CPTu dissipation and various other tests of a landfill design

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ABSTRACT: In the frame of a research on the complex energy utilization of the Pusztazámor MSW landfill hill (gas, solar and wind units), the preliminary geotechnical design of a wind turbine and its service road was made on the basis of in situ tests and, large-scale laboratory tests. The settlement of the wind turbine under static load was estimated in two parts in the starting research. The final settlement value was estimated with a subgrade method, with a parametric analysis, the result was calibrated using the settlement measured earlier in Karlsruhe and the subgrade modulus range computed on the basis of the in situ measurements. The time history was estimated with a new method based on the evaluation of the waste oedometric test data and CPTu dissipation test data. The horizontal, in-situ coefficient of consolidation c_h determined from CPTu dissipation tests using a mathematically precise method, was larger by nearly two order of magnitudes than the coefficient of consolidation c identified from the large-scale oedometer test.

Keywords: pore water dissipation, MSW landfill testing, subgrade method for settlement modelling

1. Introduction

1.1. Complex energy utilization of MSW landfill hills ("Energy hill")

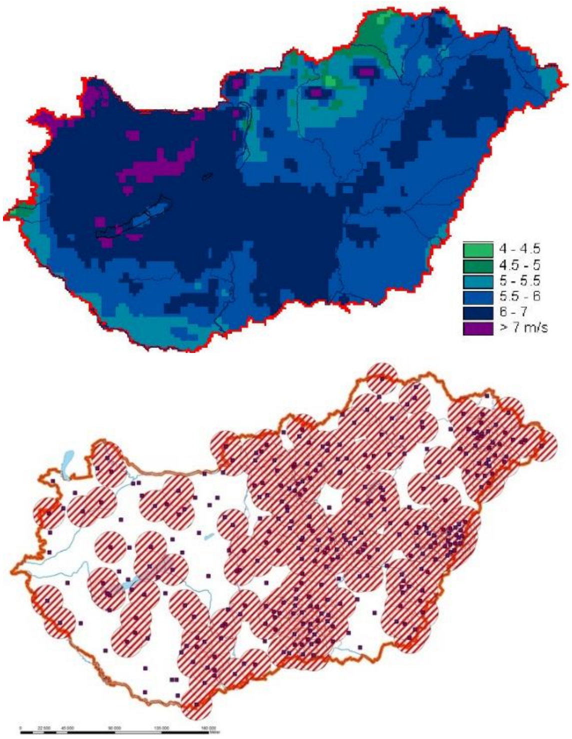
The environmental effects of the wind turbines – sound effects, the electromagnetic resonance, change of the landscape – are less disturbing in a landfill site.

In Karlsruhe, on a large landfill hill, three wind turbines – supported by gravity ring footings – were realized [26]. Monitoring of these structures over 12 years indicated almost 2 m of vertical settlement and tilting has been so far. At the Spadina Landfill (Saskachewan, Saskatoon, Canada) extensive testing was made and a wind turbine with a large gravity base was built [4])

About fifty modern municipal landfill hills have been established in Hungary in the last two decades. The wind is excellent in the altitude of hill top (Fig. 1).

Considering the 5, 10 or 15 km vicinity of the municipal landfills, the 24%, 44% and 60% of the total population of Hungary is found in the 16%, 37% and 53% of the cities, respectively.

A decentralized energy system based on the gas and wind energy may produce the 3-13 % of the yearly electricity need in Hungary, depending on the assumptions (e.g. concerning the rate of exploitation and the lifetime of the equipment, [15];[16]).



(a)

(b)

Figure 1. Wind and landfill features in Hungary. (a) Wind map in 150 m relative altitude. (b) 15 km vicinity of larger MSW landfills (> 80000 m3) where landfill gas is available

1.2. Scope of paper

The landfill hills can be used to install wind (and solar) energy units in a complex system, reducing of the need of the energy storage related to the landfill gas utilization.

The ongoing research is related to the complex utilization of the landfill gas in an interdisciplinary manner (ie., to the biodegradation landfill technology, energy, economy and geotechnical design of wind and solar units on the landfill hill) in Hungary.

For this aim, until now a statistical analysis was made on the economics significance of the complex landfill gas utilization. Some geotechnical exploration of the Pusztazámor Landfill site has been started with sounding, CPTu dissipation tests, borings, grading curve, water and organic content, shear resistance measurement. The planned final cover isolation was unsaturated permeability function tested. In the actual part of the research the preliminary geotechnical design of a wind turbine and its service road is presented.

Some new in-situ tests (light falling weight deflectometer, seismic and density tests) were made. The data measured here were validated with the data determined in Canada [4]. In addition, three large-scale compression tests were made with one-week-long stages, using the previously sampled cores. The time dependent results of the compression tests were evaluated with the modified Bjerrum model.

The settlement of a wind turbine due to static load was analyzed by AxisVM software in a parameter analysis in terms of the subgrade modulus. The analysis was calibrated based on some settlements measured at the wind turbine of the Karlsruhe landfill hill. The subgrade modulus was computed from measured in situ and laboratory test data using some simple formulae such that the effect of the immediate compression was neglected.

2. Literature review

2.1. The anaerobic decomposition and landfill layering

In this work such a layering framework of the waste hill is used that is related to the five anaerobic decomposition phases. The measured data in the previous and the actual part of the research are compared. The evolution of the grading curves during degradation previously measured in Pusztazámor is explained and verified by using the grading entropy theory. If the MSW landfill is built in horizontal layers, then the sublayers can naturally be defined on the basis degradation stage number [36]. The five anaerobic decomposition phases are as follows [34].

Phase 1 is the short initial aerobic decomposition where oxygen is still present within the landfill mass. The amount of leachate generated in the aerobic process is generally not substantial.

Phase 2 covers the immediate anaerobic degradation processes of acid-fermentation and acetogenesis. The two processes together are generally referred to as the acid production phase.

Phase 3 is a transition from the above acid phase to the next methanogenic phase with a steady growth of methanogenic bacteria. As the growth of methanogenic bacteria is initially suppressed by the acidic environment, it usually takes some time for them to develop and dominate the system.

Phase 4 is the methanogenic phase when the methanogenic bacteria have overcome the acidic environment and established themselves well in the system. It is distinguished by a steady methane production. The methane concentration for a typical landfill would be around 50 to 60% by volume with the rest being mostly carbon dioxide.

Phase 5 is the final post-methanogenic stage. There is a lack of long-term scientific data related to this maturation stage. It is believed that the rate at which such a final evolution may progress, or whether it will occur at all, depends on the landfill conditions such as moisture content and final cover.

2.2. MSW compression

An extensive testing for a wind turbine with a large gravity base was made at Spadina, Saskatchewan, Canada which confirmed adequate subgrade modulus and rotational stiffness [4].

In the research 90 m/s seismic wave velocity was measured at the surface, increasing to approximately 140 m/s at 10 m depth, with waste dry density ρ_d of 1 g/cm^3. The measured static subgrade modulus was 4400 – 6300 kPa/m on a rigid 0.91 m diameter plate and 11000-30000 kPa/m on a rigid 0.44 m diameter plate. These data are further tested in this work.

The published papers on the large-scale oedometric testing of waste ([21], [23], [7]) are partly only related to the mechanical characteristics of waste which can be measured by the usual "fast" oedometric tests, partly also to the biological degradation which can be measured by long-term tests.

There is a general observation that the visco-elasto-plastic settlement behavior of the saturated waste is identical to that proposed by Bjerrum for conventional soils. Bjerrum [1] noted that for soils creep and primary consolidation take place simultaneously.

However, the MSW material and the leachate water are extremely compressible [27], [40].

2.3. Grading entropy and degradation

The grading entropy diagrams were used to represent the typical degradation path which can be linked with the entropy principle [60], the results can be summarized as follows.

The path is monotonic in terms of the entropy parameters if these are not normalized. Being the entropy principle valid, the entropy increment increases during fragmentation, the mean log diameter and base entropy decreases due to particle degradation. However, the typical fragmentation path is iterative in terms of the normalized coordinates.

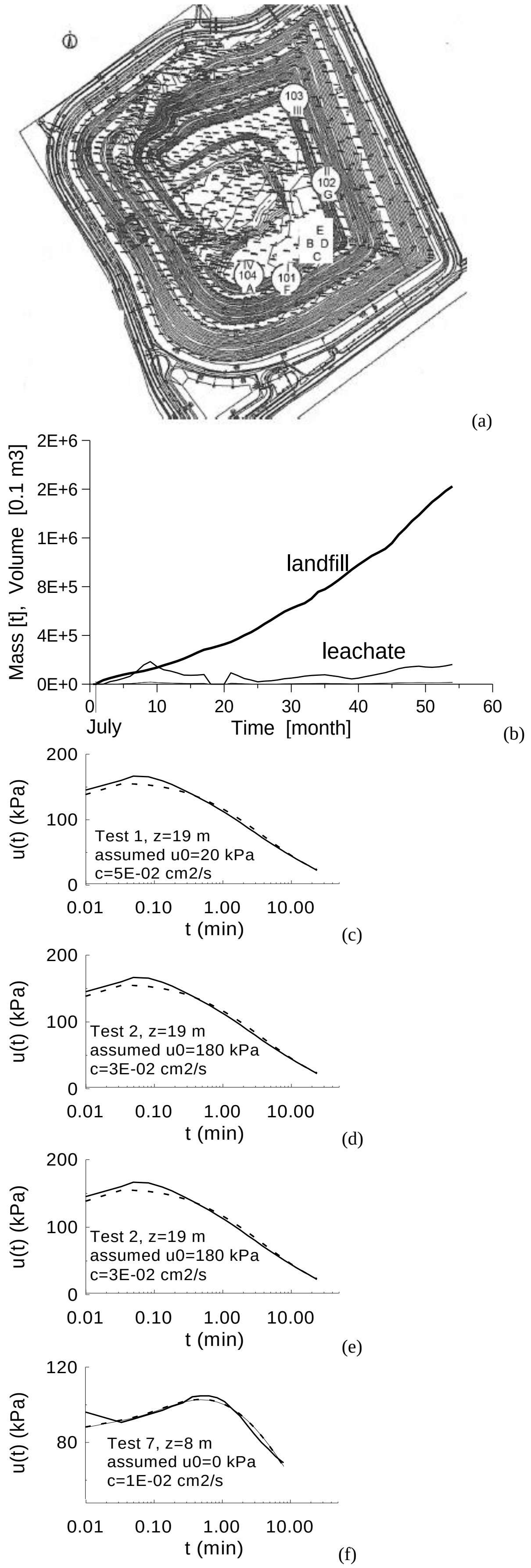


Figure 2. The Pusztazámor landfill site. (a) Site plane of the first phase, (b) Some data of the filling process.(c) to (f) Measured and fitted dissipation curves Figure 7 Measured and fitted dissipation curves (test 1, 2 and 7)

Table 1. Layer properties (mean values, after Varga [36])

Degradation phase	Organic content [%]	φ' [°]	c' [kPa]	w [%]
1st	56	35	18	32
2nd	41	26	14	53
3rd	35	23	13	84
4th	27	22	11	102
5th	19	20	4	118

Table 2. Grading test results (range, after Varga [36])

	Degradation phase				
	1.	2.	3.	4.	5.
Course (%)	66-86	58-75	40-58	30-45	25-40
Sand (%	10-25	11-27	20-35	20-35	20-35
Fine (%)	5-15	8-18	15-30	25-40	35-50

Table 3. Isotopic density measurement (mean results)

Site	Wet density [g/cm^3]	Dry density [g/cm^3]
Uncovered	1.335	1.090
Covered, surface compacted	2.004	1.690
Road	2.214	1.990

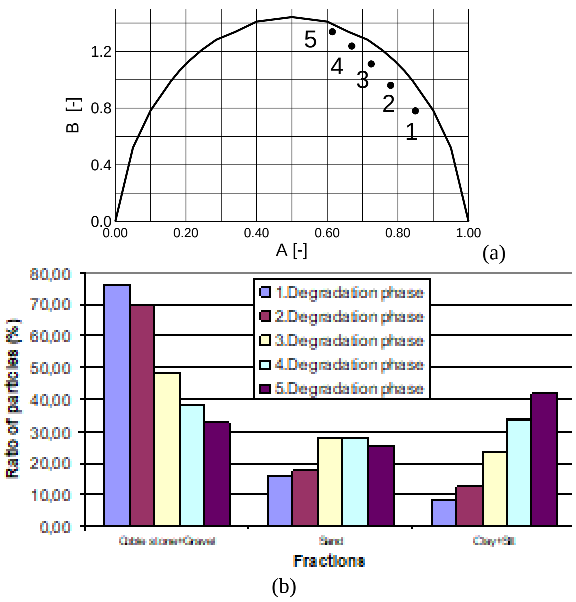


Figure 3. (a) The entropy diagram, the grading curves for degradation phases 1 to 5 (b) Grading curve data (Varga, [36], Table 2)

3. Previous measurements

The Pusztazámor landfill site (Fig. 2) is being built in 3 phases, in 25 years (2000, 2012, and 2025), in horizontal layers. Each phase is divided into four sections by levees, filling nearly simultaneously, with 55 m of maximal height. The first phase is observed in the ongoing research.

3.1. The methods

Most of the usual in situ tests (e.g. borings, on the same locations dynamic probes or CPTs beforehand), sampling and most of the usual laboratory tests for soils (e.g. shear, grading, large scale shear and compression tests, SWCC and permeability function) were generally executed in a modified manner.

The waste exploration was made gradually, to save the usual equipment as possible. At first seven dynamic sounding then static sounding were made to depths ranging from 6 to 22 meters at the shoulder of the landfill nearly at full height, and samples were recovered for testing (Fig. 2, [13]).

The CPT-s were made both in continuous and dissipation testing modes which means that the steady penetration was stopped, the penetrometer was clamped and the time variation of pore water pressure was measured in u_2 filter position [12]. The dissipation test results were evaluated using a mathematically precise method [13].

Then five boreholes with a large diameter (180 mm) were drilled, and samples were recovered for testing. From the samples taken from the boreholes for the laboratory testing, the d<16 mm particles were separated as soil like material and they were tested for water content, organic content, grain size distribution, shear strength parameters determined in large-scale shear box. The results were statistically evaluated [35].

In the present stage of the research, the cores of waste material were used to determine the compressibility of the material in the modified large-scale shear box. In addition, the present stage of the research, the goodness of the grading curve data was tested in the grading entropy context.

Concerning the design of the final cover layer, the permeability function was determined for three candidate mixtures for the mineral layer of the double insulation layer (50 cm of mineral layer and 2.5 mm of polyethylene) of the 2nd phase of the Pusztazámor landfill site. The mixtures were differing in the bentonite content, progressively increasing for sites I, II and III.

The SWCC and the permeability function were measured as follows. The samples were saturated. Each test sample was doubled. The dry density ρ_d of the samples is measured at the end of the test. No antimicrobial agent was applied. The saturated k value was measured.

The SWCC method of the RISSAC ([45]; [51]) was applied. In the suction range of u_a-$u_w \leq 50$ kPa sand plate boxes were used. The load steps were fixed for each box to avoid any disturbance of the sand layer. In the greater suction range (u_a-$u_w > 50$ kPa) pressure membrane extractors were used. The van Genuchten [44] water retention curve equation and permeability functions. The permeability function was measured on 5 sets of doubled samples with the instantaneous profile method [41] as follows. The samples were closed at the bottom and were allowed to evaporate at the top entailing vertical seepage within the sample. Every day two samples were open, were cut into 10 horizontal slices determining their water content. From this and the SWCC, the suction values were determined in discrete points.

The van Genuchten [44] water retention curve equation was fitted on the SWCC data. From this, a dimensionless van Genuchten permeability function was determined. The saturated permeability was measured by falling head tests. The van Genuchten permeability function was fitted on measured data.

3.2. The results

The previous geotechnical explorations in Pusztazámor, in terms of the five anaerobic decomposition phases ([35], [13]) are reanalyzed and recapitulated as follows. Table 1 summarizes the layer characteristics in terms of organics and water content, shear strength test results, indicating that - with the advancement of degradation -, the internal friction angle and cohesion decreases.

The results of the continuous CPTu tests indicate that the waste is a relatively homogeneous material. The results of dissipation type CPTu test were evaluated using a mathematically precise method. The result was an in-situ (horizontal) coefficient of consolidation of 2 to 6 10^{-6} m^2/s ([57]).

Table 2 depicts grading curve data in terms of fractions and degree of degradation. The amount of the coarse-grained fractions decreases by more than 50 % while the ratio of fine-grained fractions increases fivefold during degradation. The ratio of sand fraction is between 16-26 %.

The grading curves for the five layers, represented in the grading entropy diagram (Fig 3), shows the usual degradation or breakage path.

The relative base entropy A decreases, the normalized entropy increment B strictly monotonically increases during degradation. This supports the goodness of the grading test results and the fact that the entropy principle is related to the degradation process.

The validation of the grading curve data for the five layers suggest that the grading test can be used to identify five anaerobic decomposition phases.

Concerning the design of the final cover layer, the permeability function results determined partly from SWCC measurement partly from direct measurement can be seen in Figure 3.

According to the results, there is a significant difference as the bentonite content increasing for sites I, II and III. Layer III with largest bentonite content has the smallest permeability for any given suction value.

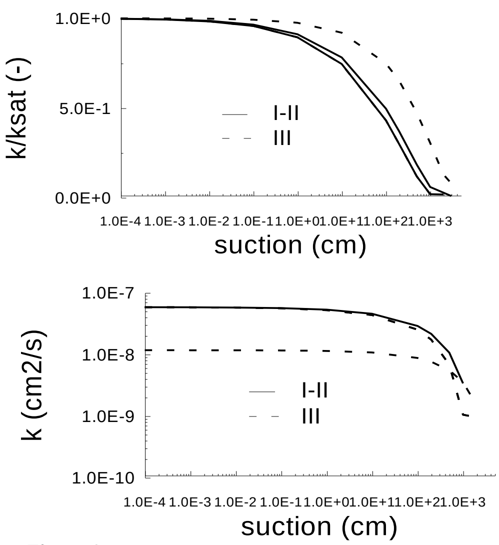


Figure 4. The permeability function of the mineral layers

Photo 1. CPT rig, Dynamic probe, In situ isotopic density measurement

4. New measurements

4.1. In situ testing methods

The in-situ tests (isotopic density tests, light falling weight-deflectometer and seismic tests) methods can be summarized as follows. The isotopic density test is one of the most widespread measurement procedures (ASTM D6938), in which a detector observes the gamma-radiation in the soil; the number of the impulsions counted under the measurement time is proportional to the wet density of the soil. Plane probe and pin probe measurements are needed as well. The Proctor compactness degree is needed also at the value of the water content as reference density. The examination time is 15-25 minutes and three examinations are averaged. The measurement accuracy is high ±5-6%.

In the light falling weight-dilatometer test the average settlement amplitude must be determined and the dynamic bearing modulus E_{vd} is computed. The test time is 10-15 minutes on site and from this. The E_2 modulus can be estimated by charts from these ([2][3]). The E_2 modulus can be determined by a longer static plate load test according to CEN ISO/TS 22476-13 using the Boussinesq-formula, with fixed disc-model multiplier, and calculated from the data of the second load step.

Concerning seismic tests, the basic requirements are that the frequency content of the records had to be low enough to obtain phase velocities at short and large wavelengths as well, 10 Hz of vertical geophones and 48 channels were used and sledgehammer as seismic sources. After careful analysis of records the fundamental mode of Rayleigh waves was investigated only. The dispersion data of recorded Rayleigh waves were inverted using a Genetic Algorithm method to obtain shear wave velocity profiles ([33]; [29]). The small-strain shear modulus G_0 was evaluated using the well-known simple formula:

$$G_0 = \rho_s v_s^2 \qquad (1)$$

where G_0 is small-strain shear modulus, v_s is the velocity of the shear wave in soil, ρ_s is the density of soils.

4.2. Laboratory testing and evaluation methods

The oedometer tests were performed in the same 50 cm x 50 cm box as for the direct shear tests ([36]) after some modification in the Geotechnical Laboratory of the Szent István University, Ybl Miklós Faculty of Arch. and Civil Engineering (see Fig. 3). A hydraulic load system was added. The maximum load of the hydraulic system was 16 t. The load and the settlement were measured.

4.2.1. Samples

Three samples were constructed from undisturbed cores of large diameter boreholes, from layers with degradation phases 1, 2 and 3. The three tested samples were built from several originally undisturbed samples (called sub-samples, see Table 6). The leachate level was about in 11 m depth below the surface in the 21.1 m deep borehole. The sub-samples of samples 1 and 2 were situated above the leachate water level (Tables 6(a) and (b), Fig. 2(a)), the sub-samples of sample 3 were situated in the possible capillary zone or under the water level. This sample might have been transformed into a saturated state due to loading [6]. Some physical properties of the tested waste samples are shown in Table 1.

4.2.2. Testing method

The conventional multistage compression test is generally used for the determination of the compression curve and the coefficient of consolidation. According to the standard ASTM D2435 90, the load increment is less than or equal to the previous load, the duration of stages is longer than 99 % of the consolidation time.

The method applied here for the waste compression test was basically the same as the standard compression testing method. The loads were as follows: 5, 10, 20, 40, 80, and 160 …640 kPa. The stages were some-week long, so no time was allowed for much (if any) biodegradation.

The samples were put in a thick plastic bag within the box; and two plastic tubes were attached to the bottom of the bag to ensure a single-drained compression testing mode. Some leachate outflow was observed during tests 2 and 3. The usual sample height was about 7 cm.

4.2.3. Evaluation method

The stages of the quasi-saturated sample 3 were evaluated by modified Terzaghi's (A) and, modified Bjerrum's (AC) models, and a parameter was included for the immediate settlement (see [58, 59]).

The applicability of the simple models follows from the previous, short term compression test results and also from the actual test results, indicating that the settlement behavior of waste is identical to that proposed by Bjerrum ([1]) for soils.

The model fitting was made with an automatic, nonlinear, global minimization procedure entailing some reliability testing possibilities ([60]). The method was based on the separation of linearly dependent parameters and nonlinearly dependent parameters ([17].

By fitting the models on the measured data, the parameters were identified, the standard deviation of the parameters was computed, the uniqueness of the inverse problem solution was tested.

The identified model parameters and their influence were as follows. The v_0 immediate compression, the v_1 primary consolidation settlement, the C_α coefficient of creep influenced the model linearly, but the c coefficient of consolidation influenced the model nonlinearly.

4.3. In situ test results

According to the results of, the mean in-situ waste bulk density ρ_n measured by isotopic density test was equal to 1.3 g/cm^3 and 2 g/cm^3 for the uncovered and covered and compacted waste, with water content of 22 % and 19 % respectively (Fig 3, Table 3). The dry density ρ_d was 1.09 g/cm^3 and 1.69 g/cm^3, respectively.

According to the results of the light falling weight deflectometer test (Table 4), the evaluation resulted in E_2=79 N/mm2 at the actual service road otherwise the E2 values are very low.

The seismic test results are shown in Table 5. The shear wave velocity of the material varied from 100 to 150 m/s between the surface and 4 m depth.

The results of measurements and preliminary computations, with 1.0 g/cm^3 for the sake of safety, are shown in Table 5 concerning the seismic small-strain shear modulus G_0. On the basis of the statistical distribution data, the characteristic velocity value can be considered as the minimum value.

Table 4. Light falling weight deflectometer measurements results

test	Settlement [mm] 1	2	3	mean	E_2 [N/mm^2]
	14.09	14.53	14.13	14.25	3.20
Covered	5.17	5.11	5.11	5.13	8.80
Covered, compacted	3.14	3.16	3.15	3.15	14.30
Road	0.58	0.58	0.56	0.57	79.00

Table 5. The seismic test results (made in layer 2), small strain shear modulus G_0 and the subgrade modulus by the linear (II) and the quadratic (III) formulae.

h [m]	z [m]	v_s [m/s]	ρ_s [g/cm^3]	G_0 [MPa]	$D_{\alpha II}$ [kPa/m]	$D_{\alpha III}$ [kPa/m]
1.5	1.5	126	1	0	67.42	50.98
0.3	1.8	120	1	14	61.64	46.62
0.3	2.1	118	1	14	59.01	44.62
0.4	2.6	115	1	13	56.82	42.97
0.7	3.2	113	1	13	54.10	40.91
0.4	3.6	110	1	12	51.33	38.82
0.6	4.3	110	1	12	50.87	38.47
0.7	5.0	108	1	12	49.39	37.35
1.0	6.0	107	1	11	48.39	36.60
1.3	7.3	106	1	11	48.03	36.32
2.1	9.4	109	1	12	50.03	37.84
3.7	13.1	116	1	13	57.51	43.49
3.7	16.8	144	1	21	89.22	67.48

Table 6. Profile of a diameter 180 mm boring 102, depth of 21.1 m

Depth [m]	Name of layer
0.0-0.2	fill
0.2-1.6	Silty sand
1.6-4.2	Waste
4.2-5.1	Silty sand
5.1-11.8	Waste
11.8-21.1	Silty waste
note	Leachate water at 11.8m (well was made. using d=50 mm access tube)

Table 7. Large scale samples from undisturbed cores

Sample	Degradation phase	Cores or sub-samples (Boring number /sampling depth)
1	2nd	103 F / 0.5, 1, 1.5, 2m, 104 F / 0.5, 1, 1.5, 2m
2	3rd	103 F / 2.5, 3.5, 4.5, 5.5 m, 104 F / 2.5, 3. 4.5, 5.5 m
3	3rd	103 F / 6.5, 7.5, 8.5, 9.5, 10.5, 11.5 m

Table 8. The data determined from the evaluation of oedometer test (sample 3), showing values for c, the constrained moduli E_{s3}, E_{s2},E_{s3} and subgrade moduli.

Load [kPa]	c [m^2/s]	E_{s3} [kPa]	E_{s2} [kPa]	E_{s1} [kPa]	$D_{\alpha 1}(E_{s3})$ [kPa/m]	$D_{\alpha 1}(E_{s2})$ [kPa/m]
5	5.00E-08	100	100	2800	7	182
10	5.00E-09	100	300	3000	9	89
40	7.00E-09	300	600	17100	24	669
80	1.00E-11	800	3200	43000	71	947
160	8.00E-10	1500	4700	86700	140	2587
640	9.00E-08	7900	17600	823000	720	33648

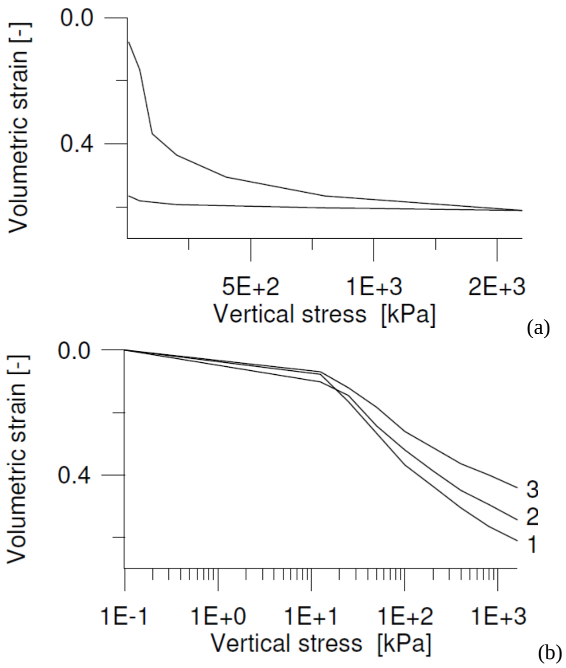


Figure 5. The compression tests. (a) Compression curve of sample 1 with unloading. (b) Compression curves for samples 1 to 3 in log scale

4.4. Laboratory testing results

4.4.1. Compression curves

The maximum volumetric strain for the waste samples 3, 2 and 1 was equal to 44%, 54%, 61%, respectively at 160 kPa of load. Therefore, the compression curves became stiffer with increasing sampling depth (Fig. 5). As a comparison, the compression curves measured on reconstituted waste ([21]) showed less maximum volumetric strain than 40 % at similar stress levels. It follows that the results showed a slightly larger compressibility than the reconstituted waste sample previously ones published ([21]). This difference can possibly partly be attributed to the fact that the samples used here were unified from sub-samples and partly to the thick plastic bag which was used within the compression cell.

It can be noted that - according to Table 1 -, with the advancement of degradation, the internal friction angle and the cohesion of the waste greatly decreased. It follows that the waste shear strength is more importantly influenced by organic depletion and less importantly influenced by preloading. In other words, compressibility and shear strength parameters in Pusztazámor have different tendencies in the function of the coupled effect of increasing phase degradation and increasing pre-consolidation stress since according to the results, the compression curves became "stiffer" with increasing depth and degree of degradation while the shear strength parameters decreased.

Within the same compression curve, the strain increment at large loads was considerably less than at medium or small loads indicating that the tested waste was a stiffening material under static load. It can be noted that similar stiffening results are found under static and dynamic load in the Spadina, where a large sample was tested under both static and cyclic load.

The measured compression curves showed a significant difference between the stiffness of the load and the unload curves. The large scale compression tests made on reconstituted waste samples ([21]) also showed a clear and consistent difference in virgin loading and unloading.

4.4.2. Identified parameters

The evaluation of the stages entailed the identification of the coefficients of consolidation and the separation of the various settlement components (immediate, primary consolidation and creep). The results of parameter identification can be seen in Table 7, Figures 6 to 8.

According to the results (Fig 6), the solution of the inverse problem was unique, but the solution has some considerable error (i.e. the deepest section of the noisy (thick line) and the noise-free (thin line) Least Squares merit functions F concerning the non-linearly dependent parameter of coefficient of consolidation c - represented in Fig 6 – show a single global minimum, the difference in these indicates the error of solution).

Computing the parameter error, the mean coefficient of variation for the coefficient of consolidation c was equal to 66 to 73%, for the immediate settlement v_0 was 6 to 11% (models A and AC), for the primary consolidation settlement v_1 was 14 to 35 % (models A and AC), and, for the coefficient of creep C_α was about 12 % (model AC).

The smaller coefficient of variation of parameters v_0, v_1 and C_α and the larger coefficient of variation of c can partly be attributed to the fact that the first set of parameters are linearly dependent parameters and the second non-linearly parameter. The former set can be determined more precisely than the latter by the given algorithm. A physical reason is that the proportion of primary consolidation in the total settlement was relatively small.

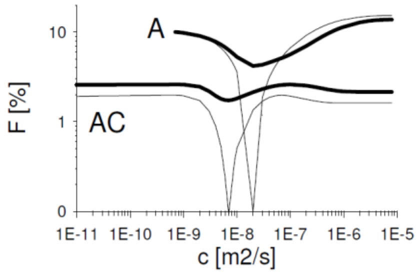
According to the results (Figs 7, 8), the mean ratio of the immediate settlement, the creep settlement and the primary consolidation settlement with respect to the total settlement for the waste was equal to 36 %, 48 %, 16 %, respectively. The immediate compression settlement was larger for small stage loads than for large loads possibly due to the combined effect of the compressibility of pore fluid and particles. For unsaturated soils the compressibility of pore fluid is large until the solution of free air in water occurs ([6]).

4.4.3. Computed modulus and modulus degradation values

The immediate settlement, creep settlement, primary consolidation settlement functions were separately assessed from the measured data. Three kinds of oedometric modulus were computed from the value of these function valid at the end of the compression test (Table 7), the usual constrained modulus (E_{s3}), the con-strained modulus without the immediate settlement (E_{s2}), and the constrained modulus with the primary consolidation settlement only (E_{s1}).

It can be noted that - using the measured G_0 seismic small-strain modulus -, the modulus degradation values were approximated as 0.003, 0.03, 0.3, respectively, for the three kinds of oedometric modulus, assuming an arbitrary value of 0.2 for Poisson's ratio. The large difference in the modulus degradation values and the large E_{s1} modulus indicate that the waste, after an excessive deformation, can be a reliable medium for foundation.

The characteristic modulus degradation value for the design was considered as 0.01 which is related to the special case when two settlement components were used, the immediate settlement component was neglected.



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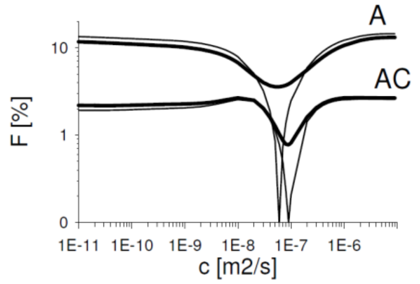
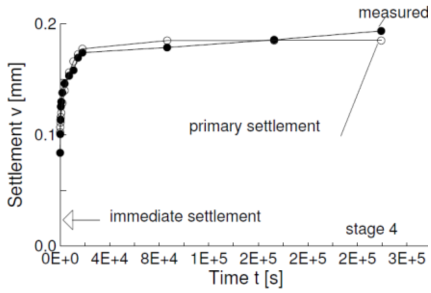
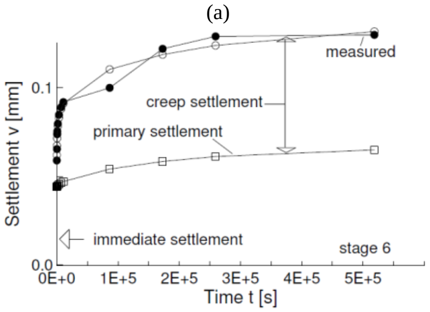


(b)

Figure 6. Figure 6. The reliability of the inverse problem solution. The compression test, sample 3, the deepest section of the real-life (thick) and the closest noise-free (thin) merit functions (indicating the uniqueness of the solution and the error of parameter *p*) with respect to parameter *c*. (a) and (b) stage 4 and stage 8, resp.
Figure 7.

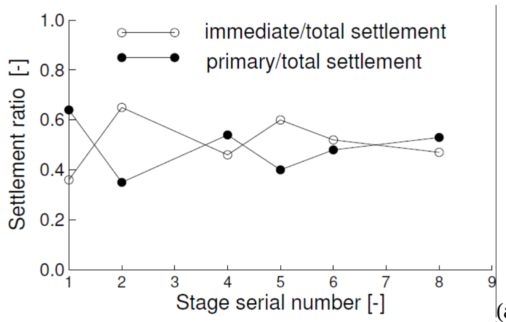


(a)

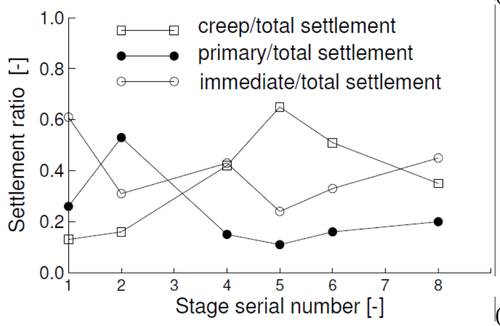


(b)

Figure 8. The compression test, sample 3. The variation of the various settlement components with time. (a) Model A, stage 4. (b) Model AC, stage 6.



(a)



(b)

Figure 9. Compression test, sample 3. The settlement components with stage load. (a) Model A (modified Terzaghi's model). (b) Model AC (modified Bjerrum's model)

5. Design

5.1. Design methods

5.1.1. The settlement of the wind turbine

The wind turbine foundation can be (i) a large monopile; (ii) a pile group or groups consisting of a number of smaller piles with a cap; and (iii) a large gravity-based shallow footings (mat or raft foundation). A gravity base foundation was assumed, consisting of a large ring footing and a concrete deck with mean diameter of 22 m. The annular base had a width of 4 m (Fig. 9).

In this preliminary work, only the effect of static load was investigated since a substantial rotational and dynamic stiffness increase was previously proved with repetitive load of MSW for the given foundation system ([26], [4]). The static load data of the planned wind energy plant were as follows (Figure 10). The self-weight of the foundation was 14791 kN. The load on the structure was a vertical force of 1100 kN, a horizontal force of 415 kN and a moment in a vertical plane of 20 400 kNm. The concentrated loads (vertical and horizontal forces and the bending moment) from the wind turbine were distributed along the bottom circumference of the turbine tower body.

The simplest possible, subgrade modulus settlement method was used since the foundation was very rigid with respect to the relatively inhomogeneous waste material and, therefore, uniform stress distributions could be assumed (Fig. 9). The subgrade modulus should be calibrated using classical settlement analyses ([31]).

The settlement under static load was computed with the AxisVM FEM software using Winkler-type spring constants under the shell elements [8], in the frame of a paramegric analysis, in the function of the subgrade modulus. The foundation under the wind turbine was modelled with quadratic plane shell elements. The triangular finite elements have six nodes.

The settlement under static load was determined in the frame of a parametric analysis in the function subgrade modulus. The subgrade modulus was calibrated by using the settlement data which were compared with the settlements measured in Karlsruhe. The measured settlement for a 75 kW wind turbine in Karlsruhe was about 2 m of magnitude. This value did not contain the effect of the immediate compression during construction.

The calibrated subgrade modulus value was compared with the subgrade modulus values computed on the basis of the data determined with the in situ and laboratory testing program evaluated such that the immediate compression settlement was neglected. Based on the results, a characteristic subgrade modulus value was suggested.

5.1.2. Subgrade modulus computations

The subgrade modulus can be computed with simple formulae, based on the G_0 small-strain modulus values measured by seismic tests, the constrained modulus measured by large-scale compression test and the modulus degradation value κ determined from the foregoing two tests.

The subgrade modulus D_α can be computed using B or A or r (the width or area or radius of the foundations) with three different formulae, either directly from the usual constrained modulus E_s as follows:

$$D_{aI} = \frac{2E_s}{B}, \text{ formula I} \quad (2)$$

or

$$D_{aII} = \frac{2E_s}{B} = 4\frac{\kappa G_0(1-\mu)}{(1-2\mu)B}, \mu < 0.5, \text{ formula II} \quad (3)$$

or from the k the spring constant

$$D_{\alpha III} = \frac{k}{A}, k = 4\frac{\kappa G_0 r}{1-\mu}, \mu < 0.5, \text{ formula III} \quad (4)$$

The constrained modulus was either determined from the compression curve (formula I, using either E_{s3} or E_{s2}), or it was computed from the G_0 seismic small-strain modulus using modulus degradation factor κ (formula II, see Table 5).

5.1.3. Service road design method

Concerning the service road, the design was based on in-situ tests using the information that minimum E_2 needed for a road base is 40 N/mm2. The E_2 parameter was determined from isotopic density tests, light falling weight-deflectometer tests.

5.2. Results of the design

5.2.1. The subgrade modulus computations

The subgrade stiffness was estimated on the basis of two formulae and methods I to III, depending on the foundation dimension (linear or 2-dimensional) and either the measured constrained modulus values or the measured G_0 seismic small-strain modulus values in conjunction with the modulus degradation value.

The small-strain modulus G_0 was determined from the seismic measured shear wave velocity values and the measured waste density values. The constrained modulus and the modulus degradation value were determined by the evaluation of the large-scale compression test, such that the immediate settlement component was neglected. The computation results of the subgrade modulus are summarized in Tables 5, 9.

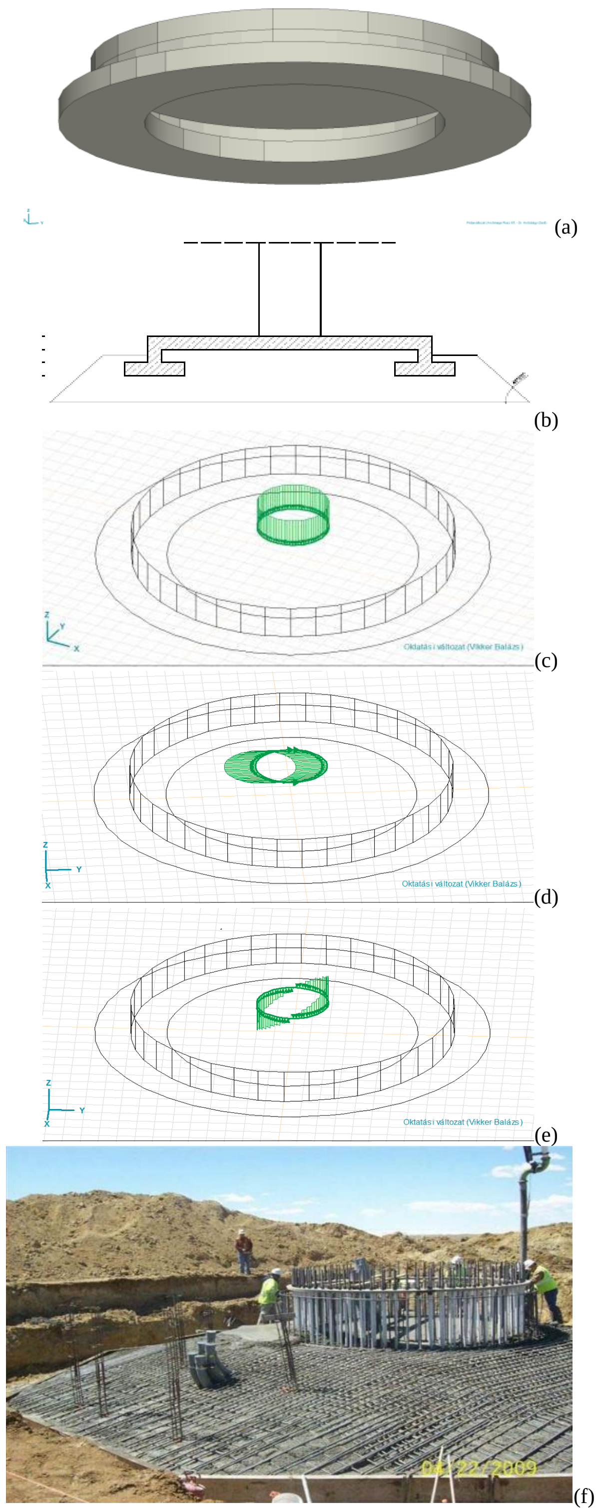


Figure 10. The ring foundation of the turbine tower body. (a) Planned in this work. The connection of the of the turbine tower body: Vertical force (b), horizontal force (c) and moment distribution (d). (f) Constructed in Spadina

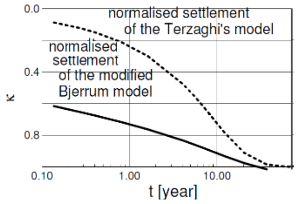


Figure 11. The time dependency of the mechanical type settlement (without biodegradation, see eg., -Gourc [7])

Table 9. Subgrade modulus computation summary

	Seismic test		Oedometer test	
	$D_{\alpha II}$ [kPa/m]	$D_{\alpha III}$ [kPa/m]	$D_{\alpha I}$ (E_{s3})	$D_{\alpha I}$ (E_{s2})
Mean	55.57	42.03	161.8	1626608
Maximum	89.22	67.48	720	33648
Minimum	17593	36.32	7	89

Table 10. Settlement in the function of the mean subgrade modulus

Subgrade stiffness D_α [kPa/m]	Settlement [mm]
10	6441,52
20	3220,71
30	2147,11
100	644,07
2000	32,12

5.2.2. Settlement

According to the results of the parameter analysis, the settlement varied between 0.6 m to 6 m in terms of the subgrade modulus. At subgrade modulus of 30 kPa/m, the settlement was about 2 m, which was the order of magnitude of the measured settlement in Karlsruhe for a somewhat smaller load (Table 9). This subgrade modulus value (30 kPa/m) was considered as characteristic value since it was approximately equal to the minimum value determined by method III (2-dimensional formula), using the characteristic velocity value and characteristic modulus degradation values.

The settlement due to the self-weight of the landfill - computed using the compression curve for sample 3, assuming immediate filling process and an estimate for the limit depth of the whole landfill - was about 25 m.

Using the coefficient of consolidation identified from the CPTu dissipation test data and classical Terzaghi's model, the 50 % and 99 % primary consolidation times are equal to about 5 and 30 years, respectively.

However, the application of the modified Bjerrum model and the different formulae and identified parameters for the immediate, creep and primary consolidation settlements, the half of the 25 m settlements was resulted within a few weeks (Figure 11).

5.2.3. The service road, foundation on the waste

The results of the isotopic density tests and light falling weight deflectometer test are shown in Table 3. The evaluation of the in situ tests resulted in E_2=79 N/mm^2 at the actual service road and low E_2 values beyond the actual service road.

Therefore, the new road can be planned on the old one (since the usual requirement under the pavement for E_2 is minimum 40 N/mm^2). However, beyond the service road, the section deep dynamic compaction is required due to the low E_2 values, and the same should apply under the foundation of wind turbine.

6. Discussion

6.1. In situ measurements

6.1.1. Seismic and density tests

The results of seismic tests showed that the shear wave velocity varied between 100 to 150 m/s between the surface and 4 m depth, and the results of in-situ waste density measurements showed a dry density of 1.09 g/cm^3.

As a comparison, in the Spadina Landfill, Saskatchewan (Canada) 90 m/s shear wave velocity value was measured at the surface, increasing to approximately 140 m/s at 10 m depth, with a waste dry density ρ_d of 1 g/cm^3 ([4]).

The fact that the shear wave velocity values and the waste density values were slightly larger in Pusztazámor than in Saskatchewan, at the Spadina landfill site was in accordance with the expectation, since in Spadina the values were slightly smaller than the values expected on the basis of the previous experiences.

6.1.2. Subgrade modulus tests

As some additional validation, the results of the in situ testing program were compared with the one previously made at the Spadina landfill site. The subgrade modulus values were compared with the results of in situ subgrade measurements made at the Spadina landfill site, using a model law.

The previous in situ subgrade modulus test data produced in the Spadina landfill site were as follows. The measured data show a static subgrade modulus of 4400 – 6300 kPa/m on a rigid 0.91 m diameter plate and 11000-30000 kPa/m on a rigid 0.44 m diameter plate.

The difference between the subgrade modulus measured in small scale and the one computed for the wind turbine can be verified by the following subgrade formula, assuming that parameter F may vary between 1.5 to 2.0:

$$D_a \approx \frac{A}{B^F} \quad (5)$$

where A is the product of a known diameter with power of parameter F and a known measured subgrade modulus for this plate determined by the in situ measurement.

If the measured static subgrade modulus is 4900 kPa/m on a rigid 0.91 m diameter plate then, by assuming F=1.5, the static subgrade modulus is 40.5 kPa/m for B=22 m and , assuming F=2, the static subgrade modulus is 8.2 kPa/m for B=22 m.

These values are comparable both with the subgrade values determined in this work and the results of the settlement calculations.

6.2. The design

6.2.1. The waste properties used for the settlement calculation

The results of seismic tests showed that the identified shear wave velocity varied between 100 to 150 m/s between the surface and 4 m depth, and the results of in-situ waste density measurements showed a dry density of 1.09 g/cm^3. The small-strain modulus G_0 was determined from the seismic measured shear wave velocity values and the measured waste density values. Similar results were reported by Fleming et al, except that the shear wave velocity, the waste density and the seismic small-strain modulus G_0 were slightly smaller in the Spadina landfill site (Saskatchewan, Canada).

The large scale oedometer test data measured on a quasi-saturated waste sample were evaluated using the modified Bjerrum model, as follows. The ratio of the immediate, primary and creep settlements versus the total settlement were separated.

The subgrade modulus was computed by neglecting the effect of the immediate settlement. It was determined from the small strain shear modulus G_0 determined by in situ seismic test data and the modulus degradation value of 0.01 (neglecting the effect of the immediate compression, considered as a characteristic value).

The subgrade modulus was calibrated using measured settlement data. According to the results, the settlement was about 2 m – the order of magnitude measured in Karlsruhe – at a subgrade modulus of 30 kPa/m. This was in agreement with the minimum value of the subgrade modulus computed using characteristic value for the velocity and modulus degradation in this work and with the result of previous seismic and in situ subgrade measurements made at the Spadina landfill site.

Therefore, the use of the G_0 small-strain modulus values measured by seismic tests in conjunction with the modulus degradation value determined from the compression test neglecting the effect of the immediate compression is suggested for further projects for the estimation of the subgrade modulus of waste.

6.2.2. The service road, final cover

Concerning the service road, the results of light falling weight deflectometer tests showed that the actual service road is acceptable as a base layer. The vehicle path for the hilltop payload large wind turbine structures should be carefully designed, and dynamic deep compaction can be suggested beyond the service load area. Due to the large settlements and inhomogeneity of the waste, adaptive structure is needed for the wind turbine.

The final cover isolation will be prepared from a double insulation layer (50 cm of mineral layer and 2.5 mm of polyethylene) of the 2nd phase of the Pusztazámor landfill site.

Three candidate mineral layer mixtures were tested for permeability function differing in the bentonite content, progressively increasing for sites I, II and III. The model test for layer proved good performance until now.

6.3. Laboratory test evaluation

6.3.1. Compression test and grading curve

The suggested evaluation method may separate the effect of the various (immediate, creep and consolidation) settlement components at the compression test duration time. According to the results, the ratio of the immediate, the creep and the primary consolidation settlement for the waste was equal to 0.36 : 0.48 : 0.16, respectively. Typically, these ratios are 0,12 : 0,65 : 0,23 for a Szeged clay as and are 0.00 : 0.51 : 0.49 for a Szeged silt. The waste has large immediate settlement and small proportion of primary consolidation. The silty soils may have zero immediate compression, the clayey soils may have large immediate compression and large creep.

Another inference of the new evaluation method is the possibility of the modification of the classical Terzaghi's settlement estimation method based on compression test results. The time evolution of the settlement components will be different in case of a layer thickness differing from the one of the compression test sample and in case of a true lifetime differing from the duration of the compression tests since the time evolution of the creep is not dependent on the layer thickness. In addition, in many problems the immediate settlement can be neglected when the modulus values or the time evolution of the settlements are considered. Further research is suggested on this.

The (previously measured) grading curves were reanalyzed in terms of grading entropy theory. The results clearly reflected the effect of degradation. This result supports the goodness of the grading curve data, the grading curves can reliably be measured. It indicates that the grading curve can be used in practice to identify the five anaerobic decomposition stages which varies during the life of the landfill hill.

Most landfill site are built in horizontal layers. As it was suggested by Varga ([36]), the sublayers can naturally be defined on the basis degradation stage number. This is a time dependent classification and need biological measurement.

6.3.2. Dissipation test evaluation

The monotonic and non-monotonic dissipation test data were evaluated using a new method [13]. In the evaluation results presented here, the spherical coupled consolidation model was included. In the non-monotonic evaluation method, the non-monotonic initial condition shape function series was used. The parameter vector $\boldsymbol{p}$ was composed from the non-linearly dependent coefficient of consolidation c, a linearly dependent parameter and up to 3 additional non-linearly dependent parameters for the shape of the initial condition. A gradient-free, automatic and mathematically precise, non-linear, inverse problem solver was used in the suggested evaluation method. In this work only the results concerning the model fitting (Figs 7 to 8) and the coefficient of consolidation are presented (Table 1). The results are approximate since the landfill structure was sometimes unstable during the test and the value of the water level in the boreholes was not known.

Concerning the identified parameters, the following can be said. The identified coefficient of consolidation *c* was 5 E-8 m^2/s as a mean for model A and was 2.45E-08 m^2/s as a mean for model AC. The dissipation test results, evaluated using a mathematically precise method, resulted in an in-situ coefficient of consolidation of 2 to 6 10^{-6} m2/s ([13]). The identified coefficient of consolidation *c* was smaller by more than nearly two order of magnitudes than the horizontal, in-situ coefficient of consolidation c_h determined from CPTu dissipation tests ([13], see section 2) possibly due to the secondary structure of waste, according to the expectations.

The secondary structure may cause a significantly larger in-situ permeability than the one measured in laboratory. This large difference is evident in the landfill sites, the water is generally coming out at the side of the landfill slopes instead of seeping down to the drain system.

6.3.3. Waste layering for five degradation phases

The compression curves determined by the large-scale compression tests showed that the stiffness of the waste increased with increasing static load and degrees of degradation. Similar stiffness increase was found in the in-situ and laboratory testing of MSW applying static and dynamic tests at the Spadina landfill site. The stiffness increase indicates that the waste, after an excessive deformation, is reliable for foundation. However, the previous shear resistance data showed a decrease with increasing degradation. This behavior is caused possibly by the biological degradation.

7. Conclusions

The paper considers the design of a wind turbine and its service road, planned to be installed at the top of the Pusztazámor Municipal Solid Waste (MSW) landfill hill, based on some geotechnical tests (*in situ* seismic and density tests, *laboratory* large-scale compression tests). The papers use the information of the first wind turbine built on a waste hill established in Karlsruhe with an annular base foundation, the settlement was about 2 m. It uses the data of the Spadina landfill site, where a wind turbine is planned, and several geotechnical tests were made. It also uses the results of the previous parts of the ongoing research related to the Pusztazámor landfill site, where a layering model with five anaerobic decomposition phases, separated on the basis of biological measurements in depth, was adopted and some shear tests and grading tests were made.

1. Some conclusions arrived at from waste testing and waste parameters estimation can be listed as follows.

- Most of the usual *in situ* tests (e.g. borings, on the same locations dynamic probes or CPTs beforehand), sampling and most of the usual *laboratory tests* for soils (e.g. shear, grading, compression) are generally executed in a modified manner when considering waste material. The actual in situ tests at the Pusztazámor landfill site (the seismic, density and light falling-weight deflectometer tests) were made with the same method as for soils. The actual laboratory compression tests were made in larger scale and were evaluated by a modified method.
- The results of the in situ seismic and density tests measured at Pusztazámor and at the Spadina landfill sites were similar, indicating that the waste properties are comparable. On the basis of the results, the small-strain shear modulus G_0 of the waste at the Pusztazámor landfill site was determined.
- On the basis of the in-situ light falling-weight deflectometer test data, the E_2 modulus was estimated. The results showed that the actual service road is acceptable as a base layer and deep compaction is needed beyond the old service load area and the foundation.
- The compression curves were determined by three large scale laboratory compression tests for layers 1 to 3 (related to anaerobic decomposition stages 1 to 3) at Pusztazámor. The results showed that the stiffness increased with increasing depth and increasing anaerobic decomposition stage.
- The data measured during the laboratory large-scale compression test made on saturated waste was evaluated using the models of Terzaghi and Bjerrum which were modified such that an immediate settlement term was included for the pore fluid and the grain compressibility. Using this term, the necessity of large strain and large displacements analysis was avoided since the automatic model fitting method gave reliable parameters with acceptable error.
- The dissipation test results, evaluated using a mathematically precise method, resulted in an in-situ coefficient of consolidation of 2 to 6 10^{-6} m2/s. Concerning the identified coefficient of consolidation *c* of the large-scale oedometer test, it was smaller by more than nearly two order of magnitudes than the horizontal, in-situ coefficient of consolidation c_h determined from CPTu dissipation tests possibly due to the secondary structure of waste, according to the expectations.
- The secondary structure may cause a significantly larger in-situ permeability than the one measured in laboratory. This large difference is evident in the landfill sites, where the water is generally coming out at the side of the landfill slopes instead of seeping down to the drain system (due to the anisotropy caused by the horizontal infilling process). Moreover, the stage loads may have compacted the waste, decreasing the permeability, according to the expectations.
- Using the identified parameters related to data measured during the laboratory large-scale compression test of the saturated waste sample, the immediate, creep and primary consolidation settlements were separated. The primary consolidation component was less than the sum of the immediate and creep components. The constrained modulus and the modulus degradation values were computed in this design such that the immediate settlement was neglected.

2. Some conclusions concerning the settlement estimation of the wind turbine and waste modelling can be listed as follows.

- In case of the analysis of the settlement of the wind turbine planned on the top of the Pusztazámor MSW hill under static load, the settlement was computed using a

Winkler type model in the function of the subgrade modulus in the form of a parameter analysis and adaptive structure was suggested for the wind turbine. The subgrade modulus was estimated from the modulus and the modulus degradation values with two formulae, reflecting the dependence on either the radius or the square of the radius of the foundation.

- The simple subgrade modulus approach gave realistic results. The settlement was equal to about 2 m - to the value measured in the Karlsruhe for a somewhat smaller load -, at the subgrade modulus of 30 kPa/m, which was about equal to the lowest value of the subgrade modulus computed on the basis of the seismic tests and, the maximum values were not too different, also. The earlier in situ subgrade modulus measurements and the presently computed data indicate that the truth seems to be in between the two formulae.
- The settlement – time function of the wind turbine was estimated by superimposing the time-dependence of the immediate, creep and primary consolidation settlements giving faster settlement times than the classical Terzaghi's theory. The result is approximate since the effect of biodegradation was neglected.

3. Some conclusions concerning waste and soil modelling can be listed as follows.

- Due to the horizontal infilling process, five layers with the different anaerobic decomposition stages were defined in Pusztazámor showing distinctly different behavior. The grading curves reflected the effect of the degree of degradation. The stiffness of the compression curve and the shear strength parameters varied in an opposite manner. This feature is suggested to be further investigated in the field of the constituting modelling of waste, e.g. in case of the HBM model. Further research is suggested on the waste parameters in terms of bio-logical degradation. These results may give further in-formation on the interdependencies; for example, the mechanical consequences of decomposition which have until now, received little attention in either the landfill or geotechnical research communities.
- For the evaluation of the compression test results of the unsaturated samples, or for a precise analysis of the wind turbine, the use of concepts associated with unsaturated soil mechanics will be used to advantage. The applied model is needed to be modified for large strains and displacements and, the constitutive model parameters are needed to be assessed for each layer with the five anaerobic decomposition stages separately.
- The method used for the evaluation of the compression test results of the saturated waste samples can be used for saturated soils and peats, with the following comment. The first results show that the immediate settlement in silts is zero (which can be related to the liquefaction potential) and, but ma widely vary in clay indicating the geological origin. Further research is suggested on this.

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