Szent Istvan University

Hydrodynamic modeling of the groundwater flow influenced by construction works

Theses of doctoral dissertation

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Budapest
2011

The PhD School

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APPLIED MAIN SYMBOLS

Symbol	Description	Dimensional unit
$\boldsymbol{v}$	flow velocity	m/s
$\boldsymbol{v_k}$	average velocity	m/s
$\boldsymbol{v_{kr}}$	critical velocity	m/s
$\boldsymbol{k}$	infiltration coefficient, k modulus, water permeability coefficient	m/s
$\boldsymbol{k_x, k_y, k_z}$	infiltration coefficient tensor	m/s
$\boldsymbol{\rho}$	density of liquid material	g/cm^3
$\boldsymbol{S_s}$	unit storage coefficient	-
$\boldsymbol{\Psi}$	hydraulic head	m
$\boldsymbol{\Theta}$	volumetric water discharge	m^3/s
$\boldsymbol{I}$	hydraulic gradient	-
$\boldsymbol{I_0}$	threshold gradient	-
$\boldsymbol{Q}$	water discharge	m^3/s
$\boldsymbol{A}$	cross-section area	m^2
$\boldsymbol{d_h}$	effective grain diameter	mm
$\boldsymbol{v}$	kinematical viscosity	m^2/s
$\boldsymbol{e}$	void ratio	-
$\boldsymbol{n}$	porosity	-
$\boldsymbol{n_0}$	effective porosity	-
$\boldsymbol{R_e}$	Reynolds number	-
$\boldsymbol{R}$	distance action	m
$\boldsymbol{\lambda}$	coefficient of friction	-
$\boldsymbol{\beta}$	grain shape coefficient	-
vv	groundwater thickness	m
vsz	groundwater level	mBf
„v"	thickness of aquifer	m
mm	dimension of structure	m
t	distance between structures	m
	time	s
ái	flow direction	-
mfp	observation point	-
x	current studied parameter independent variable	-
D	back-swelling	cm
A	subsidence	cm
LKV	Minimum water	cm; mBf
LNV	Maximum water	cm; mBf

1. THE PRELIMINARYS OF THE WORK, APPOINTED AIMS

Lately the *underground establishments of large segment* have special importance in the city planning because of the appreciation of downtown and the decreasing of the unbuilt areas. As higher and higher buildings are planned, so are formed the underground spaces deeper and deeper.
Because the environment aspects come to the front, the more and more traffic establishments (road and railway tunnels, underground express line, subway) are placed under the surface in the interest of the less disturbing of the surface and the protecting the security of the existing buildings.
In the scope of *infrastructural developments* the *development of the public utilities* becomes high priority tasks. In Europe in the near future several *natural gas transit-pipeline* with large diameter will be built
It can be seen, that several technical investments are realized, which have effect on the infiltration-hydraulic course of the groundwaters and can considerably change those. Under the surface spaces are formed, which are closed from the flow or hinder the flow.

Therefore, in lack of appropriate technical secure, the *increasing groundwater* can flood the cellar of the buildings in the surroundings of establishments or other underground structures. It can reach the rootzone of the agriculture, which can influence the productivity of the area.

On the other hand the stability of the soil can be worse because of the effect of the water, which can influence the stability and usefulness of the buildings.

By reason of *the subsidence of the groundwater* the weight-stress of the soil can significantly increase because of the ceasing of the water's buoyancy, and it can indicate extra subsidence and can result damage on the surface.

In this topic numerous unexplored questions, problems have to be solved. In the recent engineering practice there is no authentic hydrodynamic model worked out for the examination of the back-swelling and decreasing effect of the establishments and obstacles put in the way of flowing groundwater. The calculations are generally made with method of approaching and with significant theoretical simplifications.

To evaluate the courses and to draw the conclusions, it is not wide-spread. Useful theories for the practical technical-agrotechnical planning are not set up yet.

The main aim of research is to create a scientific material, which **helps the everyday practical designing** and with this there is an opportunity to explore and forecast the expectable effect of the underground obstacles, to estimate its order of magnitude and to decide about the necessity of further working sessions.

In compliance with it my main aims are the followings:

- *To set up a hydrodynamical model,* which takes into consideration the individual conditions and specifications and approaches the reality mostly.
- To follow the infiltration hydraulic processes under the surface with the help of the model. *Parameter analysis. To examine and answer the theoretical questions* with the help of a program system, which simulates the problem mostly.
- *To make local measuring*, in two water level observing wells settled at an industrial work. To check and verify the validity of the model with the help of the results of measuring.
- *To draw the final conclusions* for the practice, especially for particular engineering – agro engineering tasks in Hungarian geological – hydrogeological conditions.

In the first part of my work I review the literature according to my work, then I survey the theoretical background of the subject.

I discuss with the question of the modeling. I give the infiltration's basic equation, which forms the basis of the hydrodynamical model-calculation and the numerous solving methods of the equation too. During my research I apply numerical solution for the modeling, for that I use FEFLOW Finite Element Simulation System for Subsurface Flow (WASY FEFLOW 5.3. 3D) high-level program system

I show the experimental methods through a real problem. For my research I made measuring in the surrounding of the building of Haller-kapu (CEU), which is built in the 9th district of Budapest, in the interest of comparing the results with the model-calculations. For my measuring two groundwater level observing wells were made next to the working-pit of the multileveled deep garage bordered with slurry wall. I knew the instrument, the technique and duration of the water level measuring. I explore the geological, hydrogeological characteristics of the examined area and the technical data of the establishment. I mention in detail the steps of the models' structure.

2. MATERIAL AND METHOD

2.1. Searching program and model creation

Modeling process

For my research I developed a *modeling idea (hypothesis).* I analyzed the consequence of the change of influential parameters (for the phenomenon of backwater, droop) having influence on the outcome of the system.

I took test intervals in which I changed the parameters in defined stages. The extreme values of intervals were determined taking into account the occurring boundaries of practical flow hydraulic tasks (the calculation with less or greater extreme values has theoretical and mathematical significance). *The research results are valid in the fixed interval.*

The investigated parameters and intervals vary between wide limits therefore allow a large number of variations. Thus *the model results are widely extended and applied* to other geological and hydrogeological conditions as well.

By the model calculation I followed the principle to highlight and change one, two or three parameters at once and keeping constant the rest, I simulated they effect to the water migration processes.
I continued the investigation using the parameter configuration (variant), which had the greatest impact (back-swelling, subsidence) or caused significant difference in the outcome of the process. Because it characterizes strongest the type and tendency of the change.
In some cases the result aggregations of the simulations clarified that – taking into consideration the ambition and the obtainable aim – it should not continue the modelling process in that direction.

Since the amount of the effect of the underground object to the groundwater flow depends decisively on *the geological (soil) structures, the hydrogeological characteristics and the type of the underground block*, I extended the modeling processes to these three main areas.
Within this I examined in detail how and in which amount depends the back-swelling (D) and the subsidence (A) on effect of the changes of:

- the soil parameters
  - effective porosity (n_0) and
  - coefficient of permeability (k);

- groundwater conditions
  - direction of the groundwater flow (ái),
  - hydraulic gradient (I),
  - the thickness of the groundwater in the aquifer (vv) and
  - groundwater level (vsz),
- underground block (structure)
  - dimension (mm) and
  - in case of several structure the superposing of the effect.

$$\boxed{D, A = f\,(n_0,\ k,\ ái,\ I,\ vv,\ vsz,\ mm,\ szup.)}$$

For this developed modeling method I have prepared an illustrative diagram showing the multidirectional investigation with the different parameters and intervals (fig. 2.1.).

I also made simulations taking into consideration the original conditions (geologic, hydrogeologic, dimension of structure) of the Haller-gate project. This provided the basis for *the comparison of calculations and measurements.*

During my research I dealt with the control of interaction of the parameters at the level of checking. I examined that the received results of modeling process contradict the fundamental equation of the flowhydraulic (Darcy's law: v = k I) and empiric approximate relations ($n_0 = \frac{\sqrt[7]{k}}{2}$; R=3000 s $\sqrt{k}$) or not.

The requirement of the model's precision

In case of the investigated engineering problem the knowledge of the change of groundwater level is *expected within decimeter accuracy*. This accuracy is sufficient to decide the necessity and type of the technical interventions.
My research subject concerns geological and hydrogeological systems. They knowledge level is underdefinitive because the characteristics of the three-dimensional formations is known in points or a line.
The determination level of the parameters in the model should be significantly different from each other.
They values can be determined by on-site or laboratory analysis or with the help of empirical formulas. Thus the data obtained in different ways are heterogeneous.
The representativeness of modeling results should not exceed the representitaveness of the basic data system.
Therefore, taking into consideration the facts above described, I don't expect greater accuracy from the model than the required accuracy of engineering practice in this problem.

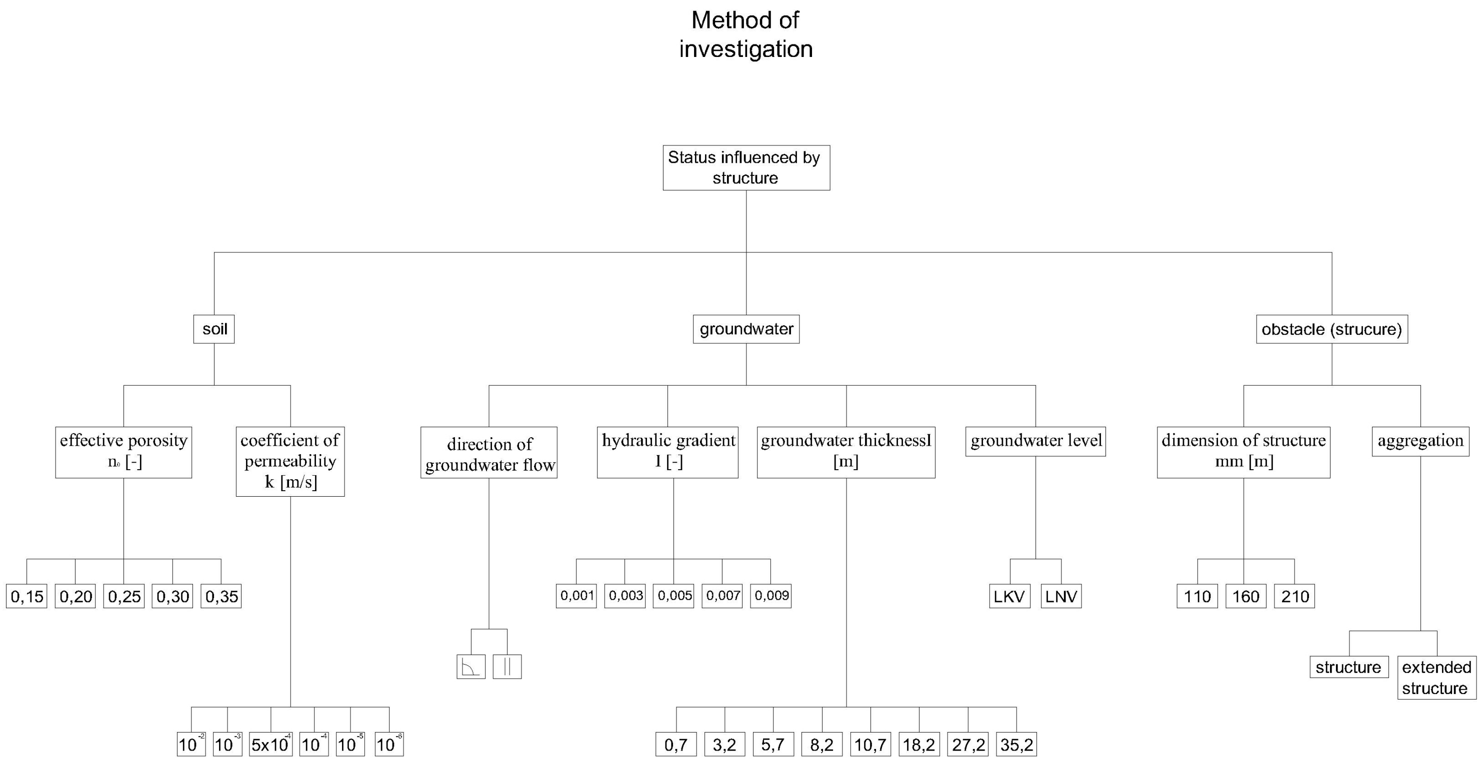


fig. 2.1. method of investigation

The practical steps of modeling process

During the modeling process preparing several models I followed the undermentioned general guideline: *preparation-geological and hydrogeological data collection-the first step of calculation-model calibration and parameter sensitivity test-the second step of calculation-evaluation of the results.*

The main steps of modeling process:

- The basic map creation of the modeling area. Creation of the modeling area
- Creation of the grid. Grid refinement process (concentration)
- Enter all the modelcharacteristics: *geological pattern, modelproperties* (initial conditions, edge conditions, material properties)
- Running the model, calibration and final run
- Showing the modeling result

The general characteristics of the prepared models to run the program are summarized below:

- Dimension: 3D
- Type: saturated
- Number of layers: 4
- Type of aquifer: unconfined aquifer
- Time period: quasi-permanent
- Time stage: 10 stages, 10 days per stages
- Calculation method: finite element method
- Type of cell: 6 nodes trilateral prism

Applied numerical computer program

In my dissertation in the course of the hydrodynamic modeling I resolve the <u>fundamental equation of the filtration by numerical</u> finite element method. This provides facilities to complete large amount of calculations from which general conclusions can be draw. High-level computer program is available to the research of the problem.

During my research I used the FEFLOW (Finite Element Simulation System for Subsurface Flow) program system, which is an accepted calculation system in the national and international practice of the hydrodynamic and transport modeling tasks. The program, which has a lot of built-in numerical algorithms solves the fundamental equation of the filtration with *Garlekin's finite element method*.

The FEFLOW is a complete modeling system, which combines successfully the powerful graphics capabilities with the modern control-optimisation analysis tools.

The main component of the program:

- ✓ Complex, comprehensive graphical toolkit allowing of the creation of the final element grid, determination of the parameter zones and indicates the edge conditions.
- ✓ Data import and interpolation algorithm.
- ✓ Reliable numerical algorithms and solution methods.
- ✓ Real-time data analysis.
- ✓ High-level 3D visualization.

2.2. Experimental methods

During my research I had the opportunity to show the studies through a definite example.
To my measurements two water wells were installed next to the building pit of the Haller Gate's (CEU) deep level garage.
Thus I could parallel simulate the effect of the building's deep level garage to the natural groundwater flow and measure the effective water level data in the monitoring wells.
By the calculations and measurements the influenced water migrations were traceable and the principles determinable.

Characterisation of the investigated area

The area is situated at the Danube bank of Pest in the Millennium city centre in the axis of Haller Street. The minimal distance from the river is 40 m. The two blocks of buildings is built with a 3 storey deep level garage. The ~110*40 m building area is built with diaphragm wall limitation. The diaphragm wall is into the oligocene clay bottom engaged. Thus, forming an artifical block it closes as a „wall" the way of the groundwater in 110 m length.
The city centre was built in the past few years with multi-storey deep level garages block of buildings with diaphragm walls as well. Between the currently under construction and the already existing structures in several kilometres length there is only a ~ 15-20 m long unbuilt sector where the flow of groundwater is not limited. At the rest area the diaphragm walls form a continuous „wall", which blocks the groundwater flow.

In geological aspect the area and its surroundings has a typical series of strata until the construction affected depth. The **bottom** layer is the Oligocene clay series of strata, which surface is situated in 13-15 m under the ground level. Between the clay layers silty sand and sand soils were deposed in varied arrangement and dimension.
The bottom clay layer is covered by Pleistocene **terrace gravel** of Danube, which is composed of gravely sand sandy gravel soils.
The **cover** layer of this series of strata is characteristically Holocene fine-grained sand and very fine sand soil, which surface is with away from the river getting thinner backfilling covered.

In flow hydraulic aspect the area is situated within the direct affection zone of the Danube ~40 m away, where the fluctuation of the groundwater is controlled by the all-time changes of Danube water levels. Due to the proximity of the river there are very dynamic groundwater ascent and descent and flow direction modifications. The magnitude of the groundwater level fluctuation can exceed several meters, in extreme cases can reach 8,0 m as well.

Groundwater level measurement

At the investigated area there are two groundwater-monitoring wells built in December 2007, situated perpendicular to the Danube in the section of 1643.700 river km. The Well I. was built at the Danube site of the working area and the Well II. at the opposite site shown in fig. 2.2 and 2.3. The wells are reached to the surface of bottom clay layer.

I weekly performed the water level measurements in the wells through one and half year with Eijkelkamp Agrisearch Equipment.

Detection of Danube water levels

Since the depth of the groundwater level and the magnitude of fluctuation are defined by the all time water level of Danube I surveyed the principle of the hydrological behaviour of the river as well.

The closest gauge to the investigated area is the *Budapest gauge* situated at the Vigadó Square.

I determined the Danube water levels at the mentioned gauge by the database of Water Data Bank.

With the help of the gauge data taking into account the drop of Danube in the investigated section the Danube water levels were definable.

The one and half year period I investigated – from December 2007 to August 2009 – involves the full range of water level fluctuation.

Relationship between the Danube water level and the groundwater level

Exploring the characteristics of flow regime of the river and the data in the groundwater monitoring wells I stated the principles of the Danube water level following groundwater flow:

In case of persistently low and under 97,8 m Baltic river water level the groundwater flows toward the river and develops a temporary steady-state condition between the river and the groundwater. This situation changes immediately when the river grows. Then the drain effect of the river ceases and begins the inflow from the river into the aquifer. Thus due to the flood the Danube water level is 1-1,5 m higher than the groundwater level of the surroundings because the groundwater only delayed, depending on the distance from the river and only after a certain time follows the water level rising of the river. The delay time concerned to the examined area can be determined in 1 day.

The above-mentioned process keeps until the river floods and the aquifer impregnates. If the river begins to droop, the above described charging of the system ceases and begins the discharge of the layer delayed as well. Consequently near the riverbank occurs 1-1,5 m level difference temporarily between the groundwater level and lower Danube water level.

This delayed dynamic water flow there and back, i.e. the constantly acting process between the river and the groundwater is a permanent acting factor.

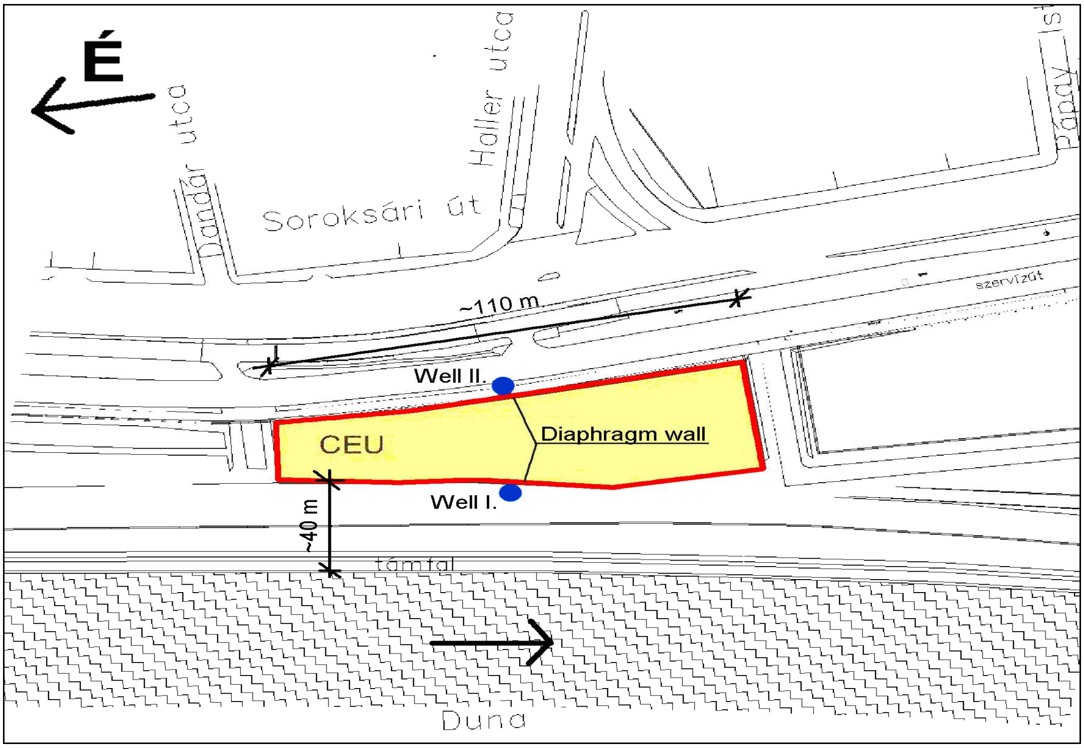


Figure 2.2. The location on the layout plan

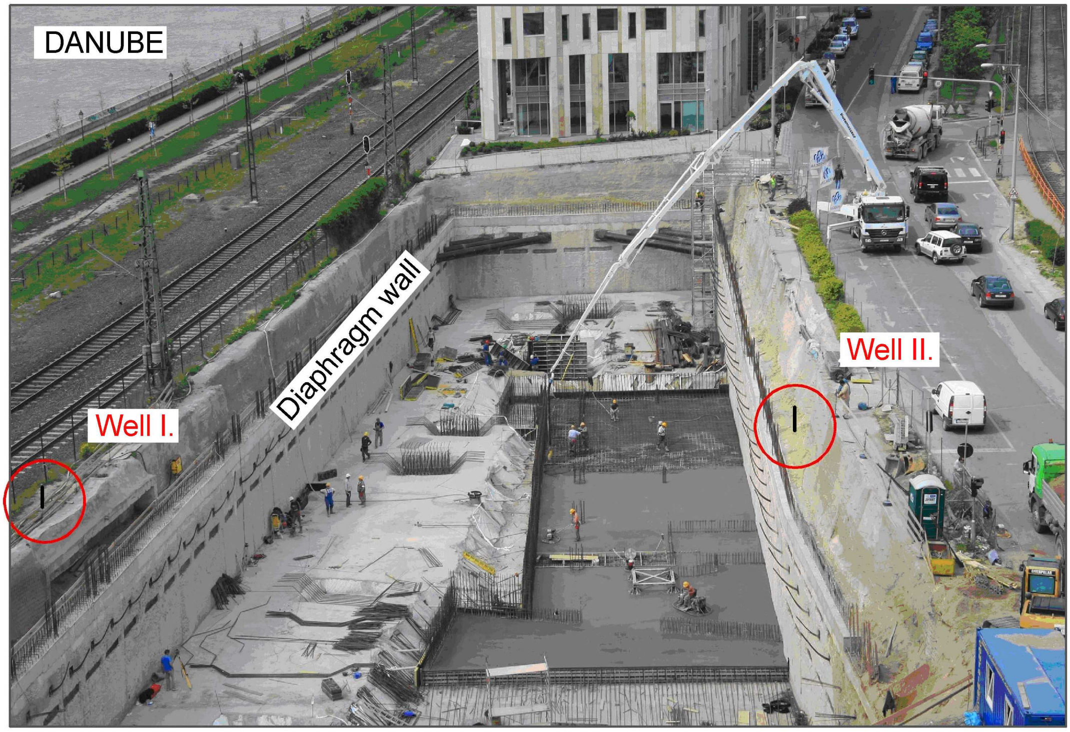


Figure 2.3. The site of the groundwater observing wells

3. RESULTS AND EVALUATION

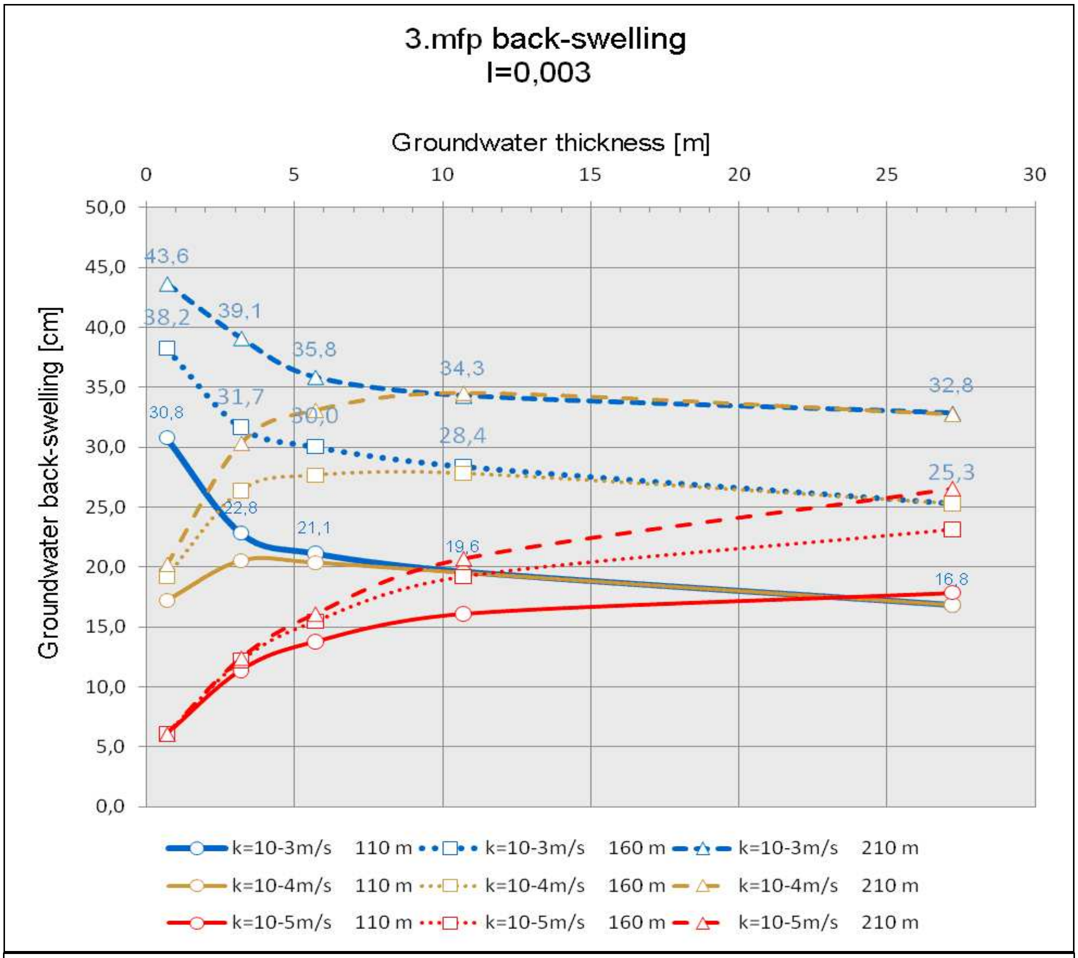
3.1. Examination of parameter sensitivity

The main aim of my research was – exploring the principles of the underground establishment's effect on the groundwater flow, with the full knowledge of them – to create a scientific material, which helps the everyday practical designing and generally usable on the technical – agrotechnical field.

During my work with the help of the simulations I got answers to the questions, and based on these I summarized my results.
The results of research are valid within the examined ranges with the exactness demanded by the task.

- ***Concerning the geometry of the geological formation, what extent of land is necessary to be examined?***

  <u>In point of horizontal extension</u> the primary point of view of taking the modeled area is that the depressions – formed as a result of flow modifications caused by the obstacles – don't go over the boundaries.
  To this question the examination of the long-distance effect gives answer. It can be stated as a result of the modeling, that the size of the examined structure and the thickness of the flowing groundwater are the determinant in the emergence of the long-distance effect and together with this at taking the size of the modeled area, besides the infiltration coefficient.
  At determining the extent of the modeled area the natural boundaries (see: line of the Danube) has to be taken into consideration, and the fact as well that at the edge of the area distortions rise compared to the real condition.
  <u>In point of depth</u> I examined 5,5 – 40 m thick water-holding layer, Together with this I changed the thickness of the flowing groundwater between 0,7 and 35 m.
  At back-swelling it can be stated, that with increase of the thickness the effects caused by the obstacles change with different tendency depending on the type of the soil (taken into consideration the range between $k=10^{-2}$ and 10^{-6} m/s). But dependent on the size of the structure from the water thickness of 20-30 m a "limit depth" comes into being and over this the effects approach to one value in different soils. Practically the back-swellings become independent from the type of the soil, the differences between them eliminate, their value becomes stable.
  At subsidence with rise of the thickness the tendency of the subsidence is the same independently of the soil. The limit depth lessens to ~10 m, where the effects have nearly the same value independently of the soil. (Figures 3.1. and 3.2.)
  In general: in lack of impermeable base, the minimum thickness of the water-holding layer is 25-35 m and the thickness of groundwater is 20-30 m, which has to be considered at the modeling.



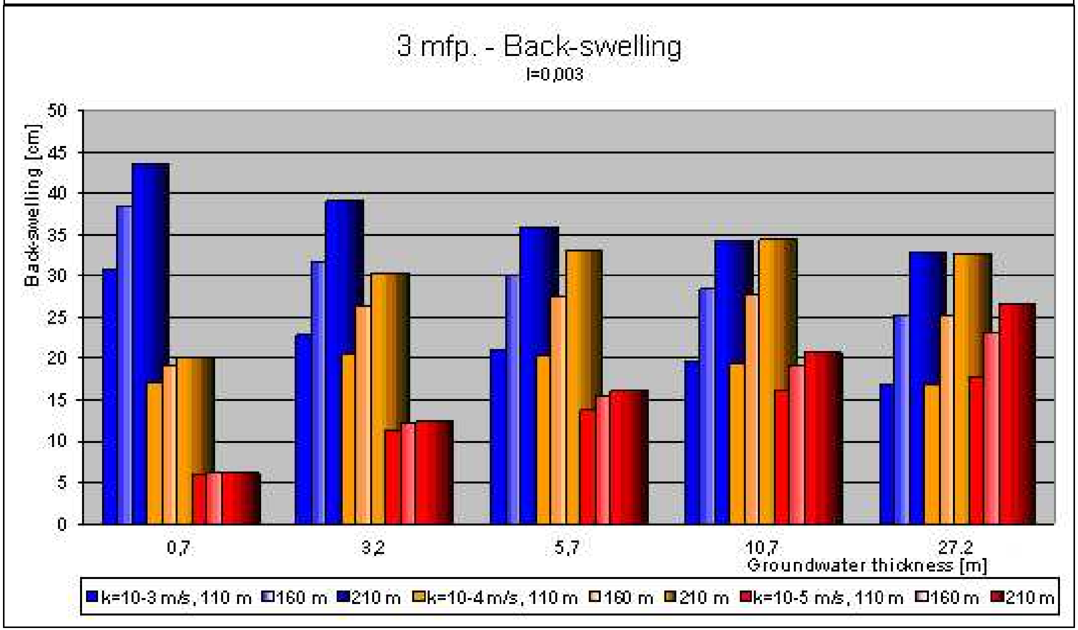
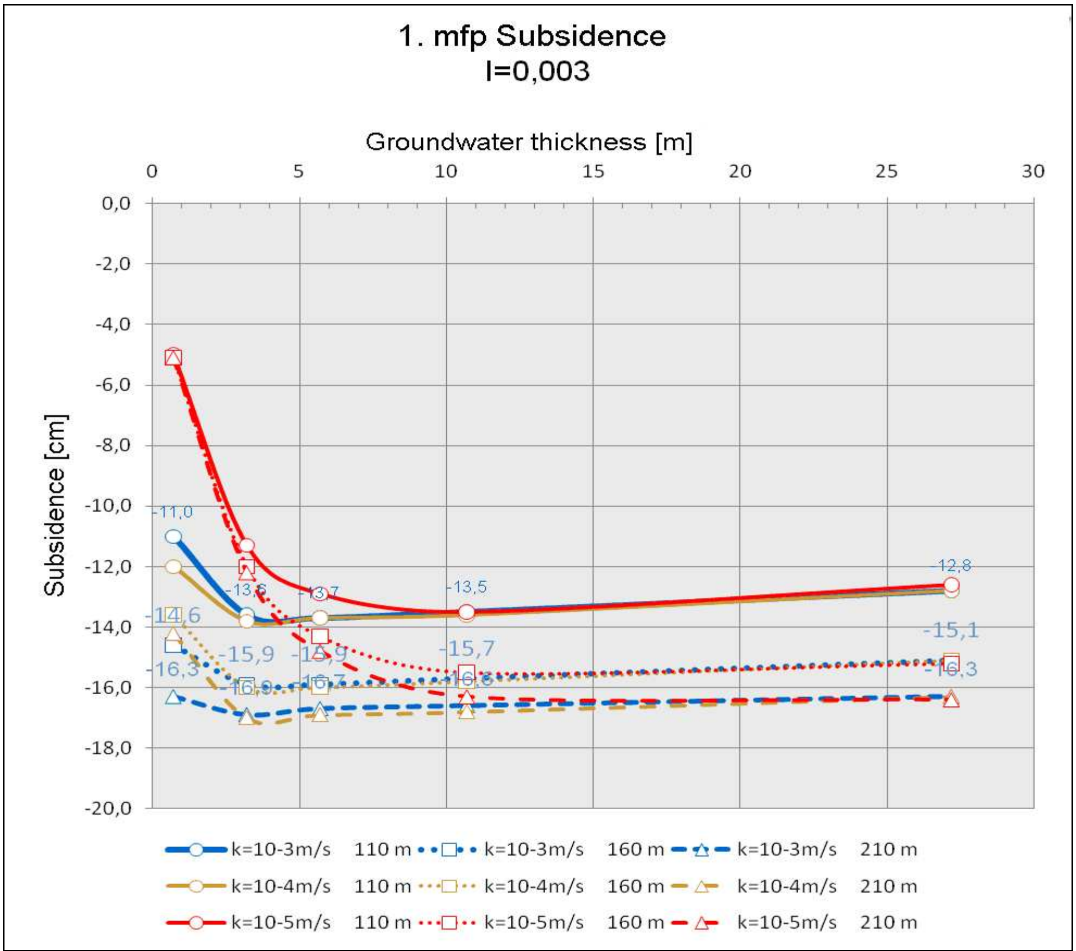


Figure 3.1. The change of the structure's size – back-swelling



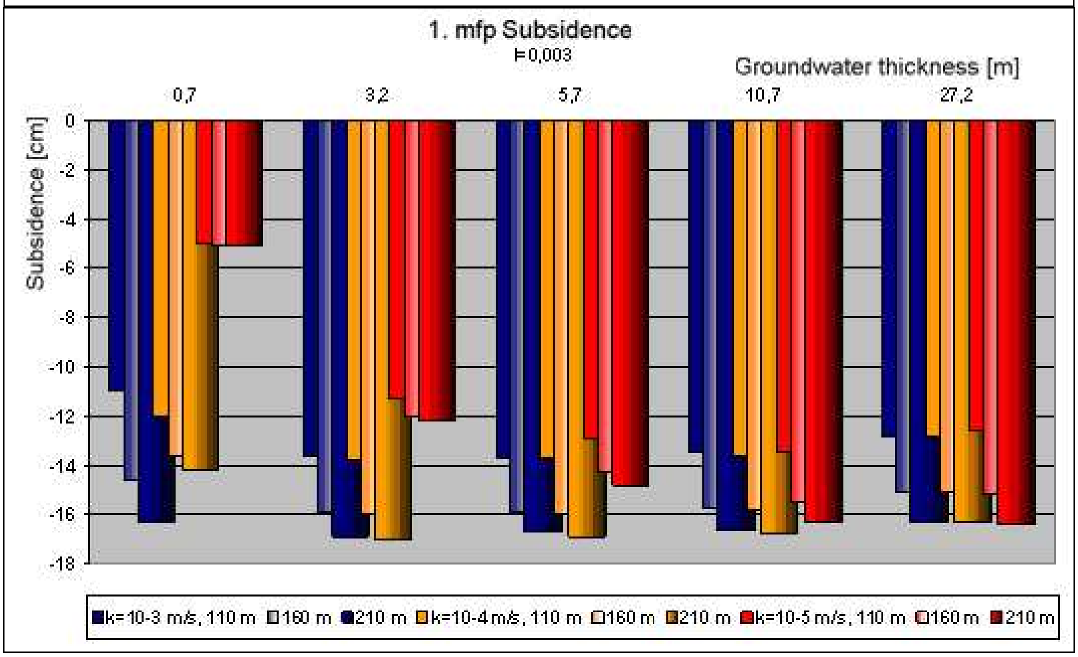


Figure 3.2. The change of the structure's size – subsidence

- ***Which of the material characteristics of the different geological formations can be considered as homogeneous? What dimension of them gives the best result?***

  In point of view of the k coefficient the examination of the soils of different material characteristics resulted the followings.
  At back-swelling considering the effect of the underground establishments the soils with infiltration coefficient of 10^{-2}, 10^{-3} and 10^{-4} m/s can be taken as homogenous, are reducible as one layer. The values of the modeled effect change within 5 cm, practically they are equal. This small difference is negligible from the point of view of the designing tasks.
  At examining of subsidence the above-mentioned homogeneous range expand with the type of the soils with 10^{-5} k coefficient. (Figure 3.4.)
  In point of effective porosity in the above-mentioned soil ranges the difference from the values in the technical literature with 5-10 % result changes only by centigrade in the effects (back-swelling, subsidence).
  So it can be stated that in case of given soil or contracted soil fractions, the application of the n_0 free gap volume average value gives a convenient result for the planning.

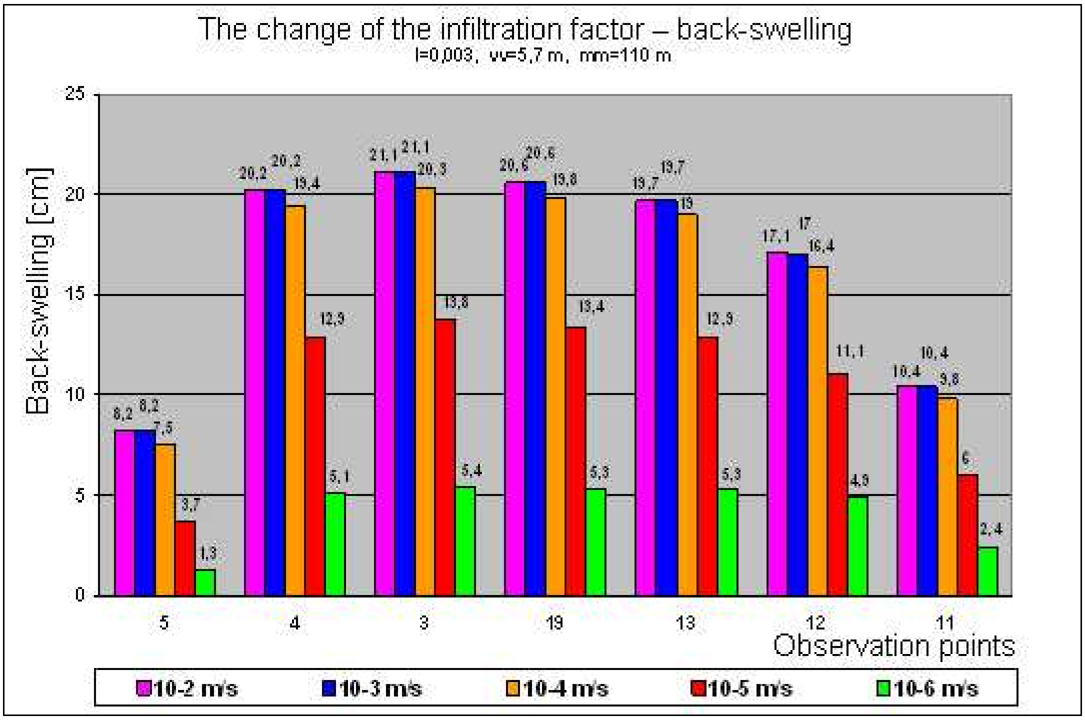


Figure 3.3. The change of the infiltration coefficient – back-swelling

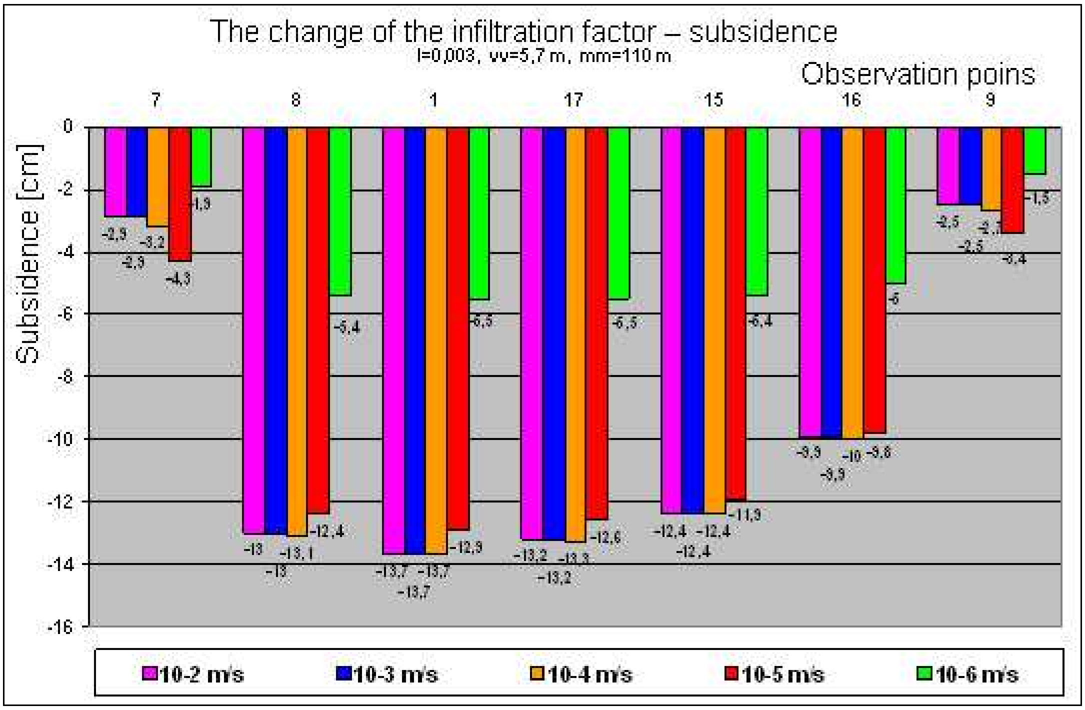


Figure 3.4. The change of the infiltration coefficient – subsidence

- ***What level of simplification of the explored rock and soil stratification is permissible?***

At defining the layer borders and the layer numbers the following soils can be mentioned as one layer: soils with infiltration coefficient of 10^{-2}, 10^{-3} and 10^{-4} m/s in point of view of back-swelling, and soils with infiltration coefficient of 10^{-2}, 10^{-3}, 10^{-4} and 10^{-5} m/s in point of view of subsidence.
It depends on the thickness of the groundwater flowing in the impermeable layer, that in the geological model can we take the layer borders as a horizontal line or not. In case of lower (~0-5-5 m) water thickness bigger differences are in the effects caused by the obstacles. So in this interval it is practical to take into consideration the slope, the skew of the layer in the interest of more punctual result.
At thickness more than 5 m taking of horizontal layer border is a good approaching.
But the exploration of the examined geological surrounding happens practically in points or sometimes along line, so the specification of the soil stratification is a result of interpolation. Therefore the basic data system of the modeling doesn't make necessary to consider the level differences within order of magnitude of 1-2 m.

- ***What extremely important parameters' determination is necessary to reach the calculation results appropriate to the aims, and with what accuracy?***

During my research the row of the <u>determinant and negligible parameters</u> become unambiguous from the point of view of the underground structures' effect on the groundwater flow:

<u>determinant parameters:</u>

- the infiltration coefficient of the soil,
- hydraulic gradient,
- the thickness of the flowing groundwater,
- the direction of the flow in relation of the structure,
- the dimension of the structure (obstacle).

<u>negligible parameters:</u>

- effective porosity

At determining the parameters the refinement of the <u>*k coefficient*</u> within the range of one order of magnitude leads to no more reliable result within the range of 10^{-2} and 10^{-4} m/s in the case of back-swelling and within the range of 10^{-2} and 10^{-5} m/s in the case of subsidence. Between these limits the difference of the effects is within 5 cm.

As a result of modeling it can be stated that between the change of the <u>*hydraulic gradient*</u> and flow modifications caused by the obstacles is linear relation in the interval of I=0,001-0,009. According to the order of magnitude of the caused effects the value of gradient is enough to be provided with the accuracy of 10 cm/100 m and be changed in such degrees on order to get appropriate results.

At the effect of the water-conducting layer and the thickness of flowing groundwater the examination in every 2-3 meters leads to determine reassuringly the dimension, tendency of back-swelling and subsidence within the groundwater's thickness of 0,5 – 10 m. Above the thickness of 10 m it is sufficient to monitor changes in every 10 m.

The modellings verified unequivocally that the largest flow modification is caused by <u>*flow direction*</u> perpendicular to the structure. It is practical at the planning to consider the resultant of the flow with an angle 0-10^{o} with the front of the structure, because of the exploration level of the real hydrogeological surrounding.

The soils with infiltration coefficient of k = 10^{-2}, 10^{-3} m/s react to the change of <u>*structure's dimension*</u> sensitively. At these soils the accurate calculation requires modification in steps of 10 m. In the case of soils with infiltration coefficient of k = 10^{-5} - 10^{-6} m/s the back-swelling and shrinking effect of the structure dimension's change is low (within decimeter). Here is sufficient to examine the effect caused by the changes of dimension in every 50 m.

For the parameters the above given and limited <u>knowledge-levels are necessary and sufficient for the accuracy of the task. (Chapter 2.1.)</u>

- ***In what extent should be practical taken into account the change of surface and groundwater data in time at the affected hydrogeological environment?***

  The daily (hourly) data of Danube water levels from the database of Water Data Bank were available to my study.
  I weekly performed the water level measurement in the installed two water level monitoring wells through one and half year.
  It can be stated, that the durability of Danube water levels and the water levels after constant water levels significantly influence the effects of structures next to the river (back-swelling, subsidence).
  Therefore, in knowledge of the results it can be stated, that near to the big river the weekly groundwater measurement is definitely necessary to establish a correct connection in aspect of the task between the measured water level data and the modelling values. The measurement period shall be determined so that the large part of the river water level interval can be appeared in the measurement period.

- ***In what extent can be the research results extended?***

  One aim of my research was that the obtained results could be applied in other geological, hydrogeological environment as well.

  The results can be widely extended according to the followings:
  - I performed the examination of several parameters in many (soil, groundwater and structure) aspects.
  - The accepted examination intervals cover a wide range of geotechnic and flow hydraulic. (My research extended from the gravel fraction to the silty sand, silt fraction).
  - The variation possibility between the intervals and the different parameters is numerous. The combination is without repetition taking account of the examined parameters:

    $$C = \binom{n}{k} = \frac{n!}{k!(n-k)!} = 4 * \left(\frac{5!}{1!(5-1)!}\right) * \left(\frac{3!}{1!(3-1)!}\right) = 5 * 5 * 5 * 5 * 3 = 1875$$

  - Towards the widespread application I prepared functional relationships described with approximate polynomials (chart I. and II.) and
  - I worked out surface diagrams in case of backwater and droop (figures 4.3. and 4.4.).

  With the help of the *surface diagrams* and the *polynomials*, which describe the tendency of the effects can be the back-swellings and subsidences caused by the blocks determined (by interpolation if necessary). The polynomials and surface diagrams are available in case of prescribed parameter configuration (variant) to determinate approximate values of unknown interstage points between prescribed intervals. With their application at different geological and hydrogeological areas and in case of different characteristics of structures we can obtain correct results with the task-required accuracy.

With the help of my scientific results, before preparing a complex, labioursome hydrodynamic modeling an opportunity presents itself to forecast and to explore the expectable effect of the underground structures, to estimate their order of magnitude and to decide the necessity of the further working phases. In terms of this:

- ***I defined descriptive survey parameters of groundwater flow influenced by structures.***
  I determined determinative and negligible parameters from the aspect of the phenomenon.
  I restricted necessary and sufficient level of knowledge of parameter according to accuracy required by the application target and the task. (see the above)

- ***In the interest of helping and lightening the establishment of the hydrodynamic model calculation's basic data and model data system, which requires long time and hard work:***
  - ***I determined the limit depth and the minimum thickness of groundwater, to which level effects caused by objects change with different tendencies (depending on infiltration coefficient of the agent). Below this limit effects converge to one value, practically becoming independent from the type of soil.***
    In the case of *back-swelling* the limit depth is: ~20-30m depending on the dimension of structure, in case of *subsidence* it lessens to: ~10m.
    Minimum thickness of water-holding layer to be taken into consideration at modeling is: 25-35 m, and it is 20-30 m in case of thickness of groundwater.
    With this I gave the necessary size of the examined geological formation, in point of depth.
  - ***I defined ranges, within soils with different material characteristics – with different infiltration coefficient – behave nearly identically from the aspect of the question in hand.***
    In case of back-swelling this range is between 10^{-2} and 10^{-4} m/s, *in case of subsidence* the range is expended by soils having k-coefficient of 10^{-5} m/s. Based on this these soils can be can be taken as homogenous, are reducible as one layer, so the soil stratification can be simplified significantly and the model can be set up easily.
  - ***I pointed out the range of groundwater thickness where slope of layer-borders has to be taken into consideration.***
    Within the range of ~ 0,5 – 5 m of water-thickness, the slope and skew of layers is expedient to be given, but level differences of 1-2 m are not necessary to take into consideration for the modeling.
    Above 5 m thickness, borders of layers can be taken as horizontal lines.

The significance of the results is that they accelerate and simplify the modeling considerably in practical planning.

- ***As a result of my research I found correlation between different thickness of flowing groundwater and the effects caused by structures put in its way that I worked out in graphical form.***(Chapter 4, Figures 4.1. and 4.2.)

The significance of the graphs is that the tendency of the back-swellings and subsidences can be given immediately and unambiguously with the knowledge of infiltration coefficient of the water-holding soils. Its dimension can be estimated quickly and with good approaching – considering the determinant joint state of parameters.
The validity range of graphs is: groundwater thickness between 0,7 - 35 m.

The tendency of the back-swelling: (Figure 3.5.)

- In the interval of $\mathbf{10^{-2} > k > 2\text{-}3 \cdot 10^{-4}}$ **m/s** the value of the back-swelling decreases gradually with the increase of groundwater's thickness.
- In the interval of $\mathbf{2\text{-}3 \cdot 10^{-4} > k > 7 \cdot 10^{-5}}$ **m/s** the value of the back-swelling increases until a given water's thickness, then gradually decreases.
- In the interval of $\mathbf{7 \cdot 10^{-5} > k > 10^{-5}}$ **m/s** the value of the back-swelling increases gradually with the increase of groundwater's thickness.
- In case of k coefficient of $\mathbf{10^{-6}}$ **m/s** the tendency is equal with the previous interval at minimal back-swelling.

The dimension of back-swelling:

Considering the different *k* coefficients at the smallest water surface is the difference the largest (more dm) in the values of back-swelling.
With increasing the water surface the difference of the resulted effects decreases at the individual infiltration coefficients.
After reaching a certain water's thickness of 20-30 m (depending on joint state of parameter) the values of the back-swelling are equal within 5 cm difference, so it practically doesn't depend on the water permeability of the soil.

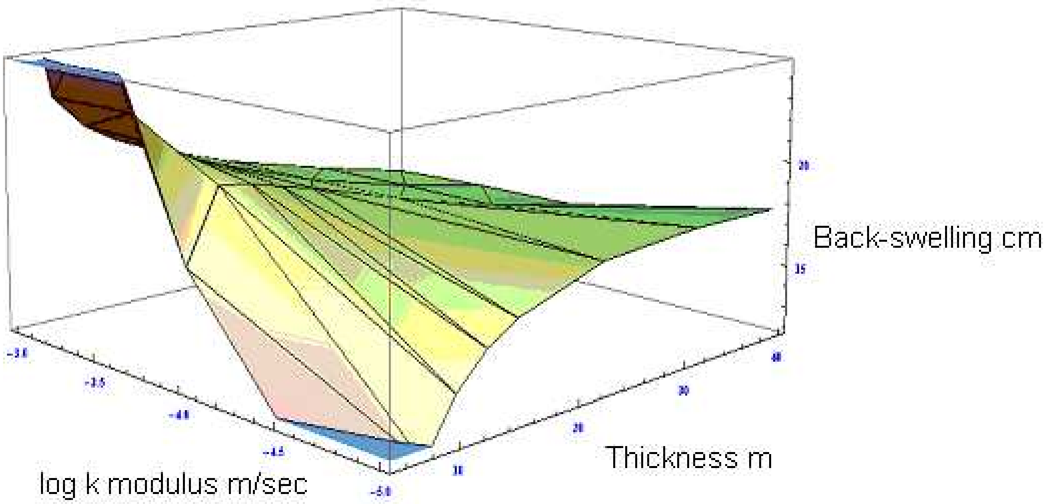


Figure 3.5. The tendency and measure of the back-swelling

The tendency of the subsidence:

- In the interval of **k = 10^{-2} - 10^{-4} m/s, between water's thickness of ~3-9 m** is the subsidence the largest, practically at equal values of subsidence. In case of smaller or larger thickness the dimension of the subsidence decreases.
- In case of infiltration coefficient of **k = 10^{-5} m/s**, **between water's thickness of ~0,7-5 m** the subsidence increases relatively abruptly, and then it decreases gradually with the increase of the thickness.
- In case of infiltration coefficient of **k = 10^{-6} m/s** there is relatively constant increase at minimal values of subsidence.

The tendency of the subsidence:

At the smallest water's thickness are the larger differences (within 10 cm) in the value of the subsidence in case of different *k* coefficient.
In case of current joint state of parameter, the values are practically the same within cm from the water's thickness of 10-15 m, so the subsidence doesn't depend on the infiltration coefficient in this interval.

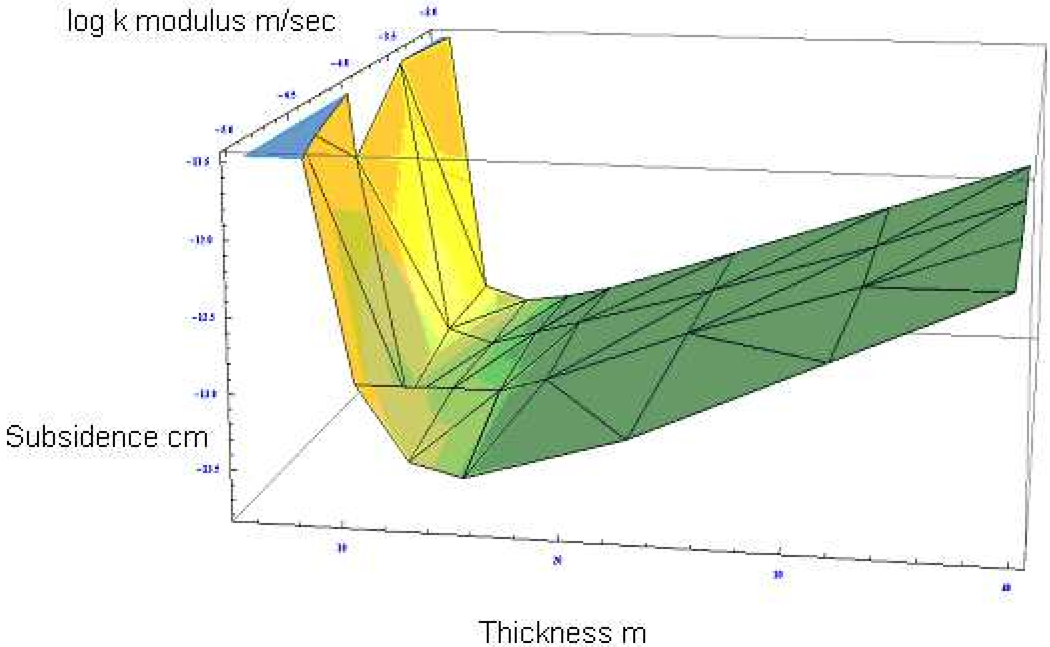


Figure 3.6. The tendency and measure of the subsidence

- ***I show the characteristics of the correlation system of infiltration coefficient, thickness of flowing groundwater and size of structure on a 3 D surface diagram. With the application of the diagrams, the value of back-swelling and subsidence can be determined easily (if coefficient "k", thickness of groundwater and size of structure is provided).*** (Chapter 4.: Figures 4.3. and 4.4.)

  The significance of creating these surface diagrams is that they help to estimate the underground establishment's effect on the groundwater flow and with this to decide and plan the necessity of further working phases.

  I prepared the calculations with hydraulic gradient value of I = 0,003 at nearly perpendicular state. In case of other parameter's joint of state (variation) the effects (read from the diagrams) can be modified considering the other determined rules.

  The surface diagrams are applicable:

  at infiltration coefficients of $k = 10^{-3} – 10^{-4} – 10^{-5}$ m/s,
  between groundwater's thicknesses of vv = 0,7 – 35 m,
  at structure's dimension of mm = 110 – 160 – 210 m.

  But the diagrams can be worked out for different (higher or lower) values too; their validity range can be extended. But from the point of view of the practice the flow between these intervals is the most characteristic generally.

- ***I developed a chart, in which I summarized the result of the prepared simulations. The chart determines the back-swelling and subsidence effects of underground structures put in the way of groundwater flow according to the examined parameters.*** (Chapter 4: Chart III.)

  With the help of the chart the tendency of the effects can be determined unambiguously, their order of magnitude can be estimated well between certain limits.
  The results of the chart are valid in case of the listed parameters, within the examination ranges given for those.

- ***I set up function relation between the change of different parameters and the back-swellings and subsidences established because of the effects of underground structures put in the way of groundwater flow. I wrote the relation with the help of convergent polynomials.*** (Charts I. and II.)

  The polynomials are suitable for determining the convergent value of unknown points, in case of certain parameter's joint of state.

  With the help of the polynomials – knowing the convergent order of magnitude of the calculated effects – it can be decided that there is necessary and worth to make further detailed hydrodynamic model calculation or not, considering the significance and importance of the examined problem.

<table>
<tr><th>Variable parameters</th><th colspan="2">Stationary parameters</th><th>Back-swelling</th></tr>
<tr><td>Hydraulic gradient
I [-]</td><td colspan="2">$k=10^{-3}$ m/s
vv=5,7 m
mm=110 m</td><td>$\left[\frac{1}{4}\left(-19,8414+49,0896x-7,22552x^{2}+0,810417x^{3}+0,0330729x^{4}\right)\right]$</td></tr>
<tr><td>Infiltration coefficient
k [m/s]</td><td colspan="2">I=0,003
vv=5,7 m
mm=110 m</td><td>$\left[\frac{1}{4}\left(326+302,392x+131,829x^{2}+23,8083x^{3}+1,47083x^{4}\right)\right]$</td></tr>
<tr><td rowspan="3">Groundwater thickness
vv [m]</td><td rowspan="3">I=0,003
mm=110</td><td>$k=10^{-3}$ m/s</td><td>$\left[\frac{1}{4}\left(787,863-301,691x+54,3213x^{2}-5,28009x^{3}+0,296191x^{4}-0,00954049x^{5}+1,62924*10^{-4}x^{6}-1,137*10^{-6}x^{7}\right)\right]$</td></tr>
<tr><td>$k=10^{-4}$ m/s</td><td>$\left[\frac{1}{4}\left(-297,126+169,817x-31,45x^{2}+3,10104x^{3}-0,175774x^{4}+0,00570675x^{5}-9,80465*10^{-5}x^{6}+6,87422*10^{-7}x^{7}\right)\right]$</td></tr>
<tr><td>$k=10^{-5}$ m/s</td><td>$\left[\frac{1}{4}\left(-205,391+93,4392x-15,1535x^{2}+1,39222x^{3}-0,0754681x^{4}+0,00237617x^{5}-3,99392*10^{-5}x^{6}+2,75572*10^{-7}x^{7}\right)\right]$</td></tr>
<tr><td>Distance between structures
t [m]</td><td colspan="2">I=0,003
$k=10^{-3}$ m/s
vv=5,7 m
mm=110 m</td><td>$35,8-1,55457x+0,102193x^{2}-0,00322438x^{3}+0,000033727x^{4}$</td></tr>
</table>

The x value in the formulas is the actually examined parameter, an independent variate, depending on this see I the change of the examined phenomena (back-swelling).

Chart I. Polynomials – back-swelling

Variable parameters	Stationary parameters		Subsidence
Hydraulic gradient I [-]	$k=10^{-3}$ m/s vv=5,7 m mm=110 m		$\left[\frac{1}{4}\left(-29{,}8133+54{,}1813x-13{,}4109x^2+1{,}71875x^3+0{,}0757813x^4\right)\right]$
Infiltration coefficient k [m/s]	I=0,003 vv=5,7 m mm=110 m		$\left[\frac{1}{4}\left(31{,}2+109{,}908x+52{,}3458x^2+10{,}7417x^3+0{,}804167x^4\right)\right]$
Groundwater thickness vv [m]	I=0,003 mm=110	$k=10^{-3}$ m/s	$\left[\frac{1}{3}\left(186{,}093-101{,}541x+18{,}8143x^2-1{,}85893x^3+0{,}105447x^4-0{,}00342304x^5+5{,}87775*10^{-5}x^6-4{,}11801*10^{-7}x^7\right)\right]$
		$k=10^{-4}$ m/s	$\left[\frac{1}{4}\left(195{,}877-116{,}04x+22{,}2023x^2-2{,}25232x^3+0{,}130541x^4-0{,}00431131x^5+7{,}50403*10^{-5}x^6-5{,}31311*10^{-7}x^7\right)\right]$
		$k=10^{-5}$ m/s	$\left[\frac{1}{3}\left(251{,}491-112{,}475x+18{,}7216x^2-1{,}71512x^3+0{,}0922078x^4-0{,}00288044x^5+4{,}81076*10^{-5}x^6-3{,}30304*10^{-7}x^7\right)\right]$
Distance between structures t [m]	I=0,003 $k=10^{-3}$ m/s vv=5,7 m mm=110 m		$16{,}7-0{,}402571x+0{,}0289975x^2-0{,}000947048x^3+0{,}0000100825x^4$

The x value in the formulas is the actually examined parameter, an independent variate, depending on this see I the change of the examined phenomena (subsidence).

Chart II. Polynomials – subsidence

3.2. Water level data measured in wells

As a result of the analysis of Danubian water level data and the observing of the groundwater level lasting two years unambiguously appeared the slurry wall's modifying effect on groundwater flow.
The differences of water levels on the two side of the slurry walls – which are only at 40 m distance from each other, are fixed into the clay substratum and can be considered as impermeable – completely verify the legitimacy of raising the problem and the necessity of the analysis of the changed conditions, effects.

The high correlation of the water levels of the Danube and the well No. 1 nearby can be read from the chart too.
I gave the layout plan location of the wells on the Figures 2.2. and 2.3. in the Chapter 2.2.

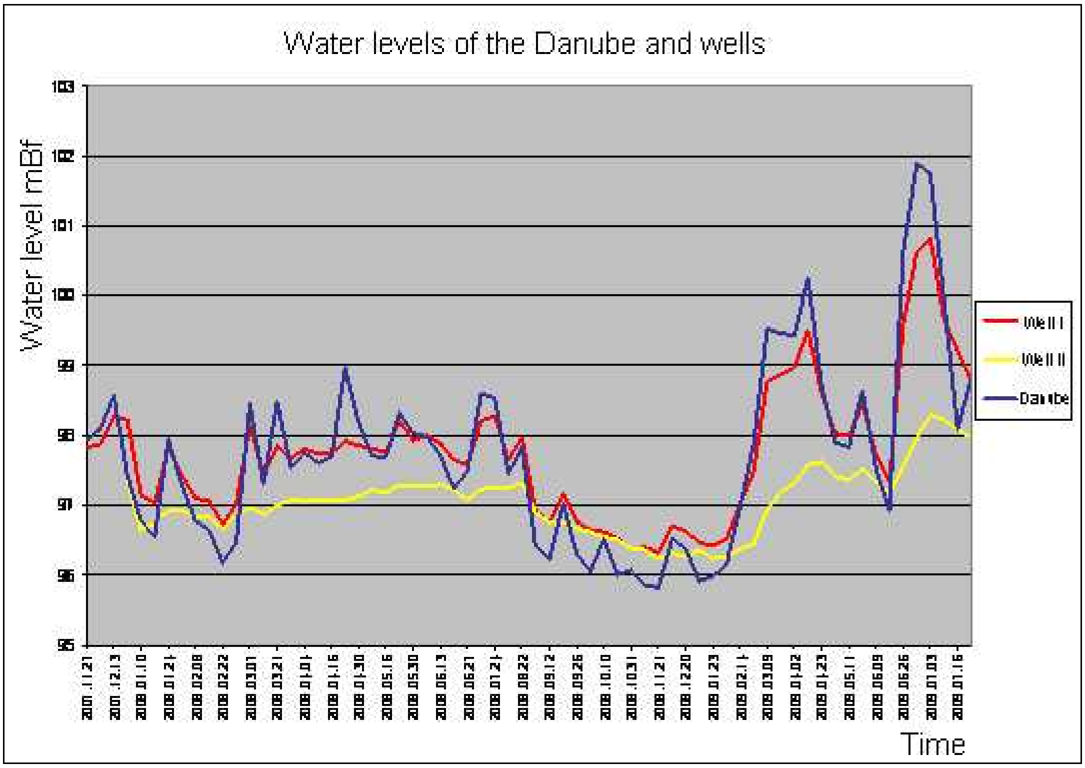


Figure 3.7. Water level data

By the measured results three cases can be separated in the analysed time, which is shown in Figure 3.8.

1. Low water period of the Danube, 95,8-96,3 m Baltic level

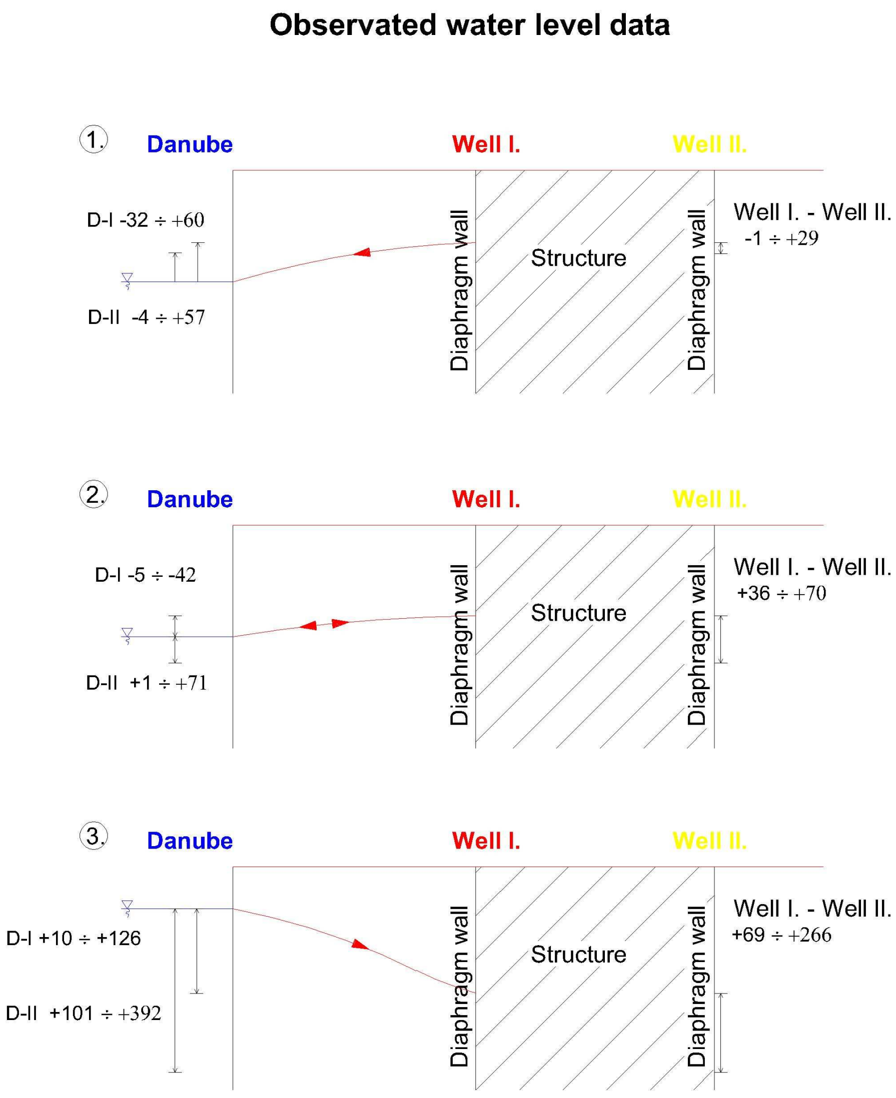
The groundwater flows towards the river Danube, which collects the water like a gallery.
In both wells the water level is higher with 4-60 cm than the water level of the Danube.
The water level difference between the two wells moves in 30 cm intervals, decisively the water levels are higher in the Well I. next to the river.
According the modelling taking into consideration the original capabilities there was a 45 cm water level difference between the water level of two wells at the two sides of the structure (block). The water level in the Well II. was lower.

2. River water level between 96,3-97,8 m Baltic level

The drain effect of the river decreases gradually, the groundwater turns into nearly stagnant state.
The water level in the Well I. is 5-42 cm higher and 1-71 cm lower in the Well II. than the level of the Danube.
The difference between the measured values of the two wells is increased, the water levels in the Well I. were 36-75 cm higher.
It should be noted that the measurements do not confirm the assertion of the professional literature that the average Danube water levels (97,8 m Baltic level) cause these conformation of stagnant water elevation.

3. River water level above 97,8 m Baltic level and high water period

In case of flood the Danube already charges into the terrace gravel aquifer.
The water level of river is 10-126 cm higher than the level in Well I. and 101-392cm higher than the level in Well II.
The water level difference between the Well I. and Well II. which are ~40 m far from each other, increases to 65-266 cm. The water level in the Well I. was lower.
According to the modelling process there is a 115 cm difference between the water level of the two wells at the two sides of the structure (block). The water level in the Well I. was lower.



Legend: D-I The difference between the water level of Danube and Well I.

D-II The difference between the water level of Danube and Well II.

D-III The difference between the water level of Well I. and Well II.

Figure 3.8. Relationship between the water level of Danube and the groundwater levels

3.3. Comparison and evaluation of the modeling and measuring results

I compared the measuring and modeling values of flow alteration and groundwater changes occurred by effect of the real structure.

The measured water level data in the wells and the simulations results considering the tendency of the phenomenon show full conformity.

The simulations were performed by the two extreme water levels (maximum and minimum levels) of Danube. The calculations verified the dynamic there and backwater flow between the Danube and the groundwater. During the low water period prevails the drain effect of the Danube. At this time the water level of wells are higher than the water level of river. The back-swelling effect develops in the Well II. During the high level period the Danube charges into the groundwater. The water levels of wells are lower than the water level of river. The back-swelling effect develops in the Well I.

The evolved differences in order of magnitude show the large complexity of the real situation contrary to the simplified model.

During the research I measured the flow modifying effect of the underground structures not with an analogy special machine but with a full size (1:1 scale) in-situ large-sample experiment, which is under the influence of countless uncertainty element of the surroundings.

However, eliminating the accumulated modifying values from the measurement results, within the task required accuracy of decimetre, the results of the modelling process are obtained.

Modifying effects which cause the differences:

- The difference between the results is caused on the one part by the huge influencing role of durability of Danube water levels. With this relationship further modifying coefficient is the storage time of the water in the aquifer and the conditions of water levels after the permanently high or low water levels.
- Another result influencing effect is that the streamlines near by the Danube connect precipitously to the river.
- The distance between the river and the diaphragm wall is relatively small (40 m).
- At the bank of the Danube there is a several meters deep embankment wall, which was built during the river regulation.
- There are numerous structures with diaphragm walls as well next to the studied object parallel with the Danube in several kilometres among which is only a 10-20 m wide sector available to the free flow.

Therefore the groundwater is crowded into the narrow sector between the structures and the Danube (gets trapped between the embankment walls and the diaphragm walls). It storages here for a long time and its level increases significantly. This phenomenon is still increased by the durability of the Danube water level. By these reason the in-situ measured back-swelling and subsidence effect is modified compared to the results of modelling process.

Therefore it can be seen, that the proximity of the large water stream (~ 40 m from the Danube) on the one hand provides facility to study various questions of flow, on the other hand it makes difficult the obvious correspondence between the measured and the modeling values.

I verified the validation of the modeling results on the other side as well. On the one hand I compared the analytic results of previous hydrogeological expertises at the surroundings of the examined area with my modeling values. On the other hand I controlled my results in a simplified numerical form with the MODFLOW modeling system based on the finite difference method. The values of the three different methods are summarised in Figure 3.9.

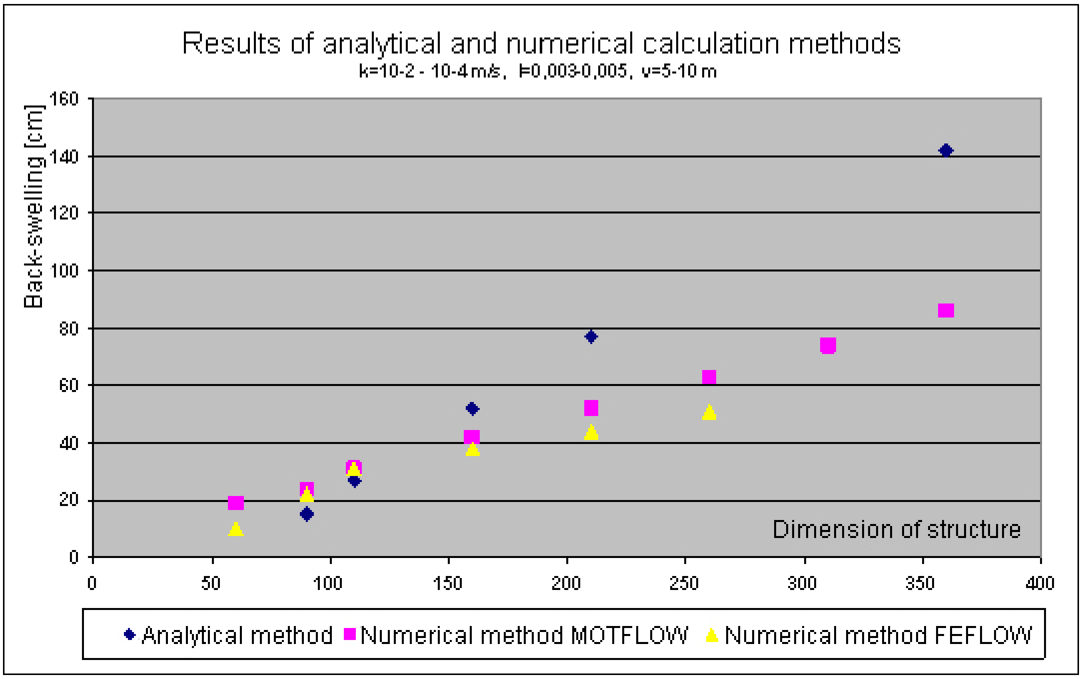


Figure 3.9. Comparison of the results

The comparison of the results of different calculation method was only in wider parameter intervals possible having regard to the analytical calculations.
By the diagram it can be said that the values of numerical methods are almost conformable within decimetre differences. The results taken from the analytical approximation calculus, until the dimension of the 200 m wide structure, have a difference in decimetre dimension compared with the backwaters of the model.

In summary it can be stated, that the hydrodynamic model prepared to the study of the effect of structures created in the way of the groundwater flow – in the definite validity limits, with the required accuracy of the task – is suitable to solve the problem.

4. NEW SCIENTIFIC RESULTS

1.) Determinative and negligible parameters and their level of knowledge

I defined descriptive survey parameters of groundwater flow influenced by structures. I determined determinative and negligible parameters from the aspect of the phenomenon (back-swelling, subsidence). *Determinative parameters*: infiltration coefficient of soil, hydraulic gradient, thickness of flowing groundwater, direction of flow according to the structure, size of structure (obstruction). *Negligible parameters*: effective porosity.

I restricted necessary and sufficient level of knowledge of parameter according to accuracy required by the application target and the task.

- Refinement of the infiltration coefficient within the range of one order of magnitude leads to no more reliable result within the range of 10^{-2} and 10^{-4} m/s in the case of back-swelling and within the range of 10^{-2} and 10^{-5} m/s in the case of subsidence.
- Value of hydraulic gradient is sufficient to be provided with the accuracy of 10 cm/100 m.
- Thickness of flowing groundwater has to be examined in every 2-3 meters within the thickness range of 0,5 – 10 m. Above the thickness of 10 m it is sufficient to monitor changes in every 10 m.
- Largest flow modification is caused by flow direction perpendicular to the structure.
- In the case of soils with infiltration coefficient of $k=10^{-2}$, 10^{-3} m/s, size of structure has to be modified in steps of 10 m. In the case of soils having infiltration coefficient of $k=10^{-5}$ - 10^{-6} m/s, effects of change in size is sufficient to be surveyed in every 50 m.

2.) Setting up data system for hydrodynamic model-calculation

I determined limit depth and minimum thickness of groundwater, to which level effects caused by objects change with different tendencies (depending on infiltration coefficient of the agent). Below this limit effects converge to one value, practically becoming independent from the type of soil.

In the case of *back-swelling* the limit depth is: 20-30m, in case of *subsidence* it is: 10m.

Minimum thickness of water retentive layer to be taken into consideration is: 25-35 m, and it is 20-30 m in case of thickness of groundwater.

I defined ranges within soils with different material properties behave nearly identically from the aspect of the question in hand.

In case of *back-swelling* this range is between 10^{-2} and 10^{-4} m/s, in case of *subsidence* the range is expended by soils having k-coefficient of 10^{-5} m/s.

I pointed out the range of groundwater thickness where tilting of layer-borders has to be taken into consideration.

Within the range of 0,5 – 5 m of water thickness, tilt of layers is expedient to be given, but differences of 1-2 m are not necessary to take into consideration.

Above 5 m thickness, borders of layers can be taken as horizontal lines.

3.) <u>Graphs applied for determining back-swelling and subsidence</u>

I found correlation between different thickness of flowing groundwater and the effects caused by objects put in its way that I worked out in graphical form.

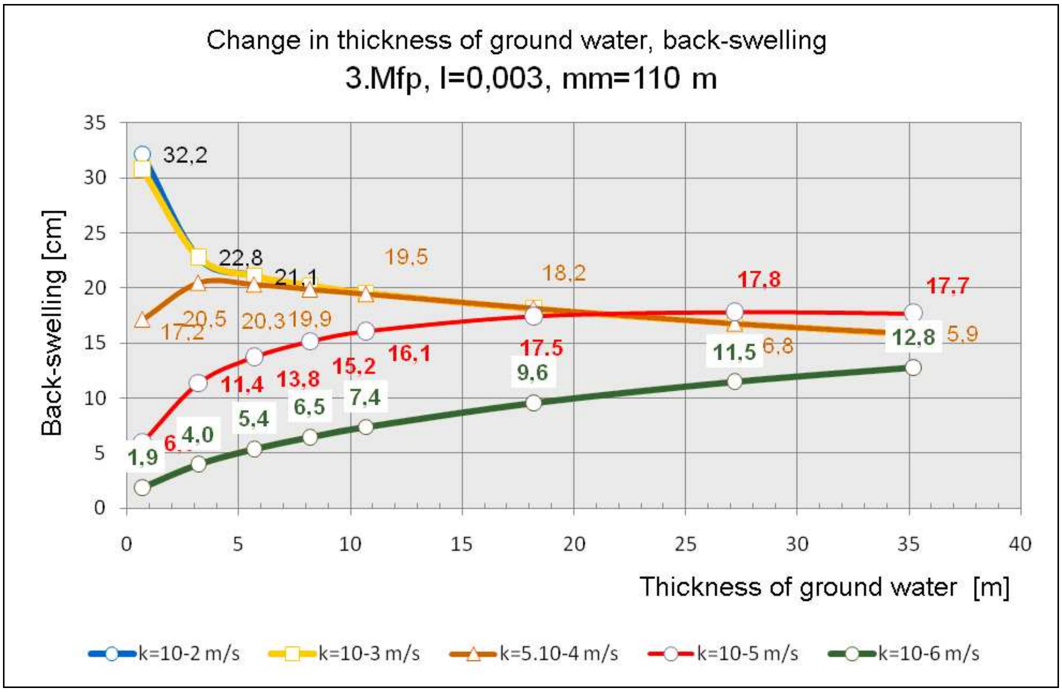


Figure 4.1. Back-swelling – graph

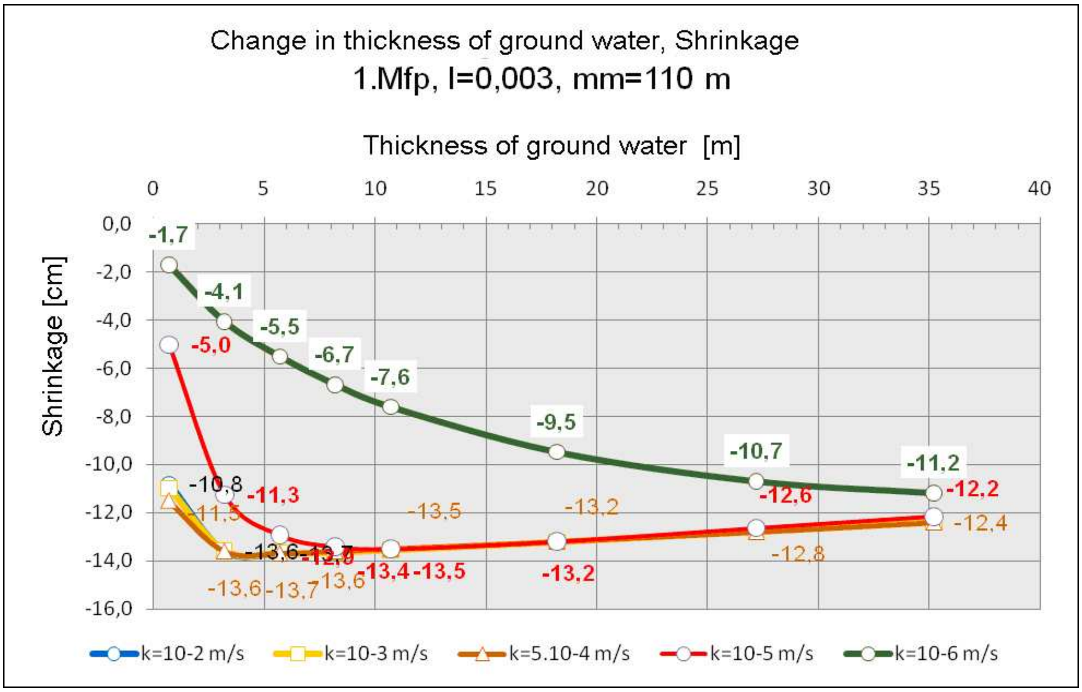
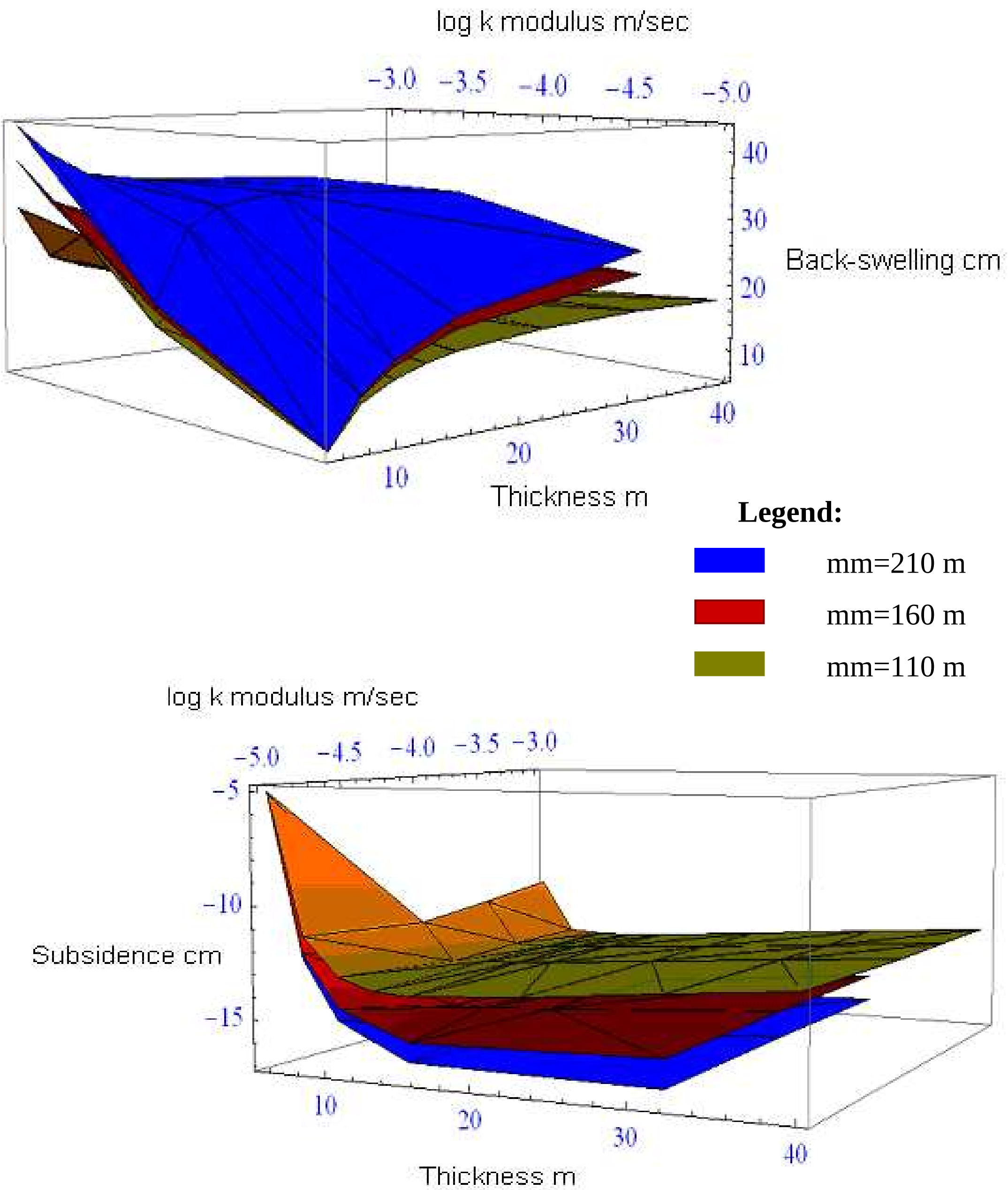


Figure 4.2. Subsidence – graph

4.) <u>Surface-figures applied for determining back-swelling and subsidence</u>

I portrayed characters of correlation system for infiltration coefficient, thickness of flowing groundwater and size of structure on a 3 D surface diagram. With the application of the diagrams, values of back-swelling and subsidence can be determined (if coefficient “k”, thickness of groundwater and size of structure is provided).



Figures 4.3. and 4.4. 3D surface diagram – Back-swelling, subsidence

5.) Table applied for determining back-swelling and subsidence

I developed a table determining back-swelling and subsidence effects of objects put in the way of groundwater flow according to the studied parameters. Tendencies of effects can be determined clearly, their order of magnitude can be estimated sufficiently.

<table>
<tr><th rowspan="2">Parameters. modeling ranges</th><th colspan="8">Tendency and order of magnitude of effects</th></tr>
<tr><th colspan="6">Back-swelling</th><th colspan="2">Subsidence</th></tr>
<tr><td>Angle between direction of flow and axle of structure is parallel - perpendicular</td><td colspan="6">Increasing</td><td colspan="2">Increasing</td></tr>
<tr><td>Hydraulic gradient $I = 0{,}001-0{,}009$</td><td colspan="6">Increasing
linear increase</td><td colspan="2">Increasing</td></tr>
<tr><td>Free volume of gaps $n_0= 0{,}15 – 0{,}35$</td><td colspan="6">Nearly identical
Order of magnitude of the change is one in a hundred</td><td colspan="2">Nearly identical
Order of magnitude of the change is one in a hundred</td></tr>
<tr><td>Infiltration coefficient $k=10^{-2} – 10^{-6}$ m/s</td><td colspan="3">Nearly identical
Change is within 50 mm between vv=3-35m</td><td colspan="3">Decreasing</td><td>Nearly identical
Change is within 50 mm</td><td>Decreasing</td></tr>
<tr><td rowspan="2">Thickness of flowing groundwater vv= 0,7 - 35,2 m</td><td colspan="2">Decreasing</td><td colspan="2">Increasing then decreasing</td><td colspan="2">Increasing</td><td>Increasing then decreasing</td><td>Gradually increasing</td></tr>
<tr><td colspan="6">Converging to one value</td><td colspan="2">Converging to one value</td></tr>
<tr><td>Size of structure (object) mm= 110-160-210 m</td><td colspan="3">Increasing</td><td colspan="3">Nearly identical
Change is within 100 mm</td><td>Nearly identical
Change is within 100 mm</td><td>Nearly identical
Change is within 100 mm</td></tr>
</table>

6. CONCLUSIONS, PROPOSALS

The back-swellings, subsidences (developing because of the effect of the underground establishments) are problem for the surrounding technical establishments or the agriculture, if the permanently changed water levels rise over the highest groundwater level till then, and subside below the lowest, or the arising long-effect reaches the borders of the danger zone.

If the effects caused by obstacles put in the way flowing groundwater increase or decrease the water level within the characteristic fluctuation zone of the groundwater, then they can be danger for their surrounding by their durability.

So one of the directions of damage’s examination is to determine the order and measure of water level increasing and decreasing. The other one is to state the durability and the possible stabilization of these effects. In that, the damage comes into being or not, the durability (time factor) has greater importance, than the measure of the back-swelling, subsidence.

Because of the effect of the high and long-lasting water level, that is different from the water level till then:

- on the agricultural areas the productivity of the vegetation can change, or maybe the damage of the roots can lead to the dying out of the whole flora; areas with inland water can come into being;
- in built-up surrounding overflow of the underground spaces can come into being;
- the stability of the soil can be significantly worse, which can result the subsidence of the buildings.

In consequence of permanently low water level:

- the productivity of agriculture can decrease, maybe the vegetation can fully shriveled;
- on urban area extra subsidences can arise because of the increase of the geostatic stress, which can result building damages.

Beyond my theme it can be subject of further examination to decide the necessity of technical steps, which serve to decrease the harmful effects and to cross the development of the effects. And to determine and work out the intervention’s method.

6. SUMMARY

During my work of research I performed the realization of the aims after the review of the technical literature.
I simulated the flowing courses modifying by the effect of the obstacles under the surface with hydrodynamic modeling. I used for my examination FEFLOW Finite Element Simulation System for Subsurface Flow (WASY FEFLOW 5.3. 3D) program system.
For my research I elaborated a modeling idea, a hypothesis. I analyzed the results of the parameters – which determine the occurrence – relating to the consequence of the system. I follow the principle that – by setting out from the real data, picking and changing one, two or three from the parameters, and holding the others on standard value – I simulated their effect on the water-migration processes. I continued the examination on the line of the parameter
I made the examination on the way of that joint state of parameter, which produces the largest effect (back-swelling, subsidence) or results a significant difference, because this describes mostly the nature and tendency of the change.
I could compare the results of the hydrodynamic modeling with measurements of two groundwater level observing wells of the site of a real industrial work and hereby I could verify the validity of the models.
The local measuring, and partly the calculations made on the basis of the analytic and numerical methods verified that the model is suitable for simulating the effect of the underground establishments on the groundwater flow.
During my research with the help of the simulations I got answers to the questions made at the aims, on the basis of these I drafted my new researching results.
The main aim of my research was – exploring the principles of the underground establishment's effect on the groundwater flow, with the full knowledge of them – to create a scientific material, which helps the everyday practical designing and generally usable on the technical – agrotechnical field.
With the help of my scientific results, before preparing a complex, laboursome hydrodynamic modeling an opportunity presents itself:

- to forecast the infiltration hydraulic processes,
- to explore the expectable effect of the underground obstacles,
- to determine unambiguously the tendency of the back-swellings, subsidences,
- to estimate their order of magnitude and
- to decide the necessity of the further working phases.

So the results of the measuring and modeling verified the lawfulness of raising the problem, and the necessity of the analysis of the changed water-migration processes.

7. LIST OF PROFESSIONAL PUBLICATIONS

Edited articles in world language

Zs. Keszey, Z., Kovács, **E. Keszeyné Say** (2000)
Geotechnical and Movement Investigation for Determining the Reasons of the Damage of a building and for Defining the Possibilities of Interfering.
Szent István University, Ybl Miklós School of Engineering Annual News 2000. 4-10. pp.

E. Keszeyné Say, K. Reisinger (2007)
Hydrodynamic modeling of underground constructions in Budapest.
Szent István University, Ybl Miklós School of Engineering Annual. News 2007. 91-97 pp

A. Benedek, **E. Keszeyné Say** (2011)
PLAXIS analysis of a circular slurry trench wall construction pit enclosure at Budapest.
Plaxis Bulletin, Amsterdam NL. (under publication)

E. Imre, S. Fityus, **E. Keszeyné Say**, T. Schanz (2011)
A comment on the ratio of the maximum and minimum dry density for sands.
SEAGJ (Southeast Asian Geotechnical Society) Journal.
(under editing)

Edited articles in Hungarian

Keszey Zs., Kovács Z., **Keszeyné Say E.** (1999)
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Görög P., **Keszeyné Say E.** (2003)
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Keszeyné Say E. (2008)
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