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Specific features of diaphragm for Trebež landfill improvement in Samobor

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Professional paper

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Specific features of diaphragm for Trebež landfill improvement in Samobor

The diaphragm forming a vertical barrier for preventing the spread of pollution from Trebež landfill (Samobor) is a buried clay-concrete structure measuring 698 m (length) and 0.8 m (width) in plan. The design and realisation requirements are described, and the entire construction process, involving design, preparatory work, construction, and quality control, is presented. Realisation of the vertical barrier is the most demanding and the costliest element of the Trebež landfill improvement project. Disturbances and challenges encountered during realisation of the barrier are presented, with a special emphasis on verticality.

Key words:
landfill improvement, Trebež, diaphragm, barrier, verticality

Stručni rad

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Specifičnosti dijafragme za sanaciju odlagališta Trebež u Samoboru

Dijafragma koja čini vertikalnu barijeru za sprječavanje širenja zagađenja s odlagališta Trebež (Samobor) je podzemna glinobetonska konstrukcija, tlocrtne duljine 698 m i širine 0,8 m. Rad opisuje zahtjeve za projekt i izvedbu, kao i cijeli proces izgradnje barijere; od projektiranja, pripreme, građenja i kontrole kvalitete. Daje se osvrt na poremećaje i inženjerske zadaće koji su se pojavili tijekom izgradnje barijere, s posebnim naglaskom na vertikalnost njezine izvedbe. Izrađen je računski model putanje grabilice za iskop dijafragme s ciljem provedbe analize utjecaja dimenzije i njihanja grabilice na postignutu vertikalnost iskopa.

Ključne riječi:
sanacija odlagališta, Trebež, dijafragma, barijera, vertikalnost

Fachbericht

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Besonderheiten des Diaphragmas für die Sanierung der Deponie Trebež in Samobor

Das Diaphragma, das eine vertikale Barriere bildet, um die Ausbreitung der Verschmutzung von der Deponie Trebež (Samobor) zu verhindern, ist eine unterirdische Ton-Beton-Struktur mit einer Länge von 698 m und einer Breite von 0,8 m. Die Abhandlung beschreibt die Anforderungen an das Projekt und die Ausführung sowie den gesamten Bauprozess der Barriere; von der Projektplanung, der Vorbereitung, des Baus und der Qualitätskontrolle. Die Ausführung der vertikalen Barriere ist das anspruchsvollste und teuerste Element der Sanierung der Deponie Trebež. Die Abhandlung gibt einen Überblick über die Störungen und Herausforderungen, die während des Baus der Barriere aufgetreten sind, mit besonderer Betonung auf der Vertikalität.

Schlüsselwörter:
Sanierung der Deponie Trebež, Diaphragma, Barriere, Vertikalität

1. Introduction

A diaphragm is a vertical underground wall built in order to separate soil and/or to separate soil from excavation work (for instance, to protect a deep foundation pit or to protect an excavation from water influx). A diaphragm is excavated using a trencher or a cable excavator. During excavation of a diaphragm, the excavated pit is stabilised against cave-in (collapse) by means of a dense liquid suspension, usually a bentonite suspension. Depending on the intended purpose and expected stresses, a diaphragm can be made of reinforced concrete, unreinforced concrete, or plastic concrete.

The term vertical barrier is used for a structure aimed at preventing the spread of polluted ground water or at redirecting the flow of polluted ground water away from a water supply well. The barrier must redirect the flow of uncontaminated ground water away from polluted areas and/or prevent the mixing of contaminated ground water with the system for purification of ground water that is to be used as drinking water [1, 2].

Both terms, i.e. diaphragm and vertical barrier, are used in this paper. The term diaphragm is used to refer to a specific type of vertical barrier, while the term barrier is used in the context of prevention of ground water flow.

The United States Environmental Protection Agency (US EPA) issued in July 1998 the national *Evaluation of subsurface engineered barriers at waste sites* [3]. The objective of this evaluation was to provide a retrospective analysis of the condition of the already realised barriers, and to collect and process the data that could be used in the preparation of guidelines for the realisation and evaluation of existing types of subsurface barriers. Additional objectives include determination of realisation results and factors that might impact the end result, namely: shaping, quality control and quality assurance relating to construction work, work-progress monitoring method, and maintenance. As many as 36 waste sites were studied in the scope of this evaluation. The waste sites were *inter alia* evaluated based on the width, continuity and verticality of the barrier, with verticality check on excavation implements.

The realisation of a vertical plastic-concrete diaphragm called Trebež is considered in this paper. This project is a specific engineering endeavour not only because of tight deadlines, high price (contractor's risk) and stringent quality requirements, but also because the experience gained on the project can be documented, as such barriers have very rarely been constructed in Croatia.

The Trebež waste site was formed on an abandoned gravel pit where municipal and industrial waste had been deposited from 1968 to 2007. As many as 300,000 square meters of waste were dumped at this site in an uncontrolled manner. The area was subsequently covered with a layer of inert soil material. A vertical barrier was to prevent the contact between the polluted water from the waste site and the surrounding ground water. The waste site was insulated by burying a vertical barrier 2 m into a silty sand layer, thus forming a weakly permeable subsurface "sheath" separating the area under the waste site from the surrounding water-bearing gravel layer.

A contract based on FIDIC (Yellow Book) was signed for the Trebež waste site improvement between the contractor and the client. The contract start date was set for 5 May 2015. The detailed design and working design documents were to be harmonized within two months and all works were to be performed within the ensuing 12 months. The works were to be completed and the operating permit delivered by 30 June 2016.

In this paper, the emphasis is placed on proving whether requirements regarding the quality and verticality of excavation work for the vertical barrier have been met. Quality control methods are described. Bucket verticality measurements for work within the excavation pit are statistically processed and critically commented on. A mathematical model of the path the bucket follows during diaphragm excavation was developed in order to consider the effects of bucket size and bucket swinging on the excavation pit verticality, and to define necessary data during the excavation work monitoring process. Further advances are expected in the development of the excavation verticality monitoring equipment, and better bucket body positioning. This aspect was not taken into account by the existing system that was used for monitoring verticality of the excavation pit.

2. Requests formulated in tendering documents

The waste site Trebež is situated near the Vrbovec Samoborski community, 4.4 km to the north-east of the town centre of Samobor, 2 km to the west of the Strmec water supply well, and 1.6 km to the south of the Sava River.

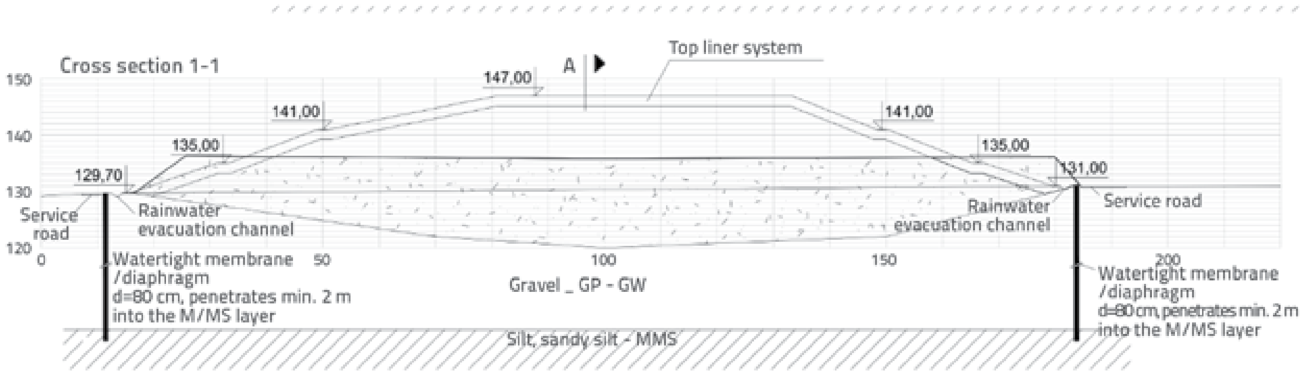

Figure 1. Typical cross section planned for Trebež waste site [4]

The typical cross section of the site was defined in the preliminary design, as shown in Figure 1 [4].

The diaphragm had to be realized in such a way to penetrate no less than two metres into the weakly permeable compacted silty sand layer with the permeability ranging from $k = 3{,}8\times10^{-10}$ to $1{,}0\times10^{-8}$ m/s. According to the client's requests, the water permeability ratio of the diaphragm had to be $k < 1\times10^{-9}$ m/s.

3. Realisation of vertical plastic concrete diaphragm at Trebež

The waste site body solution formulated in preliminary design was further elaborated in the detailed design [5, 6]. The waste site was designed as a stepped truncated pyramid, measuring about 175 x 185 m in plan and 17.5 m in height. The design slope inclination was 1:2.5. Berms two metres in width were formed on the sides at every six metres of height, measured from the toe of the slope.

The waste site body occupies an area of 33,00 square metres. The volume of the waste body on the surface of the waste site amounts to 290,000 m^3, while the volume of the entire waste site body, including the cover system, amounts to 330,000 m^3. A satellite view of the waste site body during realisation of waste site sides is shown in Figure 2.

The quantity of waste that had to be rearranged in order to obtain the design shape of the waste site body, amounted to approximately 15 % of the total volume of the waste body, i.e. the contractor had to rearrange approximately 50,000 m^3 of waste.

Figure 2. Satellite image of the Trebež waste site during remedial activities (photo taken on 25 December 2015), source: Google Earth

3.1. Investigations before the start of works

Investigations conducted at the waste site [7] involved drilling of 13 boreholes: five boreholes down to 40 m in depth, four boreholes to the depth of 45 m and four to the depth of 25 m. A total of 480 m of boreholes were drilled. All boreholes were drilled mechanically. The works were conducted in the period from 3 to 24 June 2015. All changes in the drilled formations were observed during the drilling campaign. A special attention was paid to the depth of occurrence of weakly permeable material and to the occurrence of ground water. Geotechnical classification of soil was conducted continuously on the waste site. The classification of soil was complemented with the data gained through laboratory testing. Disturbed samples of material were taken at every drilled layer, i.e. a total of 132 samples were extracted. These samples were transported to geotechnical laboratory where they were further processed and tested in accordance with the previously defined programme.

During the drilling campaign, natural compaction of soil was tested by means of standard penetration tests (SPP), while the SLUG test was conducted to determine water permeability. A total of 76 SPP and 30 SLUG tests were conducted. All on-site investigations were conducted under continuous geotechnical supervision, and the materials were examined and classified. Geophysical explorations conducted at the Trebež waste site involved realization of six geophysical cross sections using the geoelectric tomography method, and each cross section was 246 m in length. The geoelectric surveying procedure based on dipol-dipol configuration was applied. The electrodes were spaced at 6 m intervals, and a total of 42 electrodes were used for one cross section. During geophysical survey interpretation, a special attention was paid to the separation of the top layer that is mainly composed of various gravel varieties (clayey, sandy) and to underlying zones mostly composed of sand (silty or clayey sand).

3.2. Composition of soil at the waste site

Composition of natural soil at the waste site is presented in Figure 3. The soil is divided into the following three basic layers:

- Soft to firm low plasticity clay mixed with gravel. According to borehole results, individual layers vary from 1.40 to 4.40 m in thickness. As gravel had been extracted from this site prior to the disposal of waste, it is possible that this layer was locally deposited on this site. This assumption is based on local discoveries of construction waste or garbage at greater depths.
- Stiff to solid locally clayey gravel or stiff to solid gravel with traces of silt and sand. In the top zone, it occurs as a well graded gravel, while in bottom parts it occurs as clayey gravel or as grey gravel with traces of silt and sand. An interstitial fine gravel layer (0-6 mm, max. 18 mm in grain size) occurs in various thicknesses between the well graded gravel and the clayey gravel or grey gravel with traces of silt and sand. The angle of friction and SPT correlation was applied to determine layer strength parameters (GW/GP/GM). For the median SPT value ranging from N = 13 to N = 28, the selected parameter value amounts to $c = 0$ kN/m^2, $\varphi = 32°-35°$.
- Stiff to solid silty sand. It contains approximately 70 % of sand and 30 % of fine silt and clay particles (silt 20-25 %, clay 5-10 %). The layer varies from 14.0 to 27.50 m in depth. The layer thickness can not be unambiguously defined. The angle of friction and SPT correlation was applied to determine layer strength parameters (SM). For the median SPT value of N = 35, the selected parameter value amounts to $c = 0$ kN/m^2, $\varphi = 38°$. The values of the order of magnitude $k = 10^{-7}$ m/s and $k = 10^{-8}$ m/s were obtained by on-site permeability testing using the SLUG method. Laboratory testing of soil permeability was also conducted in oedometer on disturbed samples. The values obtained range from $1{,}1\times10^{-8}$ m/s to $3{,}75\times10^{-10}$ m/s.

Based on these preliminary investigations, the diaphragm position was selected taking at that care that the diaphragm does not pass through the waste layer because the waste, together with the seepage water concentrate, can chemically delay hardening of the plastic clay mix, and even prevent hardening of exposed parts of the diaphragm [2].

During the drilling campaign, it was established that ground water occurs at the depths ranging from -5,98 m to -3,42 m, measured from the top of the borehole, i.e. at the levels ranging from 125.44 to 126.40 m above sea level.

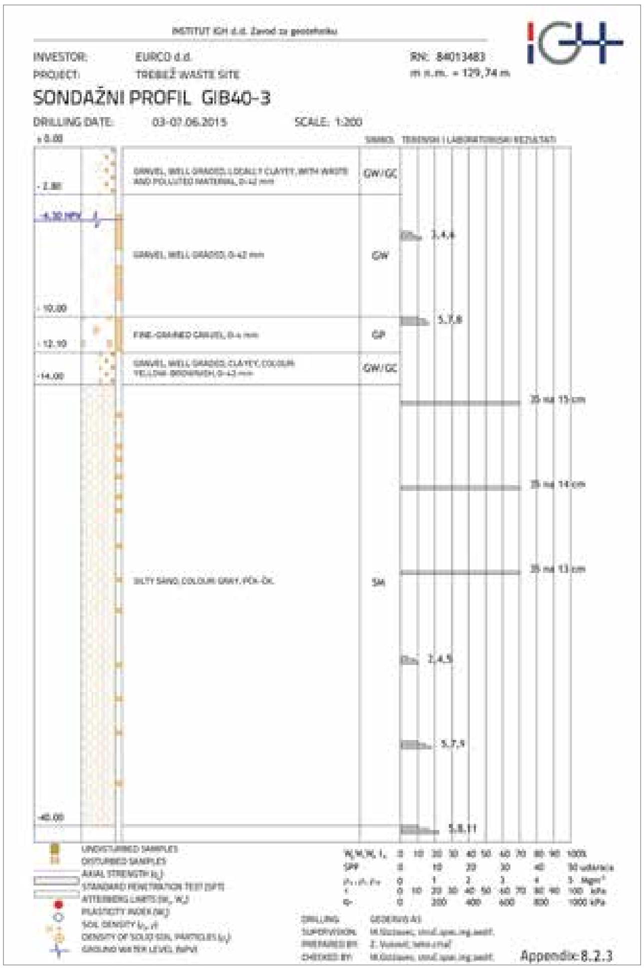

Figure 3. Typical soil profile

3.3. Watertightness issue

The spreading of pollution to the surrounding area is prevented by realisation of the weakly permeable diaphragm body, which is buried into the weakly permeable silty sand layer. An additional factor for preventing spread of pollution from the area bounded by the diaphragm is the creation of hydraulic gradient toward the waste site zone. This is achieved by monitoring level of the piezometer installed in the clayey gravel layer within the zone bounded by the diaphragm and the level of piezometer installed outside of the diaphragm perimeter. At that, it is set that the piezometric level of seepage water within the waste site body (Pu) must be lower for 0.25 to 0.5 m compared to the piezometric level of ground water outside of the waste site body (Pv). In case that Pv - Pu ≤ 0,25, one of the four submersible pumps is activated and it transports the seepage water to the nearby lagoon with the capacity of 4000 m3. The seepage water pumping is operated automatically and it lasts until the difference in piezometric level becomes Pv - Pu > 0,50. Submersible pumps are installed at four corners of the waste site and they are activated alternately. The automatic monitoring of piezometer levels and submersible pump operation is crucial for the overall monitoring and environmental protection.

3.4. Realisation of vertical barrier

A cable excavator, with open/closed clamshell bucket 3.40/2.43 m in length and 0.8 m in width, was used in diaphragm excavation. Primary panels were 9.4 m in length, while the length of secondary panels amounted to 2.6 m. A primary panel is formed of three plots 3.4 m in width, with the central plot cutting into the previously realised side plots (Figure 4).

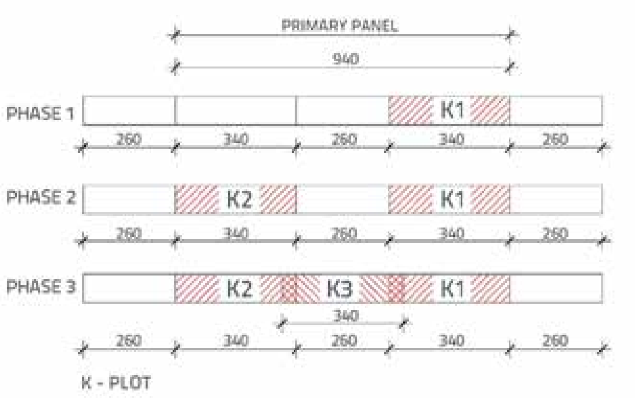

Figure 4. Primary panel excavation plan

The cutting of individual plots and panels was carried out in the length of 0.4 m. According to the realisation plan (Figure 5), the activity starts by realisation of primary panels (P1, P2 and P3), and continues with secondary panels (P4 and P5). The basic plan for realisation of primary and secondary panels is presented in Figure 5 (adopted from the subcontractor STEIN HT GmbH Spezialtiefbau, and incorporated in the working design for the diaphragm [8].

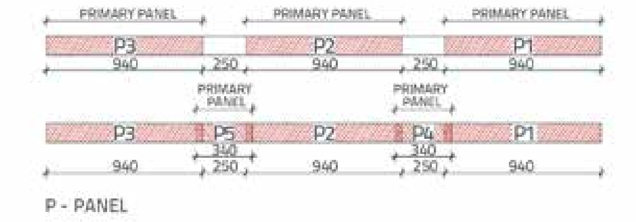

Figure 5. Arrangement of primary and secondary panels

Preliminary works for the formation of on-site roads, and for the diaphragm design investigation works, started in June 2015. In October 2015, the contractor started excavating the plastic concrete diaphragm, and the diaphragm works lasted until March 2016.

In June 2016, the contractor completed all waste site subsystems, the final on-site inspection was conducted, and operating permit was procured. The works were completed on time, below the planned budget, and in accordance with the client's requests.

3.5. Verticality of diaphragm excavation

As to verticality of diaphragm plots, it was specified that the deviation should be less than 0.2 %. The achievement of diaphragm verticality was facilitated by the inlet channel (two parallel concrete walls realized along the waste site perimeter), portable steel-made entrance funnel, and equipment for continuous monitoring of verticality. The achievement of diaphragm verticality was also facilitated by the bucket operating height of no less than 11.2 m.

The inlet channel is 83.5 cm in width. The portable entrance funnel is 83.5 cm wide in its narrowest part, and exceeds by 3.5 cm the bucket width, which is quite necessary as the bucket must be able to move – without any hindrance – to the excavation plot. The mobile entrance funnel is mounted at the top of the inlet channel and it assists the operator to accurately guide the bucket into the excavation pit (Figure 6).

Figure 6. Equipment for excavation of diaphragm, inlet channel and entrance funnel

As soon as one plot is excavated, the entrance funnel is moved to the next plot. A special equipment TARALOG TRB was used for monitoring verticality of excavation. This equipment, manufactured by JEAN LUTZ SA, registers and shows the bucket trajectory when reaching down into the excavation plot. Verticality was measured continuously throughout the excavation work. The difference between the vertical centre of the designed excavation plot, and the bucket trajectory along the excavated panel, constitutes the deviation from the vertical. The TARALOG TRB equipment contains two sensors: one for determining the excavation depth (z) and the other (NEMO sensor) for measuring vertical deviation and rotation. The NEMO sensor is mounted on top of the bucket and it measures deviation of the bucket top in the directions x and y from the ideal vertical axis of the plot centre, while also measuring bucket rotation – around the vertical axis z. These data are also recorded in a memory card. Figure 7 shows the allowed deviation of the plot from the specified verticality at the depth of 20 m (red dashed line) and positions of bucket edges (blue thin line) with respect to the ideal (designed) position of the plot (black thin line).

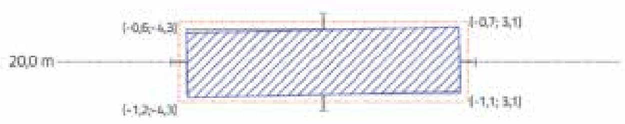

Figure 7. Deviation of excavation from design position; deviation in x and y directions [in cm] is shown in parentheses

The reference check of the excavation depth and verticality is conducted when the panel is excavated down to the design depth. Then the bucket is lowered from the initial position on top of the excavation (bucket bottom is initially at the top of the inlet channel) to the bottom of the excavation. Once the bucket is lowered, the operator rotates the bucket about the vertical axis for 180° and the measurement is repeated. An example of the overlapping of excavated plots (for panel 102) a the depth of 20 m is shown in Figure 8. Spatial arrangement of excavated plots is conducted automatically and is stored, for all plots, into computer memory.

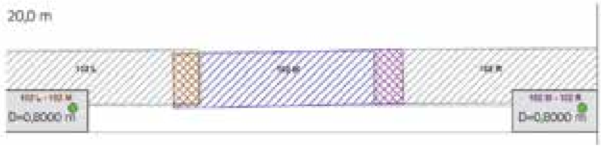

Figure 8. Overlapping of plots at panel 102, depth: 20 m

The link between individual plots, necessary to achieve watertightness and continuity, was realized by panels cutting one into another. The system for monitoring verticality of excavation work is used to continuously check that this plot cutting/overlapping is sufficient. The following acceptable plot overlapping criterion has been adopted: the diagonal between two opposite edges of neighbouring plots must have the length that is longer or equal to the nominal width of the diaphragm (Figure 9).

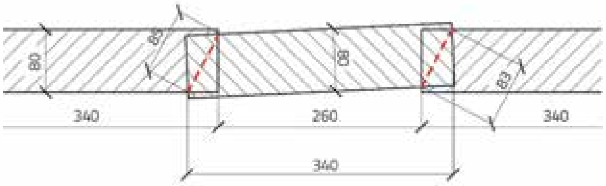

Figure 9. Criterion of sufficient plot overlapping/cutting for ensuring proper diaphragm continuity

This measure ensures that the seepage is not facilitated at plot or panel connections. In this stage, the contractor shows by bucket trajectory measurements that this criterion has been met along all plot and panel connections. The representation of plot connections after realisation of individual panels was submitted to the supervising engineer for inspection.

The NEMO sensor accuracy with regard to deviation measurement in x and y directions is 1 cm/10 m, and the accuracy in measuring rotation about the vertical axis is 0.08°/10 m.

3.6. Depth, panel shape, cutting

The realised length of the diaphragm is 698 m, and its maximum depth is 31.1 m. The total realised area of the diaphragm is 17,445 m^2. The coefficient of permeability k for the material placed in the diaphragm is $3{,}9\times10^{-11}$ m/s.

The checking of excavation work, and checking compliance with the criterion that the diaphragm must penetrate by at least two metres into the lower-permeability layer, was conducted at the excavation site, and involved continuous geotechnical supervision.

3.7. Routine tests for plastic concrete mixture

The diaphragm was realised in a single phase using the self hardening slurry. The excavation protection slurry “gelled” over time and gained in strength, and so it gradually transformed into a hard barrier. The stability of diaphragm excavation, and prevention of slurry pollution by seepage water from the underground, were ensured by providing for an appropriate level of slurry in the inlet channel. Thus, during excavation, the inlet channel had to be filled with slurry at all times, and its level had to be maintained above the plane of minimum 20 cm below the top edge of the inlet channel.

The vertical barrier was made of a special type of plastic concrete, by mixing the powder commercially known as Tiwodur ® 274 H with water (originating from the nearby lake). According to the sampling plan, the routine testing involved taking five samples from the fresh mix per each primary panel, and five samples for each of the two secondary panels, as several secondary panels (2 to 4) were realized every day. The routine test results had to comply with limit values presented in Table 1.

An external accredited laboratory conducted control tests on the fresh mix (Marsh’s funnel viscosity test, and density testing). During the testing of fresh plastic concrete properties by the accredited laboratory, samples were also taken for testing properties of hardened plastic concrete.

3.8. Control tests for plastic concrete mixture

The control testing [9] comprised the following tests: coefficient of permeability k, uniaxial compressive strength q_u, elastic modulus E, and bulk density r, in accordance with Table 2.

When evaluating quality of plastic concrete incorporated in the structure, at least 90 % of test results for each property must meet limit the values specified in Table 2, and every result must not be lower by more than 15 % compared to the specified values. Control test results are summed up in Table 3, [10].

3.9. Penetration of plastic concrete mixture into the surrounding soil

A trial excavation was made to check the level of penetration of the plastic concrete mixture into the surrounding soil. The penetration of mixture into the surrounding soil depends on the grain size distribution in the surrounding soil, permeability of the surrounding soil, and difference in pressure between the plastic concrete and water pressure in pores of the surrounding soil. At the trial excavation made in our case, conducted down to the depth of 2.5 m in gravel with a high proportion of sand and silt, the penetration of the fresh plastic concrete mix did

Table 1. Target results for routine tests of the plastic concrete mix used in diaphragm construction [8]

Suspension properties	Unit of measure	Value	Test standard
Density	kN/m^3	12	ÖNORM B 4452. API RP 13B-1
Funnel viscosity test (Marsh)	s/l	35-45	ÖNORM B 4452. API RP 13B-2
Liquid limit (ball test)	N/m^2	≥25	ÖNORM B 4452. API RP 13B-3
Quantity of filtered water (Filter press test)	cm^3	≤60	ÖNORM B 4452. API RP 13B-4
Deposition after 2 hours	Vol %	≥1	ÖNORM B 4452. API RP 13B-5

Table 2. Design parameters for plastic concrete mixture

Property	Criterion (project requirements)
Compressive strength (14 days) according to DIN 18 136	> 0.1 MPa
Compressive strength (28 days) according to DIN 18 136	> 1.00 MPa
Density according to DIN 18 136	1.2 kg/dm^3
Elastic modulus (56 days) according to DIN 18 136	> 150 MPa
Coefficient of permeability according to DIN 18 130-1	$< 10^{-9}$

Table 3. Control test results for plastic concrete mixture

Tested property	Sample No.	Measured minimum value	Required criterion	Procedure *	Result
Compressive strength (14 days)	88	$q_{u.min}$ = 0.102 MPa	$q_{u.min} \geq$ 0.85x0.1 = 0.085 MPa	100	Satisfactory
Compressive strength (28 days)	93	$q_{u.min}$ = 0.871 MPa	$q_{u.min} \geq$ 0.85x1.0 = 0.85 MPa	95	Satisfactory
Compressive strength (56 days)	93	$q_{u.min}$ = 1.754 MPa	$q_{u.min} \geq$ 0.85x2.0 = 1.70 MPa	98	Satisfactory
Elastic modulus (56 days)	93	$E_{u.min}$ = 209.3 MPa	$E_{u.min} \geq$ 0.85x150 = 127.5 MPa	100	Satisfactory
Coefficient of permeability (28 days)	93	$k_{f.max}$ = 5.6x10^{-11} m/s	$k_{f.max} \leq$ 1.15x10^{-9} m/s	100	Satisfactory
* Percentage of the total number of samples meeting limit values from Table 2					

not exceed 5 mm. After inspection of the excavation (Figure 10), it was concluded that the mixture filled in all pores in soil that were formed under the contour of the inlet channel created by the bucket. In fact, soil detached from the inlet channel wall and the fresh plastic concrete mix successfully filled in the detached volume of soil. Visual inspection made at the trial excavation site revealed that the seepage water did not affect quality of the plastic concrete mix as the colour of the hardened plastic concrete was uniform, without dark stains (that would point to the passage of seepage water), and all inspected surfaces of the plastic concrete excavation were hard.

4. Statistical processing of measured bucket path in diaphragm excavation pit

The objective of statistical processing of bucket path was to determine whether diaphragm plots were realized in accordance with requirements contained in contract documents and, if possible, to make an appropriate conclusion about the excavation considering the fact that, according to our knowledge, statistical processing of this type has not as yet been published.

The subcontractor (STEIN HT GmbH Specialtiefbau) conducted reference measurements after completion of each plot, and it made a drawing of movement of the bucket top along the depth of the excavation pit. The reference measurement of bucket path within the completed excavation pit contains data about the depth z, deviation in the x and y directions (from an ideal vertical centre of the plot), and rotation of excavation from the initial position - around the vertical. Direct measurement of verticality of diaphragm plot was not conducted, but the path of the top of the excavation was drawn in form of a spatial 3D body, i.e. of the spatial curve showing the rotation. The statistical processing of the bucket path data is in fact the indicator of verticality of diaphragm plot. The bucket path data do not provide a realistic representation of position of the centre of mass of cross section of individual diaphragm plots, nor do they constitute a measurement of the really excavated plot width. In fact, the bucket path measurement begins when a greater part of the bucket is outside of the excavation $z \geq 2$m, and the position measurement is vertically translated for the bucket length, while the path is associated with the path of the bucket bottom.

Figure 10. Trial excavation for checking penetration of plastic concrete mix into the surrounding soil

During interpretation of deviation from the vertical, at depths lower than the bucket length ($z < 11$ m), the measuring equipment shows deviation from the vertical although the bucket is not yet fully positioned within the excavation pit. This phenomenon can be explained by swinging and oscillation of the bucket body during entrance to the excavation pit via the entrance funnel and inlet channel. It is obvious that the bucket hanging from the cable, in a way similar to a mathematical pendulum, has a natural tendency toward the state of minimum potential energy (vertical) but, due to the presence of obstacles – such as the edge of the inlet channel or the edge of the excavation - the bucket sways and oscillates around the x and y axes. The measuring equipment positioned on top of the bucket does not unfortunately measure, and does not have the possibility to determine, the position of the bucket bottom, but assumes that the displacements at the top are vertically lower for the entire length of the bucket.

In addition, the horizontal cross-section of excavation of a particular plot is always wider than the cross-section of the bucket (otherwise the bucket would not be able to reach the design depth), and this widening is not taken into account when estimating the verticality of a plot; however, the displacement of the top of the bucket due to excavation widening can wrongly be interpreted as deviation of the bottom from the vertical. A total of 63,640 bucket position measurements were made and, at that, one measurement contained four data about the bucket position (z, x, y, φ).

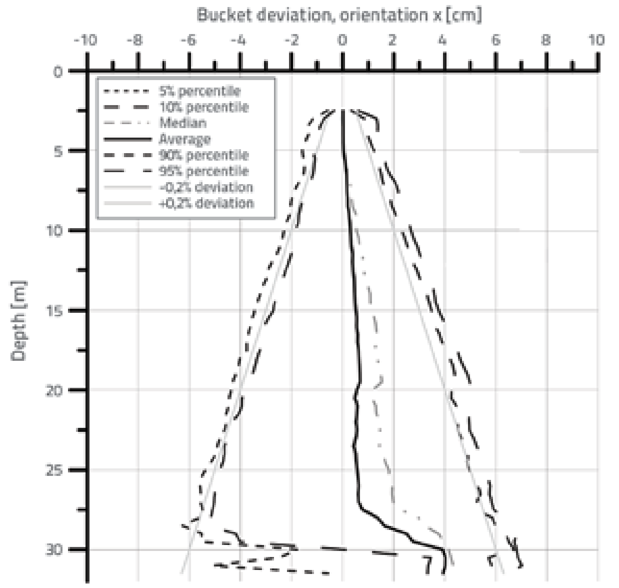

Figure 11. Deviation of excavation from vertical in the x direction

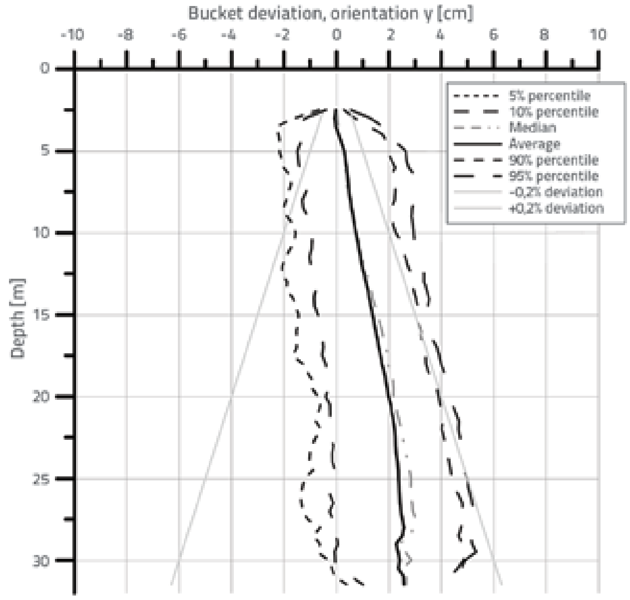

Figure 12. Deviation of diaphragm excavation in the y direction

4.1. Deviation of excavation toward the x axis

The x direction is the deviation from verticality along the diaphragm route. Figure 11 shows 5 %, 10 %, 90 %, and 95 % of the percentile of deviation in the x direction, median, average deviation, and allowable deviation (0.2 % of the depth).

4.2. Deviation of excavation toward the y axis

The y direction is perpendicular to the diaphragm plot spreading direction. The deviation of excavation in the y direction along the depth is shown in Figure 12. It can be observed that, at the depth of 8 m, more than 10 % of registered deviations have a deviation in the y direction that is greater than the spacing between the inlet channel and bucket width, i.e. that is greater than 1.75 cm in the positive and negative directions (i.e. 3.5 cm in total). The greatest deviation of the bucket path was measured in the first 7 meters of the excavation, which can be neglected as the bucket is not in the inlet channel for the full depth, and the tolerance provided by the width of the inlet channel covers such deviations, i.e. the minimum width of the diaphragm is 83.5 cm at the depths of less than 7 meters. Thus, the deviation of excavation gives a wrong impression of possible "deviation" while, in reality, it is a widening of excavation until the edge of the inlet channel.

There is a clear tendency of excavation turning toward a positive direction, i.e. toward the waste site body, and away from the cable excavator. With an increase in depth, this tendency of average deviation in the positive direction becomes more pronounced, but the dissipation of deviations reduces with the depth.

4.3. Rotation of excavation plot

A criterion that would define allowable rotation of individual plots around the vertical axis is not specified in the design. The distribution of deviations presented in Figure 13 reveals that most deviations do not exceed ±1,0° a that there is a natural tendency of bucket rotation within the excavation in the positive and negative directions.

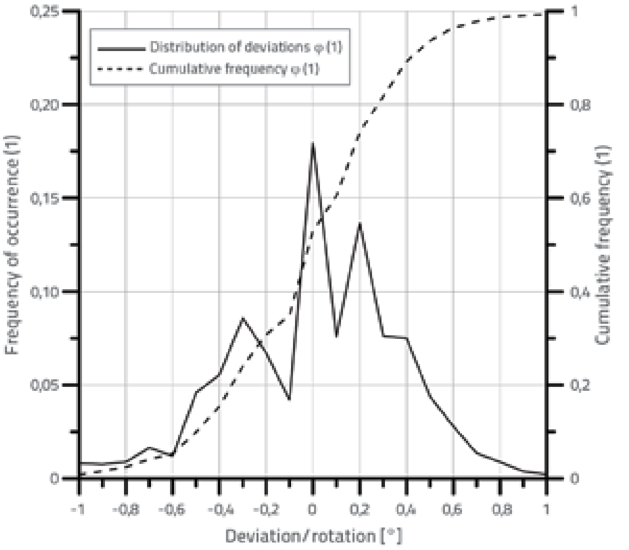

Figure 13. Distribution of deviations caused by rotation of excavation tool

Rotation-caused deviation in excavation pit along the excavation depth is presented in Figure 14. It can be seen in Figure 14 that the difficulty of maintaining excavation parallel increases with the depth of excavation. The bucket hangs from the cable and a simple mechanism for correcting the bucket rotation around the excavation axis actually does not exist. The bucket rotation is not a problem in excavation depths that are lower than the length of the bucket. For excavation depths that exceed the length of the bucket, the bucket should have the possibility to continuously monitor and correct the rotation.

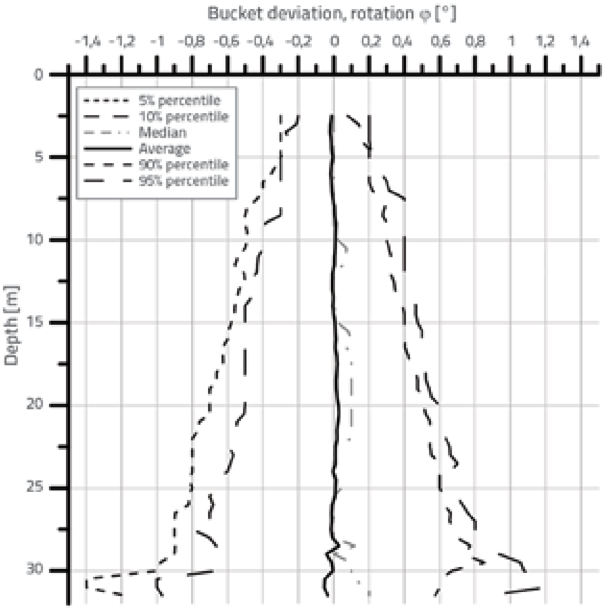

Figure 14. Deviations in bucket rotation along the depth

4.4. Standard deviations along the depth

Standard deviation from verticality of excavation in the x and y directions, and standard deviation in bucket rotation φ, are shown in Figure 15. The deviation from the vertical in the x direction becomes balanced and reduces with the depth. The deviation from the vertical in the y direction is pronounced during the first seven meters, and reduces with the depth. The deviation in bucket rotation becomes more pronounced with an increase in excavation depth. This is due to the fact that the bucket hanging from the cable can not be controlled.

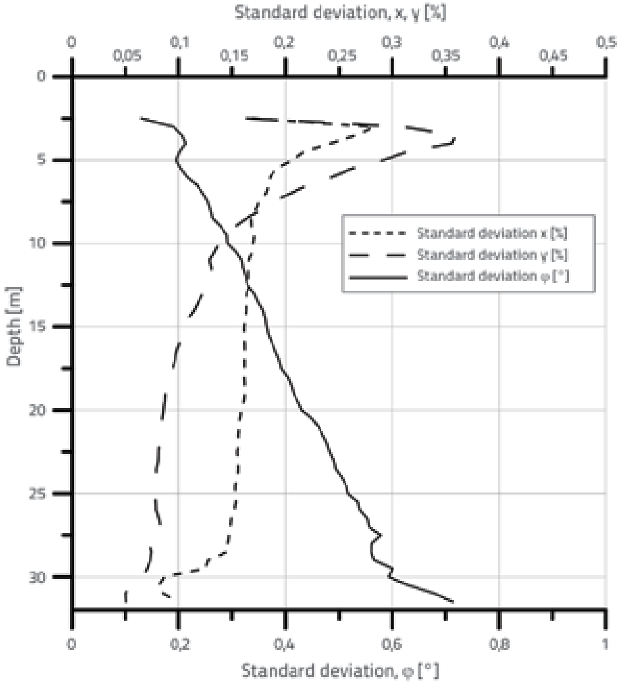

Figure 15. Deviation of excavation in the x and y directions, and in rotation along the depth

5. Mathematical model of bucket path in y plane

A mathematical model showing the path of the bucket hanging from the cable, with deviation in y direction, was developed as a contribution to the determination of the verticality and width of excavation. The forward movement of the bucket top part (shown as a red line) was defined mathematically in advance (figures 16 and 17) so that in this model the bucket, i.e. its centre of mass (blue dot), acts as a mathematical pendulum with forced movement of the top part. The red line in figures 16 and 17 represents the forced motion, and the red dot represents the top of the bucket, while two dots in turquoise colour represent the boundary condition of the model, i.e. the inlet channel that is displaced for 1.75 cm to the left and right of the central vertical, which exactly corresponds to the amount by which the inlet channel is wider than the bucket (3.5 cm).

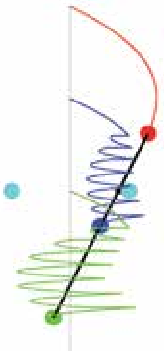

Figure 16. Model for determining path of bucket body regarded as mathematical pendulum

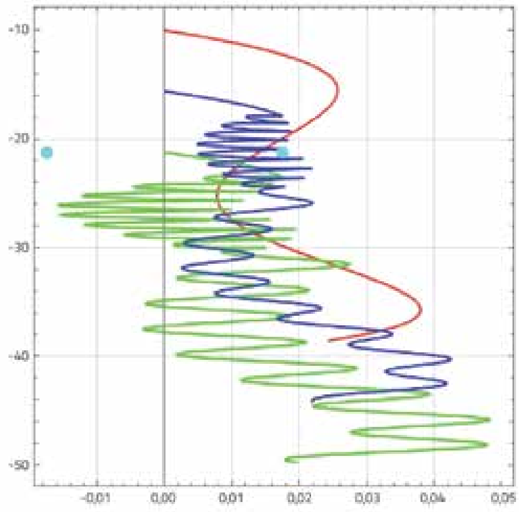

Figure 17. Result obtained by mechanical modelling of bucket movement in excavation pit

The absolute value of the vector showing the speed of motion of the top part of the bucket is constant and amounts to 0.5 m/s (this information corresponds to the speed of the bucket winch release and pull, as presented in technical specification for the bucket used in this excavation work). As the top of the bucket deviates in positive direction in the y axis, thus also the centre of mass sways to the right. When the bucket moves along the predefined path, it hits by its bode the walls of the inlet channel, and sways (oscillates) within the space of the inlet channel. The blue dot represents the trajectory of the centre of mass, which is defined in the model with the value of 16,500 kg (from technical specifications for the bucket), while the green dot represents the bottom of the bucket. In this mathematical model, the bottom of the bucket is not an added mass. The path of the bucket body is therefore not defined by the predefined path of the bucket top only, but also by the path of its entire body and well as by boundary conditions (inlet channel). The foundation soil of the excavation pit and its properties have not been taken into account, i.e. no additional boundary condition was set with regard to bucket movement.

Bucket path results were used to create a representation of bucket movement along its path through the excavation pit. It can be concluded from interpretation of bucket top movement according to this model (Figure 17) that the excavated panel does not meet the verticality criterion (<0,2 %) at the depths from 0 to 8.5 m when the bucket body is mostly outside of the excavation, and the result of the movement is translated vertically to the bottom of the bucket. However, the model actually represents the widening of the diaphragm panel excavation, although the top of the bucket deviated from the criterion. The measured deviation of the bucket top from the vertical does not mean that the panel deviates from the vertical, but rather that the panel width is locally greater. The greatest widening of the excavation is registered on the model at the depth of 12 m and it amounts to 4 cm.

6. Conclusion

Realisation of a plastic concrete barrier is a complex technical process. The quality of the design, the process of maintaining proper composition of the planned mixture, and realisation method, must all be properly conceived so that good results can be achieved at the end of the project. Several disturbances occurred during realisation of the Trebež barrier, which had an unfavourable effect on the time schedule set for the project. However, the quality of the work remained unaffected. The following guidelines and suggestions are given for the future plastic concrete diaphragm projects:

a) Although the planned route of the barrier was tested by deep exploratory boreholes spaced at approximately 50 m intervals, it proved necessary to subsequently determine - via shallower boreholes 10 m in depth spaced at 10 m intervals - the existence of underground pockets of waste. The progress of works can greatly be affected by subsequent change in barrier route in order to avoid the impact of waste on the fresh plastic-concrete mixture and, consequently, by realisation of a new inlet channel.

b) The control of reaching the design depth of excavation, and control for keeping the proper level of fresh mix in inlet channel, must be continuously monitored and provided for in a timely manner.

The control of monitoring activity and control aimed at ensuring proper level of fresh mix in the inlet channel is sometimes difficult to realise because of weather or on-site constraints. Generally, remedial works can be avoided or reduced with proper planning of control activities.

The following conclusions can be made based on experience gained during realization of Trebež diaphragm, and based on statistical analysis performed on the project to check verticality of the plastic concrete diaphragm excavation pit. It is first of all advisable and useful to conduct the diaphragm excavation work with equipment that can monitor verticality and rotation of excavation. According to data collected on the project, and based on statistical treatment of reference measurements of bucket path in excavated plots, it could be concluded that the described measurement method does not enable determination of the deviation from verticality in case of excavation widening. The necessary widening of excavation results in oscillation of the bucket within the excavation pit.

The main criterion for ensuring continuity of the diaphragm is representation of the cutting of plots (and panels) in such a way that the cutting diagonal has the same or greater length compared to the diaphragm length (see Figure 9). During the realisation stage, the contractor demonstrated – by bucket path measurements – that this criterion was met along all diaphragm plot and panel connections. The following technical deficiencies of the criterion that defines deviation from the vertical were noted:

- Diaphragm widening in the inlet channel and along the excavation route can wrongly be interpreted as deviation from allowable verticality.
- Deviation from the vertical was most often measured at positions where a half of the bucket was outside of the excavation pit, i.e. at the entrance of the bucket into the excavation pit. The bucket path simulation has shown that such deviations actually widen the excavation, and the barrier continuity requirement is met.
- Statistical processing of measurement data relating to the deviation of equipment for the excavation of diaphragm plots has revealed that, despite the satisfactory verticality of excavation pit, the rotation of excavation implement around the vertical axis can disturb continuity of excavation work.

As an addition to the procedure for determining the excavation envelope, a separate representation of the path followed by the entire bucket body along the excavation is proposed, because dimensions of excavation implements are considerable (in this case: 11.2 x 2.43 x 0.8 m).

REFERENCES

[1] Van Deuren, J., Lloyd, T., Chhetry, S., Raycharn, L., Peck, J.: Remediation Technologies Screening Matrix and Reference Guide, Federal Remediation Technologies Roundtable, 2002: 4.

[2] Bagchi, A.: Design of landfills and integrated solid waste management, 9.6. In situ remediation maethods, pp 170-212, 2004

[3] United States Environmental Protection Agency, Evaluation of subsurface engineered barriers at waste sites, 1998, https://www.epa.gov/remedytech/evaluation-subsurface-engineered-barriers-waste-sites-volumes-1-and-2, [Accessed: 21-November-2016]

[4] Pašović, D., Blažević., D., Vedrina, D.S.: Sanacija odlagališta otpada Trebež u Samoboru, Idejni projekt - izmjene i dopune, Hidroplan d.o.o., Zagreb, rujan 2014.

[5] Hudec, S.: Sanacija odlagališta otpada Trebež u Samoboru, Tehnološko - građevinski projekt sanacije odlagališta, Hudec Plan d.o.o., Zagreb, srpanj 2015.

[6] Matković, I.: Sanacija odlagališta otpada Trebež, Knjiga 2 – gradevinski projekt dijafragme, Institut IGH d.d., Zagreb, srpanj 2015.

[7] Gizdavec, M.: Sanacija odlagališta otpada Trebež, Knjiga 8 – Geotehnički elaborat, Institut IGH d.d., Zagreb, srpanj 2015.

[8] Matković, I.: Sanacija odlagališta otpada Trebež, Knjiga 2 – Građevinski projekt dijafragme, Izvedbeni građevinski projekt, Institut IGH d.d., Zagreb, rujan 2015.

[9] Jelavić, T.: Sanacija odlagališta otpada Trebež, Knjiga 8 – Plan kvalitete izvedbe betonske konstrukcije, Izvedbeni građevinski projekt, Institut IGH d.d., Zagreb, listopad 2015.

[10] Matković, I., Kavur, B., Jelavić T., Galić Kotarski, M., Stanić, A.: Sanacija odlagališta otpada Trebež izvedbom glinobetonske dijafragme, Sabor hrvatskih graditelja 2016, EU i Hrvatsko graditeljstvo (ur. Lakušić, S.), pp. 783-795, Zbornik radova sabora hrvatskih graditelja 2016., Cavtat, 17.-18. listopada 2016.