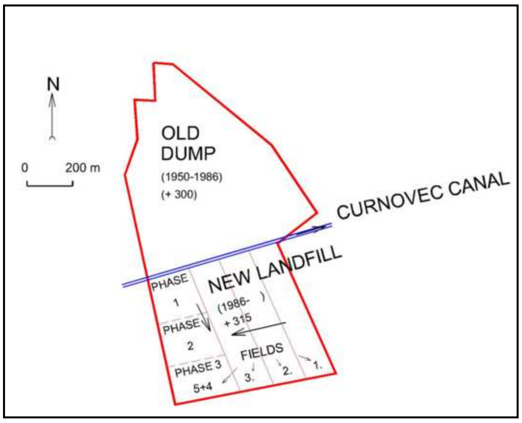

Figure 1. Schematic presentation of the landfill Barje.

The new part of the landfill is divided into 5 fields, which can be divided into 3 sections according to the construction design and the execution of bottom sealing (Figure 1). Field 1 and 2 were finished in 1986, still with the presumption that natural clayey soil has sufficient self-sealing characteristics; for this reason no bottom sealing was carried out. Settlement of wastes, proved with calculations, into the area of the groundwater was not taken into account. Additional sealing was carried out at the waste height of about 7 m, only after negative impacts of such construction on the environment had been confirmed.

Field 3 was finished in 1993. To prevent the sinking of the bottom lining system into the influential area of the groundwater, a "compensation" layer was designed, using inertial gravel material in the height of the calculated ground settlements. The bottom sealing was carried out with a 75 cm thick clayey barrier and a 2.5 mm PEHD membrane. Monitoring of the drainage system showed that the efficiency of the bottom drainages was diminished due to large differential settlements.

Uniform fields 4 and 5 started to be designed in 2000. To reduce negative effects of settlements on the bottom lining system, a concept of preloading was adopted. Ideally, the preloading should be carried out in the magnitude of the total foreseen load and at the total surface of the field. However, the adopted solution is a compromise between the geotechnical wishes on one side and financial and time constraints on the other.

Preloading is carried out only for about 70 % of the magnitude of the final load (q =250 kPa), by moving the mass of ballast in sections, representing only 15 – 20 % of the total depositing field (12.61 ha). Between 2001 and 2004 three such mass movements of ballast were carried out with the average time of preloading between 7 and 12 months. In the time of preloading we measured ground settlements in the magnitude between 40 and 70 cm. Part of the settlements was always missed, since soft soil required us to first spread at least 1 m of gravel material on the wet land.

Since 1998 a geotechnical and hydrogeological monitoring system has been under construction at the total influential area of the landfill, with the purpose to monitor the ground and waste deposit settlements, seepage water in the landfill and quality and dynamics of groundwater below the landfill. So far over 30 settlement slabs, 4 horizontal inclinometers with the length of 80 m to control the settlements, 4 piezometer boreholes to control seepage water in the landfill and 19 sampling hydrogeological boreholes around the landfill have been carried out.

3 GEOLOGICAL CONDITIONS

The Landfill Barje is located on the 140 m thick formation of quaternary sediments. The basement is Triassic dolomite.

To understand the complex nature of the geological composition of the soil below the landfill, it is important to know the paleorelief of the Triassic base. Geophysical investigations show that at the widest influential area of the landfill two explicit main valleys and several side valleys are cut into the prequaternary base. The morphology of the base shows explicit strong changing of the former main and marginal side surface flows. Changes of the surface flows followed in sequence with temporary sedimentation in the sinking depression, which caused depositing of intermediary fine-grained sediments. The last sedimentation in the youngest quaternary resulted in the deposit of a 33 - 43 m thick layer of fine grained sediments – so called Top layers, mainly consisting of silt and clay. Due to the vicinity of steep edges of the depression, also individual thinner layers of sandy and gravel material deposited far into the plane part of the flooded dam sediments, brought by the surrounding brooks. The consequence of such development of the area is extremely variegated composition of quaternary sediments.

The Top layers, up to 43 m thick, consist mainly of soft clays (CL, CH), loose silts and sands (ML, SM, SP), locally also individual lenses of peat and organic clay (Pt, OL). A specialty among the Top layers sediments is a 2 – 6 m thick layer of gravel, so called First gravel layer, deposited between soft soils.

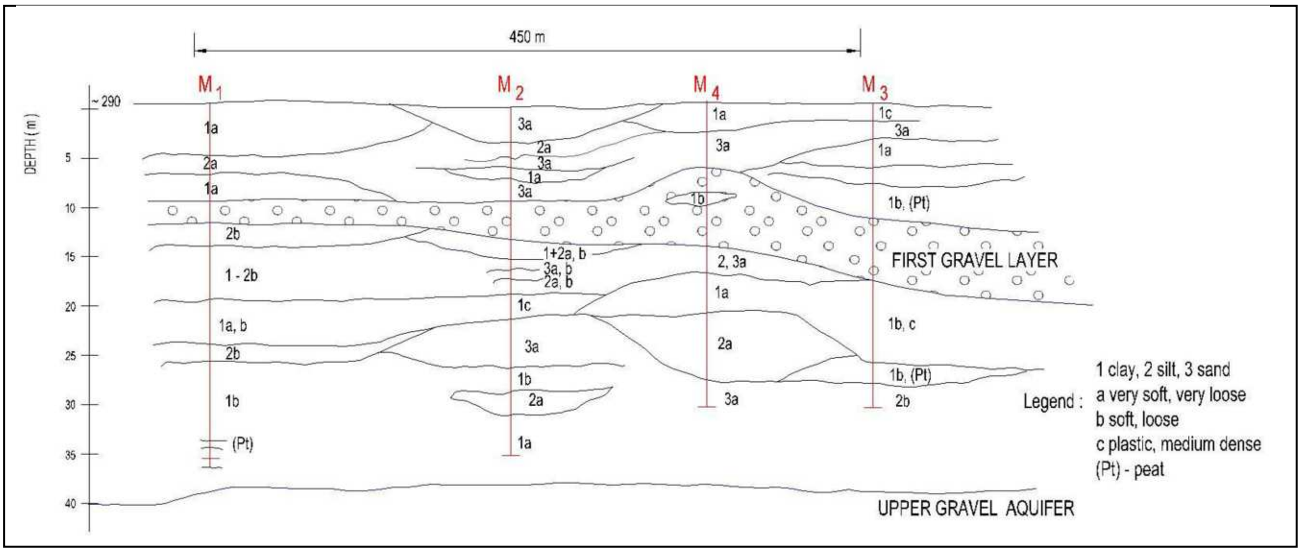

Figure 2. Typical geotechnical profile of Top layers

The structure and properties of the soil were established by drilling, SPT, CPT, field vane and laboratory tests. The monitoring has shown, that the distances between 120 and 250 m between individual point tests are practically too large for a reliable geotechnical prediction of settlements. A typical local profile of the Top layers in the area of the eastern edge of the 4. field is presented in Figure 2.

Below the Top layers there is in the depth of 30 – 43 m the Upper gravel aquifer, followed once again by about 30 - 40 m thick layer of clayey soils (CH, CL, OL) with individual, up to 1 m thick layers of peat (Pt). At the depth of about 70 - 80 m there is the Lower gravel aquifer and directly below it the fissured Dolomite aquifer in prequaternary base. The schematic hydrogeological ground cross-section is presented in Figure 3.

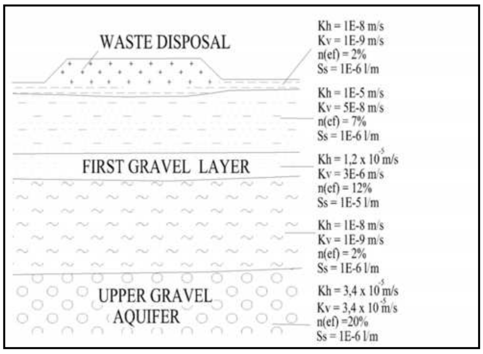

Figure 3. Schematic hydro geological cross-section

4 FOUR AQUIFERS AND GROUNDWATER DYNAMICS

Bellow the landfill bottom, there are four different aquifers: Dolomite aquifer in base, Lower gravel aquifer, Upper gravel aquifer, and First gravel layer in the Top layers.

All aquifers are confined or semi-confined aquifers. The piezometric level is artesian or sub-artesian. Decisive for the spreading of the polluted groundwater is the distribution of pore pressures in the First gravel layer and in the Upper gravel aquifer. The piezometric level in the Upper aquifer is in some places higher than the piezometric level in the First gravel layer. Further on, at the southern-most part of the landfill the difference is 1.5 m, and by the canal Curnovec the piezometric levels are equal. Towards the north the piezometric level in the Upper gravel aquifer then drops below the surface of the First gravel layer and is in the northern edge already 4 m lower.

The ground water pressure in the Upper gravel aquifer is artesian, about 1 m above the height of the surface in the new part of the landfill, and in the old part it drops by about 5 m below the surface height and is sub-artesian. In the First gravel layer the piezometric pressure is up to 0.5 m below the surface in the most south-western part of the landfill, and in the northern-most part about it is 1 m below the surface.

Despite unfavourable geotechnical structure the hydraulic conditions are from the standpoint of protection against the spreading of pollution from the landfill into the ground fairly favourable in the southern part of the landfill, where the gradient of the vertical flow component is negative. In this part the polluted waters drain in a pronounced way into the surface side canals. Less favourable conditions are in the northern part of the landfill, where the difference in piezometric pressures allows seepage of the water deeper into the upper layers.

The groundwater dynamics is extremely complicated, due to heterogeneous nature of the ground, due to different directions of groundwater flow, variegated distribution of water pressures, impacts of soil consolidation and sinking, as well as due to important role of ditches, which in parts recharge and in parts drain the groundwater. To recognize the basic groundwater dynamics, we used a mathematical model elaborated with the aid of the tool MIKE SHE (DHI).

Already during the calibration of the mathematical model it was clear that the groundwater dynamics is explicitly influenced by the reduction of permeability and seepage of the water from the Top layer into the First gravel layer and Upper gravel aquifer. The seepage water quantity due to consolidation was very important especially in the first few years, compared to the total water quantity flowing through the First gravel layer and the Upper part of the First aquifer. When calibrating the model, the impact of consolidation was taken by reducing the permeability coefficient and by adapting the values of efficient infiltration for individual layer below the landfill body.

The results of modelling showed that pollution spreading is possible with the flow of groundwater in the horizontal as well as vertical direction. The calculated velocity of flow in the upper layers is 0.069 m/day, which means that in ten years the advection distance of 250 m would be reached. In the First gravel layer the velocity is slightly higher, 0.093 m/day. The flow component in the vertical direction is considerably smaller than in the horizontal direction. Figure 4 shows modelled plume of a conservative pollutant, which would have permanent source in the landfill body with the contents of 10mg/l in 50 years.

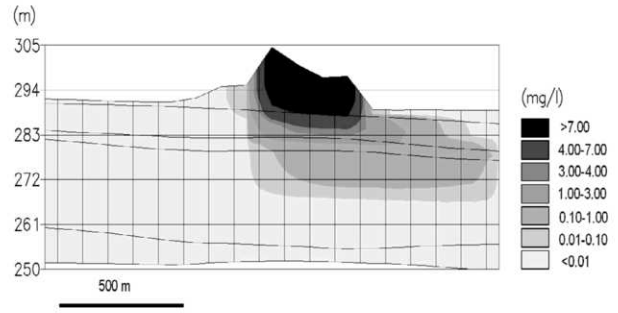

Figure 4. Modelled cloud of spreading of an imaginary contaminator with advection

5 SETTLEMENT MEASUREMENTS

Although the landfill Barje has been filled for more than 50 years, until 1998 only individual randomly measured settlement data were gathered, showing that the ground under individual parts of the landfill were strongly and differential settled. Measured settlements followed the computational predictions, performed for the first time already in 1985.

In 1998 a new system for permanent geotechnical monitoring of the landfill was initiated. The system includes:

- Permanent measurement of settlements of the landfill bottom and surface using robust settlement slabs
- Horizontal inclinometers measurements
- Piezometers for monitoring the seepage water levels in the landfill body,
- Temporary measurements of the settlements below the preloaded embankments.

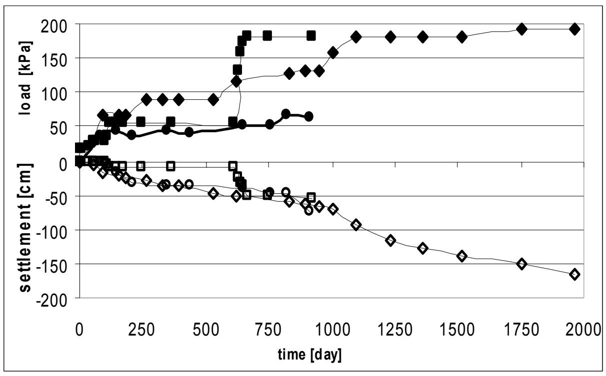

Figure 5. Time loading and settlement curves for some typical points

For the moment it is not yet possible to elaborate isolines of measured settlements. However, the analysis of results obtained from monitoring the neighbouring measuring points show extremely large differences between mobilised settlements, which is in the first place the consequence of lenticular and highly heterogeneous soil composition in the upper, soft layer. In the area of field 2 the measured bottom settlements exceeded the magnitude of 1.8 m (Figure 5), and bellow the preloading embankments, the settlements of 40 – 70 cm are mobilised before the construction of bottom sealing starts.

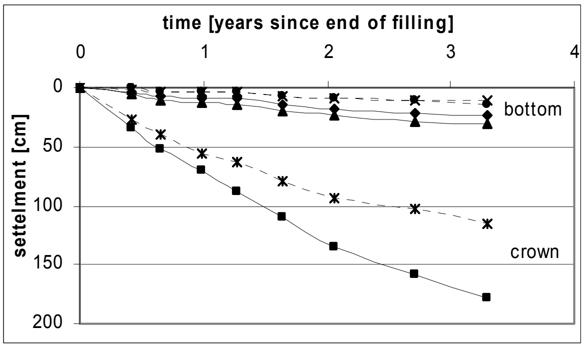

Figure 6. Time settlement curves for bottom and crown of central part of field 3 - after finishing the land filling

6 DEVELOPMENT OF GEOCHEMICAL PROCESSES

By samplings and chemical analysis of the water from 19 boreholes in the vicinity of the landfill we were able to establish the influence of reduction conditions in the Top layers and in the Upper aquifer. Figure 7 shows the contents of Mn in the groundwater from the First gravel layer. Apart from Mn it was also found out that there appear increased contents of other reduction parameters, such as Fe (up to 3.1 mg/l), NH_3 (up to 3.3 mg/l), As (up to 0.039mg/l) and sulphides. Other elements, such as metals Cu, Ni, Cd, Cr^{6+}, Pb, Zn, Al, and organic substances, such as polycyclic hydrocarbons, phenols, AOX, pesticides, etc., are in the water-bearing layers in direct vicinity of the landfill below the standard levels for drinking water. Contamination with these substances is present only in clayey-silt layers between the bottom of the landfill and the First gravel layer.

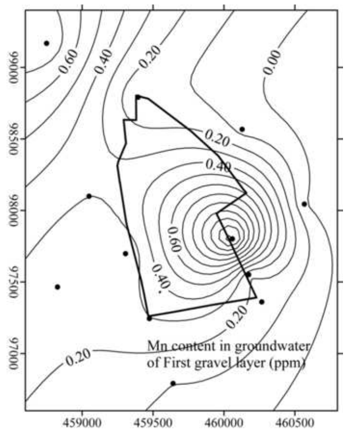

Figure 7. Contents of Mn in the groundwater of the first gravel layer

The oxidation-reduction processes were present in the geological layers of the Marshland already in the natural layers. With the seepage of water in the water-bearing layer due to the consolidation of soft Top layers the reduction types are developing also in the deeper layers below the landfill, although the vertical hydraulic gradient is negative and these layers drain into the surface canals. Similar increase of the contents of oxidation-reduction substances as the consequence of the processes due to ground consolidation appear not only below the landfill, but also below other engineering structures, such as motorway and other engineering embankments in the area of the urbanisation north-west of the landfill (e.g. monitoring borehole DBP-1/99).

7 CONCLUSIONS

With the introduction of preloading and with the construction of compensation layer before the execution of bottom lining system, additional measures for the protection of the ground and the groundwater against negative impacts of the landfill were adopted at the landfill Barje. These measures allowed us to ensure efficient drainage of the foundation ground in the area of soft soil, and thus to essentially limit the spreading of the development of oxidation-reduction processes in the geological layers further away from the landfill.

The geotechnical monitorings performed so far are warning us that by analysing the data from the test boreholes, carried out at a distance of 100 or 200 m, it is not computationally reliable to predict the magnitude and the time development of settlements with the desired precision and accuracy, considering the fact that the ground is extremely heterogeneous. Individual local settlements, noticed by monitoring during the construction, can still deviate substantially from those that were predicted.

Extremely important are the findings of the hydrogeological monitoring and modelling of the pollution spreading. An essential impact of the landfill on the ground and the groundwater is evidently not the spreading of contaminants, such as Cd, Cr, other metals and inorganic contaminants by advection. The most important impact is the increase of chemical substances, typical of the oxidation-reduction processes as the consequence of combined impacts of the soft soil consolidation bellow the body of wastes on large surfaces, leakage as well as soil consolidation consequences due to other engineering structures in the landfill vicinity. These results also show that with the spreading of built structures at the Marshland, beside geotechnical analyses also hydrogeological analyses should be performed, as it is obvious that the consolidation processes trigger in the foundation ground important biochemical processes and consequently changes of chemism of the groundwater. Monitoring and directing the soil consolidation dynamics should be one of the key activities within the protection measures against the spreading of the landfill impact into the groundwater for the duration of the landfill lifetime, as well as after the shut-down of the old landfill, which had from the contemporary standpoint a completely inadequate design.

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