SZENT ISTVÁN UNIVERSITY

# Modelling of waste hills

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NOMENCLATURE

| | | |
|---|---|---|
| A | mix ratio | [-] |
| $c_k$ | weight coefficient | [-] |
| $c_v$ | consolidation factor | [m$^2$/s] |
| $C_\alpha$ | creep index | [-] |
| d | grain diameter | [mm] |
| E | Young modulus | [N/m$^2$] |
| $e_0$ | initial void ratio | [-] |
| $E_s$ ($E_{oed}$) | compression modules | [kN/m$^2$] |
| H | leakage lenght | [m] |
| k | water permeability coefficient | [m/s] |
| S | underweight | [m%] |
| t | time | [s] |
| $t_0$ | time parameter | [s] |
| $u_a$–$u_v$ | suction, tension | [kPa] |
| v(t) | vertical dislocation of the top of sample | [m] |
| $v_0$ | initial deformation | [m] |
| $v_1$(t) | consolidation deformation | [m] |
| $v_2$(t) | creep | [m] |
| $v_n$ | normalized volumetric water content | [-] |

***Greek Letters:***

| | | |
|---|---|---|
| $\eta$ | dynamic viscosity | [Pa s] |
| $\varepsilon$ | normalized deformation | [-] |
| $\sigma$’ | effective normal stress | [kN/m$^2$] |
| $\upsilon$ | Poisson ratio | [-] |

# 1. INTRODUCTION, OBJECTIVES

With my dissertation I would like to contribute to a part of environment management, namely waste management, specifically the technological development of disposal of municipal solid waste. My objective is to conduce a more secure and more economical way of waste disposal meaning less environmental risk.

## 1.1. Actuality and significance of the chosen theme

In the last few decades, environment management, environment protection, and prevention of pollution have become more and more important in Hungary too. The actuality of the theme is proven by a large number of vocational books, journals, conferences, laws and press news.

Establishing a long term operable (maintainable) environment management is a social need, demanding the accomplishment of new technological objectives. It is not an overstatement to declare that proper waste management is an integral part of responsible environment management, since in a broader sense almost all of the issues of environment protection, energetics and economization are also waste management issues.

Inadequate waste management could be a cause for environmental catastrophes both in short- and long terms. The expected change of climate puts waste management already loaded with several dysfunctions through further challenges.

Dumping waste into landfills is not the best handling solution. In spite of this, technological knowledge concerning landfills is very important, since these are going to further operate for a long time. Beyond secure operation, the mechanical (waste physical) characteristics of landfills are also needed for the exploitation of the areas of full, re-cultivated refuse dumps. Economic planning of the groundwork of engineering contraptions is only possible upon knowing these, as in this case the „substrate” is the dumped waste.

## 1.2. Objectives

There are several technological and non-technological fields of research concerning municipal solid waste dumps. Naturally, my dissertation concentrates on technological issues, but even these topics would greatly exceed my available frameworks and resources.

I have chosen modelling of waste dumps as my closer field of research. Modelling waste dumps is an important task, as it helps in the estimation and planning of available escarpments, deflections, quantity, composition, paths of arising leachate and gases. Several kinds of models – mechanical, hydraulic, biological, complex – are available depending on the type of the question to be answered. I have undertaken the modelling and research of two subdivisions:

• mechanical modelling of waste dumps, more specifically estimation of deformations in space and time (on an applied research level),
• hydraulic modelling concerning waste dumps (on an applied basic research level).

According to the listings above, together with the results of my own conclusions drawn from specialized literature and my own experiences, also considering my qualifications and knowing certain compulsions, limitations, possibilities I could undertake answering the following questions:

1. Modified compressional examination of samples taken from a chosen refuse dump, and according to these examinations – depending on the degree of degradation – description of compressional curves, definition of depression modulus and Poisson ratio typical to the given waste, recalculation of permeability coefficient, investigation of the rate of residual and flexible deformations;

2. Upon evaluation of the results of the modified compressional examination, setting up a curve of consolidation, in other words, soil mechanics based consolidated waste analysis according to the degree of degradation;

3. Upon evaluation of the results of the modified compressional examination, setting up a rheological model in the light of degree of degradation;

4. Soil mechanics based modelling of deformations of the chosen waste sample with the help of a program using numeric (finite element) method, using the waste-physical characteristics defined in the previous points. Validating and verifying the model(s) by localized settlement measurement, investigation of non-considered factors.

5. Defining the function of water retention by calculations based on the retention curves of the fractions of a theoretical water collection system in connection with the hydraulic modelling of the chosen waste dump. Monitoring laboratory measurements, precision of the existing academic definition.

In order to reach the above mentioned goals and to certify them with laboratory experiments it is necessary to work out new measurement tools and methods, as often we have to apply non-routine measurements, thus in this case measurement technology is an important area, providing direct help to the research.

# 2. MATERIAL AND METHOD

In this chapter the experimental methods and tools used to accomplish my research goals are presented.

## 2.1. Initial assumptions

Before starting the investigations, I had the following assumptions:

• The deformation of dumped, solid communal (municipal) quasi saturated waste can be investigated with the toolset of soil-mechanics/mechanics (physical processes, examination tools, theories etc.), although analogy with soil is not perfect, still, from the aspect of the investigated phenomenon, waste can be considered as a granular medium.
• During the modelling I consider even-aged dumped waste as homogenic and isotropic, concerning its mechanical characteristics, while from the aspect of hydraulics I consider it as homogenic but anisotropic.
• Leaking and covering granular layers can be considered as a mix of the fractions, thus the probative and entropic conception of grain size distribution can be applied.
• I conduct my investigations according to the existing standards (in case if there is any), thus securing their comparability with other examinations.
• From the applied investigations, theories, modelling I always look for the most simplistic, providing acceptable accuracy, since for practical purposes it is the most favourable.

## 2.2. Investigational locations

The examined communal waste dump was the Regional Waste Management Center of Pusztazámor (PRHK), whose first cycle have reached 99% fullness by the end of 2012 (Fig. 2a). I have conducted the laboratory examinations of waste samples in the Geotechnical Laboratory of Ybl Miklós Faculty, and the measurements concerning water retention with the help of the Pedology and Agro-Chemistry Research Institute of the Hungarian Academy of Sciences.

## 2.3. Examined materials

The object of my investigation is the material of the waste body (communal waste with daily covering) and the mineral material of the lower and upper closing being part to the dump (runoff (drain) layer, covering etc.), and I also had to examine the layer compound under the dump. As usual in geotechnics, I investigated a sample material (respectively, a theoretical sample) from the artificial layers, however, it was necessary to take actual samples from the dumped waste, which was implemented by the deepening of four large-diameter drillings (12-21 m bottom depth).

From the 22 samples of waste I have composed sample averages:

1. sample (S-1), (2. degradation level):
   103 F / 0,50, 1,00, 1,50, 2,00 m, 104 F / 0,50, 1,00, 1,50, 2,00 m.
2. sample (S-2), (3. degradation level):
   103 F / 2,50, 3,50, 4,50, 5,50 m, 104 F / 2,50, 3,00, 4,50, 5,50 m.
3. sample (S-3), (4. degradation level):
   103 F / 6,50, 7,50, 8,50, 9,50, 10,50, 11,50 m.

Degree of degradation expresses the level of physical, chemical, biological transformation of the waste, where degradation level 1. marks fresh waste, and degradation level 5. is completely transformed, decomposed waste.

As of hydraulic modelling, upon water retention curve measurements I have examined granular soil samples; four fractions of grain (d=2,0 – 0,5 mm), and six optimal compound (A=2/3) of these.

## 2.4. Investigation methods, instruments

Waste and soil are different materials, thus it was necessary to adapt the soil-mechanical instruments and measuring methods, and for the investigation of artificially built layers I had to adapt and develop pedologic and unsaturated soil-mechanical methods.

### *2.4.1. Modified compressional investigation*

I had to construct such a device, which is capable of operating vertical weights of various size while it measures the extent of deflection of the samples. Considering the height of the waste hill, the volume density of waste and the diametric area of the sample (50x50 cm), the modified oedometer had to be capable of implementing 0-150 kN of vertical force.

a) oedometer (5 kN) | b) oedometer (5-150 kN) | c) sand-layer equipment

Fig. 1. Laboratory invastigation instruments

Operating the contraption with static burden is possible between 0-5 kN (Fig. 1a), beyond this I have used a hydraulic press (a tank hoist) (Fig. 1b). To gain more information from the measurements for modelling, we have built in two steel-membrane pressure sensors into the walls of the box.

The operational test of the equipment was carried out by the manufacturer, while laboratory testing was done by me with use of sanded gravel. Due to its simple design, the laboratory equipment is cheap, but operates reliably, however this comes with the disadvantage that in the phase of lifting the weights with the hydraulic hoist, it requires quasi constant supervision. The operator has to correct the weight loss caused by the deflection of the sample. It was provided all the way through the measurements.

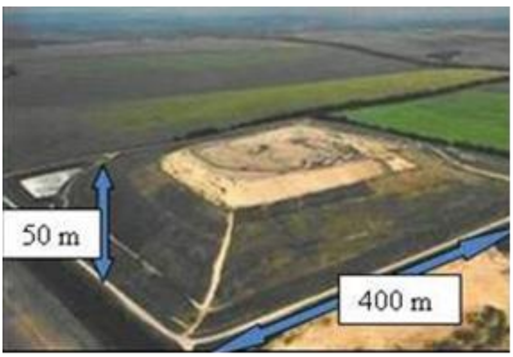
### *2.4.2. Measurement of water retention curve*

Knowing the expected course of the curve, and also considering our possibilities, I have applied two methods: the method of pendant water column with sand-layer equipment, and pressure chamber method.

Sand-layer equipment operates under constant pressure, however during the research program the dominant range of load was between 1-100 water column-cm, thus we have built and applied a new measurement protocol and a modified device (Fig. 1c), while I also implemented the domestic introduction of pressure chamber equipment.

### *2.4.3. Other measurements*

These are respective routine measurements, documented data provided by the landfill, or documented measurements of other researchers. I’d like to highlight two groups of measurements from these. On one hand I have received the data of peripheral settlement among others from PRHK (Fig. 2b), and I have also used the results of shear strength and other investigations carried out with parallel samples at BME.




a) wase hill of the first phase

b) leveling point

Fig. 2. The examined MSW landfill (PRHK)

# 3. RESULTS

In this chapter I introduce the new scientific outcomes gained from my work of research, helping the modelling of waste hills.

## 3.1. Compression of the investigated waste

Deformation of waste (being similar to soil) is a temporal process, thus requiring rheological investigation. However, for soil-mechanics based modelling it is expedient to investigate the load-dependent value (compression) and temporal course (consolidation) of deformations separately at first. Knowing these two, we can construct a model that describes deformations in an acceptable manner. It is an own characteristic of waste that it contains organic and decomposing materials in a non-negligible extent, causing extra depression. On the other hand, decomposing and fragmenting changes the material, thus changing the constants and parameters of the applicable equation, which has to be taken in consideration - the application of degrees of degradation being a possible solution to this.

The dependence of deflection from the degrees of degradation is well illustrated by the compressional curves drawn into the joint figure (Fig. 3).

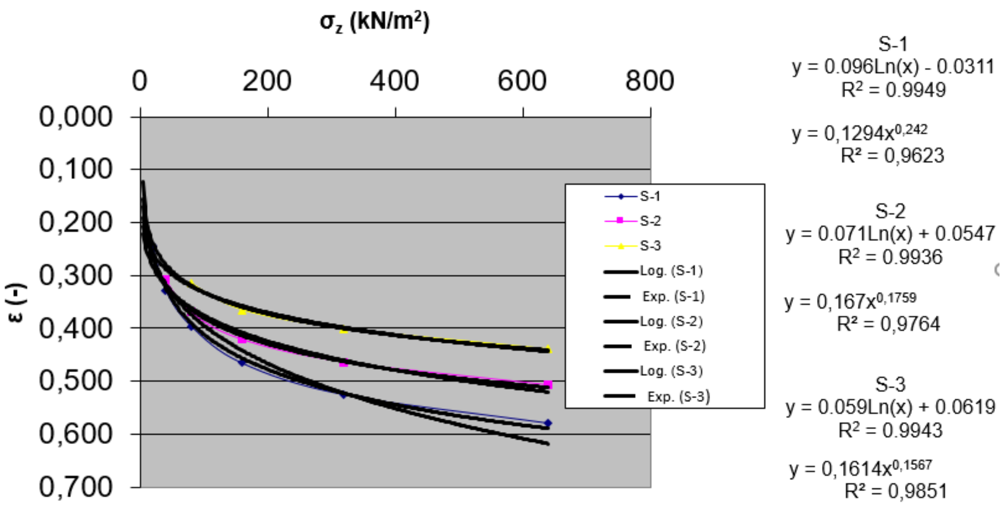



Fig. 3. The compressions curves

Upon increase of load, the samples become stiffer, namely they show characteristics similar to soils. Upon the increase of degree of degradation, samples also become more stiff, and in my opinion it is not because of preload, as curves "does not find each other", but rather degradation (biological decomposition, chemical transformation, mechanical fragmentation), changing the material itself. Hence, I suggest that instead of the one or twofold (fresh and degraded) waste models (being almost exclusively used in specialized literature) due to their practicality and simplicity, one should describe the waste of five different degrees of degradation with separate material-equations characterized by different constants. Due to the characteristics of the curves, the use of logarithmic- or power functions regularly used in soil mechanics is the practical approach, but it is expedient to ignore the loads of the given samples emerging under preload tensions, thus the results are shown in Fig. 3.

We have to investigate the inaccuracies caused by sampling – sample preparations – measuring; which is possible by the analysis of physical processes instead of a statistical analysis. Taking samples causes loosening, thus, our measurement is false until we reach the level of preload conditions. On the other hand in my opinion, being preloaded has a different effect than in the case of soils, since while in case of soils it predominantly causes compaction, in case of waste there is more beyond this, taking in account that the “solid part” is deflectable, breakable, thus in this case preload causes a permanent change, due to the loosening caused by the circumstances of sampling.

Phase-to-phase linearization and exposing the deflection modulus depending on the degree of degradation can be very useful for later calculations (Ct. 4.).

*Allocating the degree of degradation with* deformation *characteristics*

I have allocated the deformation characteristics of waste samples depending on their degree of degradation. Using the outcome of the investigation we can establish such deformation characteristic – normal tension ranges, with which the categorization of waste samples with unknown degree of degradation is possible, according to the degree of degradation. In Fig. 4. I have defined the ranges of degradation degrees with compressional curves, and also published the equations of borderline curves.

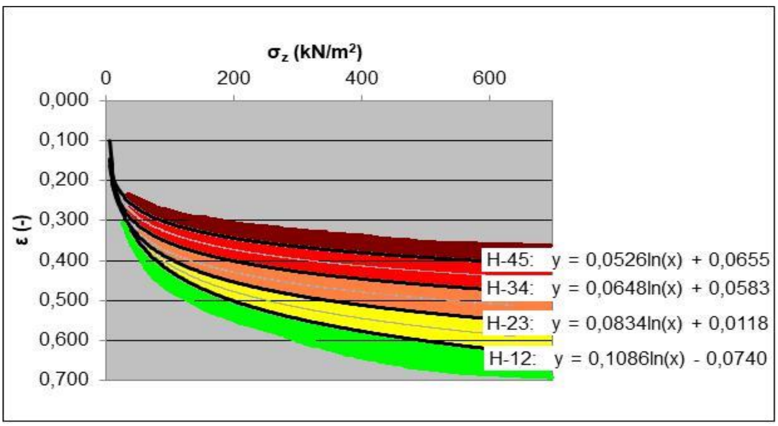



Fig. 4. Degradations levels with compression curves

*Change of Poisson ratio*

During compressional investigation I have also done side pressure measurements, thus Poisson ratio became calculable (Table 1). This is possible depending on the degradation degrees, and because of the non-linear behaviour it has to be done in separate load intervals.

Table 1. The variance table of Poisson ratio

| pressure (kN/m$^2$) \ sample | S-1 | S-2 | S-3 |
|---|---|---|---|
| 40 | 0,48 | 0,47 | 0,45 |
| 80 | 0,41 | 0,39 | 0,38 |
| 160 | 0,36 | 0,35 | 0,34 |

Upon increase of the degree of degradation and load, the value of Poisson ratio decreases. The reason for this is, that degradation and of course condensation also makes the examined material stiffer. Tension dependence can be explained with the non-linear behaviour.

*Evaluation of disencumberment*

Upon evaluating disencumberment (and re-encumberment) we can determine that a dominant part of deformations (more than 90%) is permanent, and in a rheological sense, irreversible(Table 2). Hysteresis effect was not measurable.

Table 2. Rate of the part of deformation

| | S-1 | S-2 | S-3 |
|---|---|---|---|
| elastic- / plastic deformation [%] | 9 / 91 | 6 / 94 | 6 / 94 |

The reason for the large rate of permanent deformations can be found in the material composition of waste and in its transformation under load. If we also consider the fact, that deformation caused by degradation is also permanent, the rate of flexible deformation is even smaller.

## 3.2. Consolidation of the investigated waste

During my investigations, I use the idea of consolidation in a sense according to Fredlund, D.G. The temporal course of deformation is even more nondescript than deflection, as it depends on several, hardly calculable factors. Concerning (soil)mechanics based consolidational examination I remark that from my measured consolidational curves, load-dependant deflection and short-term secondary deflection (crawling caused by viscous characteristic) can also be calculated. Long-term secondary deflection (crawling caused by degradation) can be estimated from local measurements, literature data and long-term measurements of sample S-3.

According to the experiences during laboratory investigations, the examined waste samples were quasi saturated, this is due to the lack of upper closure on one hand, and the unstable nature of drainage conditions, high humidity of dumped waste and decomposition processes on the other.

After laboratory definition of consolidational curves I have evaluated them with three methods:

- Classic soil-mechanical evaluation (Casagrande-Taylor-method),
- Modification of the Terzaghi model:

$$v(t) = v_0 + v_1(t)\,, \tag{1}$$

where: v(t) – is vertical dislocation of the top of sample,
$v_0$ – is initial deformation,
$v_1(t)$ – is consolidational deformation.

Consolidational deformation can be calculated with the following formula:

$$v_1(c_v, t) = v_{1,\infty}\left[1 - \int_0^{2H} \frac{u(c_v, t, x)dx}{2H\sigma}\right], \tag{2}$$

where: $v_{1,\infty} = 2H\sigma / E_s$ – is the end value of consolidational deformation.

- Modification of the Bjerrum model:

$$v(t) = v_0 + v_1(t) + v_2(t), \tag{3}$$

where: $v_2(t)$ – is secondary consolidational deformation.

Secondary consolidational deformation (creep) can be calculated with the following formula:

$$v_2(t) = C_\alpha \frac{2H}{1+e_0} \log \frac{t+t_0}{t_0}\,. \tag{4}$$

Modification of known consolidation models is necessary, applying initial deformation, as without it, they are less suitable for modelling.

We can establish that the modified Bjerrum model gives the best description of reality, knowing the deformation behaviour of waste, and also according to regression indexes. For further calculations, the values of Table 3. should be taken into account.

As compared to soils, we can establish that immediate deformation of waste is significant, which of course can also be a consequence of unsaturation, but the presence of deflectable “solid particles” is a much better explanation. Of course, crawling is also significant because of viscous nature; long-term crawling can be explained with degradation. The rate of components of settlement is contained in Table 4.

Table 3. The parameters of the consolidation behaviour

| sample | degradation level | consolidation factor ($c_v$) ($m^2/s$) | creep index ($C_\alpha$) (-) |
|---|---|---|---|
| S-1 | 2 | 3,20E-08 | 0,00283 |
| S-2 | 3 | 4,58E-08 | 0,00273 |
| S-3 | 4 | 7,89E-08 | 0,00156 |

Table 4. Rate of the part of settlement

| initial compression | consolidation compression | creep |
|---|---|---|
| $v_0 / v$ | $v_2 / v$ | $v_2 / v$ |
| 0,47 | 0,42 | 0,11 |

*Recalculation of water permeability coefficient*

It is known from the conception of consolidation, that upon knowing the consolidation coefficient, water permeability coefficient can be recalculated (Table 5). From the outcome, one can establish that upon increase of normal vertical tension (depression of the sample) the value of k-factor decreases; upon increase of degradation degree it also decreases in a smaller measure; however the correlation here is not completely unambiguous, but in its tendency is true (best trend). Load dependency is a consequence of the depression of the sample, degradation degree dependency is a result of mechanical fragmentation.

Table 5. Change of the water permeability coefficient [m/s]

| pressure ($kN/m^2$) \ sample | S-1 | S-2 | S-3 |
|---|---|---|---|
| 5 | 2,21E-08 | 4,29E-08 | 3,16E-08 |
| 10 | 2,67E-08 | 3,56E-09 | 1,06E-08 |
| 20 | nd. | 5,14E-09 | 4,66E-09 |
| 40 | 7,44E-09 | 8,64E-10 | 2,08E-09 |
| 80 | 2,55E-09 | 9,29E-10 | 2,31E-09 |
| 160 | 4,22E-10 | 5,74E-10 | 4,74E-10 |
| 320 | 2,58E-10 | 7,67E-11 | 2,02E-10 |
| 640 | 4,50E-11 | 6,00E-12 | 8,36E-11 |

### 3.3. Rheological modelling of the deformation of the examined waste

A model system consisting of elementary idealized material models (flexible, plastic, viscous) is supposed to reflect realistic behaviour in a large extent. Out of the above mentioned variations, the use of visco-elastic model is reasonable. From an infinite number of models we have to choose the one describing the phenomenon in the simplest way, with adequate accuracy to the objective. In this choice the taxonomy of Müller is a help for us. Knowing the measurement outcomes and the occurring processes, Poyting-Thomson (”PT”) classified in class I. and Burger-model (BU) in class IV. seems to be the appropriate choice (Fig. 5).


a) Poyting-Thomson model    b) Burger model

Fig. 5. Rheological models

As for the leap of tension in the response functions describing crawling, it is as follows:

A ”PT” modell esetén: $$\varepsilon(t) = \sigma_1\left(\frac{1}{E_1} + \frac{1}{E_3} - \frac{1}{E_3}\cdot e^{-\frac{E_3}{\eta}t}\right). \quad (5)$$

A ”BU” modell esetén: $$\varepsilon(t) = \sigma_1\left(\frac{t}{\eta_1} + \frac{1}{E_1} + \frac{1}{E_3} - \frac{1}{E_3}\cdot e^{-\frac{E_3}{\eta_2}t}\right). \quad (6)$$

Table 6. The constants of the“PT” and “BU” models

| | model „PT” | | | model „BU” | | | |
|---|---|---|---|---|---|---|---|
| | E1 (kN/m$^2$) | E3 (kN/m$^2$) | η (Ns/m$^2$) | E1 (kN/m$^2$) | E3 (kN/m$^2$) | η1 (Ns/m$^2$) | η2 (Ns/m$^2$) |
| S 1 | (101) – 569 | (1267)- 20928 | (12214)- 4.25E+6 | (101)- 570 | (1337)- 29965 | (4.40E+6)- 2.06E+8 | (7720)- 222367 |
| S 2 | (73) – 661 | (694)- 15636 | (165607) 3.04E+6 | (74)- 614 | (988)- 33462 | (6.68E+6)- 4.92E+8 | (32622)- 326783 |
| S 3 | (183)- 759 | (3256)- 20745 | (71326)- 679807 | (184)- 761 | (1763)- 23030 | (6.18E+6)- 2.36E+8 | (16595)- 389163 |

I have allocated the constants of the model and the material constants (Table 6). We can establish that the investigated phenomenon can be described with adequate accuracy with the two applied visco-elastic models. Out of the two models, Burger-model draws closer to the measured data line, regression coefficient is above 0,98 in both cases. If we take physical (biological-chemical) processes into account at the analysis, we can establish that short-term deformation is more accurately modelled with the Burger-model. However, for long-term behaviour I recommend Poyting-Thomson-model, as the movements have finite values.

### 3.4. Soil-mechanics based modelling of the deformation of waste hills

I have chosen Plaxis 2D FEM program as an instrument for modelling, thus I tried to adapt this program basically developed for the examination of soils and structures. Modelling is two-dimensional, since for the estimation of deformations, considering the reliability and accuracy of input data, 2D model has proven to be of adequate accuracy. The objective is non-conventional, so I chose to walk down the path of a modelling work process based on preconceptions.

*1. Preparation of the objective*

Collection and classification of waste-physical characteristics and geometrical knowledge. Analysis of the data according to reliability is necessary, and at the validation of the model it is expedient to consider less reliable data as variable parameters.

*2. Setting up a modelling conception (working hypothesis)*

The given objective can be examined (approximately) with the above mentioned, soil-mechanics based program. However, we have to consider this program using a method with finite elements, as such an instrument that has to be adjusted to the characteristics of waste.

The most important factor to decide is the choice of material model. The decision is influenced by whether the given material model can estimate the behaviour of the material well, how well-known it is, and also by the nature of measured data. The use of MC model is backed by the easily achievable (measurable with well-known examinations) simple input data, and also by the lots of comparable experiences gained on different soils. HS model is more advanced, and according to previous experiences, gives a more accurate description about the deformation of soils. SSC model has the advantage of taking crawling also in account, thus being applicable in case of weaker soil-waste analogy. Of course this applicability also depends on the composition of the waste. Since I investigated municipal solid waste, my statements appertain to this.

*3. Establishing the modelling data system*

According to the previous two paragraphs I have worked with the following input data:

- Geometry is as planned, with simplifications, analysis of a mid-section.
- Chosen material models: Mohr –Coulomb (MC), Hardening soil (HS), Soft soil model with creep (SSC).
- Waste-physical characteristics assigned to degrees of degradation.

*4. Executing numeric calculations*

Numeric calculations are executed by the computer; modelling is closer to reality if the waste hill is divided into layers according to degradation, and layers are put into next phase as time passes by, always assigning the physical characteristics that belong to the given degree of degradation and depth. Then we had to execute the analysis of parameter sensitivity.

*5. Validation of the model, evaluation of outcomes*

I have compared the calculated settlement to the values measured at the dump, and in possession of such knowledge I was able to validate all three models. At the evaluation of the outcomes I have compared the values of further calculations to the measurements (averages) of the higher leveling-measuring points, and have done control examination. HS and SSC models reflected reality in their characteristics. MC model does not even describe reality in its characteristics in the peripheral, terminal points of the waste hill (Fig. 6).

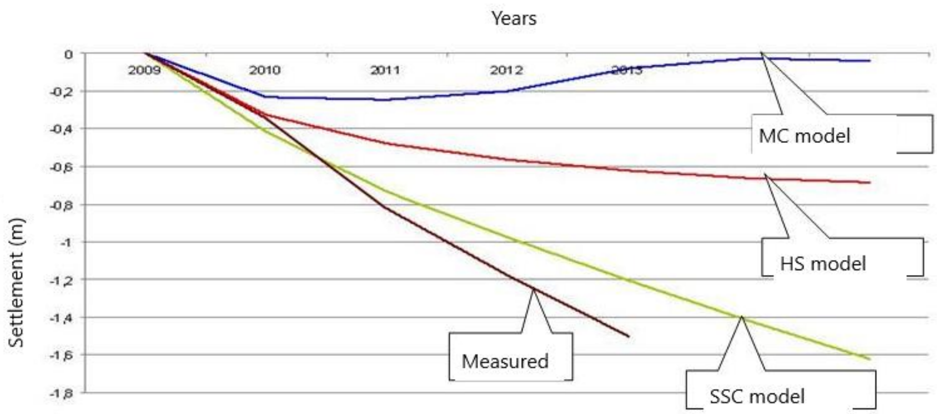



Fig. 6. Soil-mechanics based models

SSC model is the most accurate, as it also takes creep into account. Thus, the deformation of the dumped waste can be well modelled in the course of time, in spite of the fact that the physical content of the components of settlement is different in case of soil and waste. I have collected post-validation waste-physical characteristics in Table 7.

Table 7. The parameters of the SSC model

| layer | $\lambda^*$ [-] | $\kappa^*$ [-] | $\mu^*$ [-] | k [m/s] |
|---|---|---|---|---|
| 1. degradation level | 0,01660 | 0,018500 | 0,00002658 | 1,5E-7 |
| 2. degradation level | 0,01547 | 0,016280 | 0,00002975 | 1,0E-7 |
| 3. degradation level | 0,01449 | 0,012230 | 0,00003341 | 9,0E-8 |
| 4. degradation level | 0,01195 | 0,008174 | 0,00003725 | 7,0E-8 |
| 5. degradation level | 0,10000 | 0,006700 | 0,00003951 | 5,0E-8 |
| subsoil | 0,15000 | 0,016000 | 0,00400000 | 1,0E-10 |

*6. Applicability and utilization of the model*

The validated model can be used to examine the long-term mechanical behaviour of the landfill, which has practical significance: on one hand, concerning further moves that take place due to dry-weight, on the other hand the estimation of deformation caused by encumberment (due to area exploitation) at a given moment in time becomes possible, together with the analysis of stability.

### 3.5. Hydraulic modelling in connection with waste dumps

For the modelling of fluxation issues of water-collecting layers, it is also necessary to allocate their water retention curves. In case of knowing the water retention curves of fractions composing granular soil it is also possible by calculations, with the help of Imre-Genovese model. The grain size distribution of the compounds is the weighted sum of the grain size distribution of the fractions:

$$\mathrm{S_{NJ}}(\mathrm{d}) = \sum_{k=1}^{i} x_k \mathrm{S_k}(\mathrm{d}), \tag{7}$$

where: $x_k$ is the frequency of the “k”[th] fraction.

A similar definition is true to the water retention curves of the compositions:

$$\mathrm{w_{NJ}}(\mathrm{u_a} - u_w) = \sum_{k=1}^{i} c_k \mathrm{w_k}(\mathrm{u_a} - u_w), \tag{8}$$

where $c_k$ is the weight coefficient: $\sum_{k=1}^{N} c_k = 1,\ \ c_k \geq 0$.

Further assumptions are:

1) in case of optimal A=2/3 compositions, the weights $c_k$ (k=1…N) are equal,
2) the water retention curve model of the fractions is a trilinear function in a semi-logarithmic scale,
3) non-constant parts of the SWRC of fractions do not overlap.

I have examined the effect of changing $c_k$ – weights upon the accuracy of the model, and looked for optimal weighting. I have done it by applying the well-known van Genuchten-function to water retention curve points of the soils calculated with different weighting, and then compared it to the van Genuchten-function applied to the measured water retention curves of the compounds. Upon changing the weights, the accuracy of the model increased (Fig. 7). Upon looking for best regression, the exfoliation of weights can be seen in Table 8.

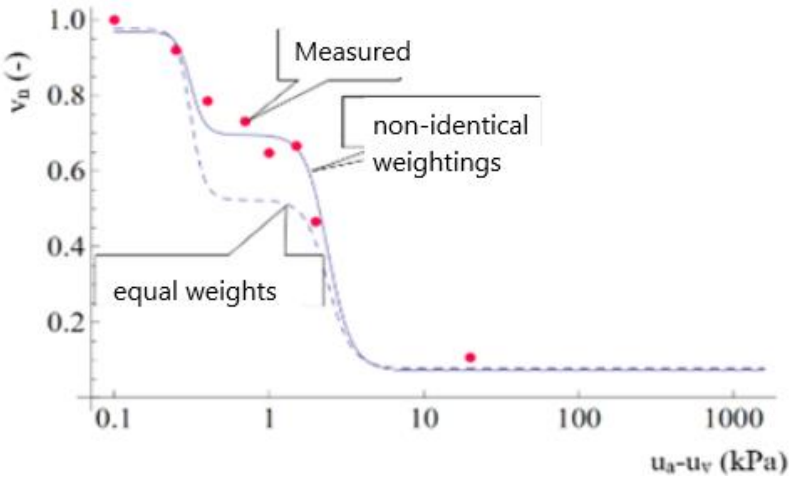



Fig. 7. SWRC of the 1-4 grain mixture

Table 8. The weights of SWRC of grain mixture separately to fractions

| mixture | $c_k$ (rougher fraction) | $c_k$ (finer fraction) |
|---|---|---|
| 1-2: | 0,29 | 0,71 |
| 1-3: | 0,10 | 0,90 |
| 1-4: | 0,30 | 0,70 |
| 2-3: | 0,40 | 0,60 |
| 2-4: | 0,34 | 0,66 |
| 3-4: | 0,43 | 0,57 |

We can establish, that the Imre-Genovese model is applicable for the investigated compounds, having increased accuracy with non-identical weightings. On the average, rougher fraction was taken into account with less than half of the weight (averagely 0,31) while finer fraction was considered with more than half of the weight (0,69).

## 4. NEW SCIENTIFIC RESULTS

*1. Compression of the investigated waste*

Based on laboratory investigation results I have established, that the waste, also characterized by its degree of degradation, underbears such vertical depression due to its own weight and outside mechanical load, which depends on the applied normal tension in a non-linear fashion. Waste becomes stiffer, and as result of degradation, the constants of material law describing the connection between load and deformation are altered. Determination of this alteration is also connected to the degree of degradation, since upon the increase of it, waste becomes stiffer.

Compressional curves can be well converged with logarithmic functions whose parameters are different, according to their degrees of degradation:

2. degradation phase: $\varepsilon = 0{,}0960 \ln(\sigma) - 0{,}0311$.

3. degradation phase: $\varepsilon = 0{,}0708 \ln(\sigma) + 0{,}0547$.

4. degradation phase: $\varepsilon = 0{,}0587 \ln(\sigma) + 0{,}0619$.

Linearized into sections defined by load, upon calculating with post-preload phase and then extrapolating it, the depression modulus is ($\sigma$ [kN/m$^2$]) according to the degree of degradation of the waste:

2. degradation phase: $E_s = 9{,}734\ \sigma - 322{,}980$ or, $E_s = 9{,}022\ \sigma$.

3. degradation phase: $E_s = 12{,}085\ \sigma - 269{,}940$ or, $E_s = 11{,}523\ \sigma$.

4. degradation phase: $E_s = 13{,}099\ \sigma - 29{,}463$ or, $E_s = 13{,}127\ \sigma$ .

I have established that instead of the one or two (fresh and degraded) waste models (almost exclusively used in specialized literature) it is expedient to describe waste having different degrees of degradation with various material equations characterized by different constants, thus making the description of compression more accurate.

Using the outcomes of modified compressional investigation I have established that upon increase of degree of degradation or load, Poisson ratio decreases. Dominant part of deformations (more than 90%) is permanent, and in a rheological sense, irreversible. Hysteresis effect was not measurable.

*2. Consolidation of the investigated waste*

Based on the modified oedometric examination of the quasi saturated waste samples having various degrees of degradation, I have demonstrated that due to its own weight and because of outside mechanical load, the examined waste goes through such vertical depression in the course of time, which can be well described with the altered versions of consolidation models used in soil mechanics, although with significantly different parameterization.

With the modification of Terzaghi and Bjerrum consolidational models and the addition of initial deflection, considering regression analysis and crawling I suggest the use of the correlation with the following alterations:

$$v(t) = v_0 + v_1(t) + v_2(t) = v_0 + v_{1,\infty}\left[1 - \int_0^{2H} \frac{u(c_v, t, x)dx}{2H\sigma}\right] + C_\alpha \frac{2H}{1+e_0} \log\frac{t+t_0}{t_0}.$$

I have determined and published the constants of consolidation models depending upon degree of degradation and load, as well as the rate of settlement components.

*3. Rheological modelling of the deformation of the examined waste*

With laboratory examinations, I have proven that the deformation of waste samples can be appropriately described with visco-elastic rheological models. Modelling becomes more accurate, if it is done according to the degree of degradation of the waste; short-term behaviour is described more accurately by the Burger-model, which previously was never applied to waste, than with Poyting-Thompson-model, which was recommended for the description of long-term behaviour so far. The response function to tension leap, describing crawling is as follows:

$$\varepsilon(t) = \sigma_1\left(\frac{t}{\eta_1} + \frac{1}{E_1} + \frac{1}{E_3} - \frac{1}{E_3} \cdot e^{-\frac{E_3}{\eta_2}t}\right).$$

I have determined and established the constants of consolidation models depending upon load and degree of degradation. Upon analysis of the data I have established that depending on degree of degradation and load there is an unambiguous tendency amongst the material constants of the model. In the course of its degradation and upon applying load, waste becomes stiffer concerning deformation.

*4. Soil mechanics based model of the deformation of waste hill*

I have developed such a new soil mechanics based modelling process, in which I considered the routine geotechnical program (Plaxis) using a method with finite as a general instrument, and I have adapted it adjusted to the characteristics of the landfill. This objective is not usual, thus I have also allocated the necessary steps of a preconception-based modelling work process. For the calculations I have used the results of my oedometric- and other complementary examinations. I have validated, verified the calculations with local settlement measurements. Thus, the developed modelling work process can be applied to any other waste dump, taking into consideration the unique characteristics of the given landfill.

For the purpose of material model, soft model with crawling (SSC) has proven to be best, thus I recommend this. I have determined and established the parameters of the model. Compared to previous models, the accuracy of calculations became better because I have recorded waste physical parameters in the light of degree of degradation and depth (pressure), and I have only advanced it into the next phase of degradation after a given period of time. Depth-wise division of the waste dump faithfully follows the layered distribution of dumping, just as the alteration of waste-physical characteristics according to degrees of degradation follows the process of degradation.

*5. Refinement of the hydraulic model of waste hill*

For the hydraulic investigation of the lower and upper closing and water collecting layers, I have made the calculation of their water retention functions more accurate. For the sake of general usefulness I have examined granular soil samples and their compound. I have certified with laboratory experiments and with the attachment of the altered model that the calculations of water retention functions of optimal (A=2/3) granular soil compounds (d=2,0 – 0,5 mm) – knowing the water retention functions of different fractions – can be more accurate upon the use of weighting.

Upon knowing grain size distributions, the water retention function of the compounds can be allocated with calculations from the measured water retention functions of the investigated fractions using the Imre-Genovese-model. According to the applied model, the water retention function of the compounds is the sum of the water retention functions of the fractions:

$$w_{NJ}\left(u_a - u_w\right) = \sum_{k=1}^{i} c_k w_k \left(u_a - u_w\right),$$

where: $c_k$ is the weight coefficient and $\sum_{k=1}^{N} c_k = 1,\ c_k \geq 0$.

I have made one of the previous assumptions, namely that $c_k$ weights (k=1…N) are equal, more accurate. I have examined the effect of changing the $c_k$ - weights on the accuracy of the model, and I looked for optimal weighting. I have established that the accuracy of the model can increase with about 20% if the rougher fraction is taken into calculation with less than half of weight (0,31 at average), while the finer fraction with more than half of weight (0,69 at average).

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# 5. CONCLUSIONS AND SUGGESTIONS

The main objective of my research was the modelling of the deformation of hills consisting of municipal solid waste and increasing the accuracy of the hydraulic model.

For the modelling of the deformation of hills consisting of waste, I have chosen to walk down the following path. The samples, taken from the waste, originated from different depths, thus on the account of dumping technologies were of different age. The age of waste, owing to the constant physical-chemical-biological transformations, also means a level of decomposition, which can be expressed with the degree of degradation. I have organized the samples to be average samples according to their degree of degradation, and thus I have performed an altered oedometric examination with a contraption of proprietary development. I have also evaluated the outcomes of the measurements with the help of soil-mechanics- and rheology-based models. I have published the received waste-physical characteristics, which can serve as initial data in case of a later planning, or in case of the investigated or other municipal solid waste dump. I have modelled the waste dump of the first cycle of PRHK with a geotechnical program using finite-element method, and worked out a possible way of computer-aided planning. Compared to the previous models, the accuracy of calculations increased because the depth-wise division of the hill faithfully follows the layered distribution of dumping, just as the alteration of waste-physical characteristics according to degrees of degradation follows the process of degradation. The control of the calculations was provided by the own peripheral, geodesial measurements of the landfill. This method of modelling can be generalised, however the unique characteristics of the landfills have to be taken into consideration.

Concerning the development of the hydraulic model, I have concentrated on the allocation of the function of water retention curve, constituting the base of modelling. For the time being, concerning the complementary contraptions (drainage collector), but as a long-term objective the water retention curve of dumped waste should also be allocated; thus the modelling of deformations could also be more precise. I have perfected the calculated construction of water retention curves of granular soil compounds upon knowing the water retention functions of the fractions constituting them. This part of my dissertation can be considered as a small step; the objective is to work out a method, which, upon knowing the grain size distribution entropy of soils, could help to determine their water retention curve without direct measurements. Thus, the next step of my research could be the investigation of non-ideal compounds.

# 6. SUMMARY

My objective was the promotion of a more secure and economic waste disposal, also meaning less environmental risks. This connects to agriculture in a natural fashion, as significant part of disposed waste originates directly from agricultural products, or connected to them as packaging materials.

With laboratory measurements of waste samples taken from a municipal solid waste dump (PRHK) I have allocated the change of waste-physical characteristics, depending on degradation and load. Upon the knowledge of these factors I have modelled the deformation of the whole landfill in the course of time with numeric calculations, simulating the staves of dumping and degradation; and then I validated the model with the data of local measurements. Concerning hydraulic model, I have dealt with the investigation of drainage- and closing layers. More precisely I have concentrated on the allocation of the water retention curve, which has a key importance in many aspects.

My dissertation is dominantly supported by my own measurement outcomes. For the oedometric investigation of waste samples I have applied a new laboratory instrument and measurement method of proprietary development. I have further perfected, adapted and renewed the method of laboratory measurement of water retention function.

I have cooperated with fellow researchers, and the thus achieved results concerning mechanical modelling can be considered as complete, while on the area hydraulic modelling they mean a new step towards a complex solution. Of course, description of deformations in space and time is only possible with the use of certain simplifications, idealizations, since the number of influencing factors is excessive, thus I tried to find a way giving acceptable accuracy with use of simple calculations, since for practical aspects usually this is the best.

It would be expedient to conduct the modelling process with data of other landfills, thus recognizing the effects of their unique characteristics. It would be worth to expand water retention experiments to non-optimal compounds.

The dissertation can be used for the estimation of disposable waste quantity, for the closing of the waste dump, or it can provide basic data for the planning of bedding during a later posterior exploitation of further areas.

My personal objective was to review, use, and adapt the results of different spheres of science, to interpret identical or similar conceptions in an uniform fashion, thus gaining a knowledge expanding my basic qualifications. The chosen topic has served these objectives well, being essentially an interdisciplinary subject.

# 7. THE MOST IMPORTANT PUBLICATIONS RELATED TO THE THESIS


*Proofread articles in an international language*

1. **Firgi, T.,** Telekes, G. (2016): Modelling the deformation of a MSW landfill based on tests, Procedia Engineering, Volume 161, Elsevier, pp. 318-323.
2. Tang, A.M., Askarinejad, A., Brencic, M., Cui, Y-J., Diez, J., Dijkstra, T., **Firgi, T.,** Gajewska, B., Gentile, F., Grossi, G., Jommi, C., Hughes, P., Kehagia, F., Koda, E., Maat, H., Lenart, S., Lourenco, S., Oliveira, M., Osinski, P., Springman, S., Stirling, R., Toll, D., Van Beek, V. (2018): Atmosphere - vegetation - soil interactions in a climate change context; changing conditions impacting on engineered transport infrastructure slopes in Europe, Quarterly Journal of Engineering Geology and Hydrogeology, Vol. 51, pp. 156-168. (IF: 1.102)

*Proofread articles in Hungarian*

1. Imre, E., Rajkai, K., **Firgi, T.,** Havrán T., Trang P., Telekes G., Lőrincz J. (2008): A homokfrakciók és homokkeverékek víztartási görbéje közti kapcsolat, Hidrológiai Közlöny 88:(5), 52-56. o.
2. Imre, E., Kovács, M., Trang, P., **Firgi, T.,** Telekes, G., Kovács, K. (2012): A hazai hulladéklerakó dombok felmérése energetikai felhasználás céljából, Műszaki Ellenőr 1., 39-42. o.
3. **Firgi, T**. (2015): Települési hulladék domb alakváltozás vizsgálata, Economica 8:(3), 95-104. o.
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6. **Firgi, T.,** Keszeyné Say, E., Telekes, G. (2018): A geotechnika területén a talajok víztartási függvényének alkalmazási köre és laboratóriumi mérésének tapasztalatai, Műszaki Szemle 72, EMT, 8-17. o.