TECHNICAL TRANSACTIONS | **CZASOPISMO TECHNICZNE**
ENVIRONMENTAL ENGINEERING | ŚRODOWISKO

2-Ś/2015

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ANALYSIS OF CHANGES IN GROUNDWATER AND SOIL CONDITIONS IN A HIGHLY URBANIZED AREA DUE TO DEEP BUILDING FOUNDATIONS

ANALIZA ZMIAN WARUNKÓW WODNO-GRUNTOWYCH NA TERENIE SILNIE ZURBANIZOWANYM NA SKUTEK GŁĘBOKIEGO POSADOWIENIA

Abstract

The article describes an urban environment and the anthropogenic factors that influence groundwater and soil conditions. Deep building foundations impact on changes in both groundwater flow and soil consistency, which may occur due to filtration phenomena. Suffusion and internal erosion were described, determining the criteria applied for assessment of soil susceptibility to these phenomena. The results of numerical modelling executed with Visual Modflow software are presented. It is stated that the creation of deep building foundations in an extensively urban area may influence the groundwater and soil conditions.

Keywords: groundwater, filtration, suffusion, internal erosion, deep foundation

Streszczenie

W artykule scharakteryzowano środowisko zurbanizowane oraz opisano wpływ czynników antropogenicznych na warunki gruntowo-wodne. Uwzględniono wpływ głęboko posadowionych budynków na zmiany przepływu wód gruntowych i zmiany stanu gruntu, które mogą być wywołane przez zjawiska filtracyjne. Opisano zagadnienie sufozji i erozji wewnętrznej oraz określono, jakie kryteria są stosowane do oceny podatności gruntu na wystąpienie tego zjawiska. Przedstawiono wyniki modelowania numerycznego wykonanego w programie Visual Modflow. Stwierdzono, że realizacja głęboko posadowionych obiektów w terenie silnie zurbanizowanym może wpływać na warunki wodno-gruntowe.

Słowa kluczowe: woda gruntowa, filtracja, sufozja, erozja wewnętrzna, głębokie posadowienia

DOI: 10.4467/2353737XCT.15.222.4608

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1. Introduction

Issues related to groundwater flow in urban areas have become a topic of growing importance over recent years. Cities currently remain home to c.a. 50% of the world’s population and the population inhabiting urban areas is expected to increase by mid-century to 70% [28]. Due to dynamic city development, appropriate planning and execution of developments stand out as the key element for the balanced and safe development of the urban environment. To allow this, it is necessary to recognize and understand the natural and anthropogenic processes that form the city ecosystem, which are characteristic for urban areas. What distinguishes the hydrology of urban areas from other hydrological systems, is the frequency of occurrence of certain “elements”, which influence both groundwater flow and its chemistry (Fig. 1.).

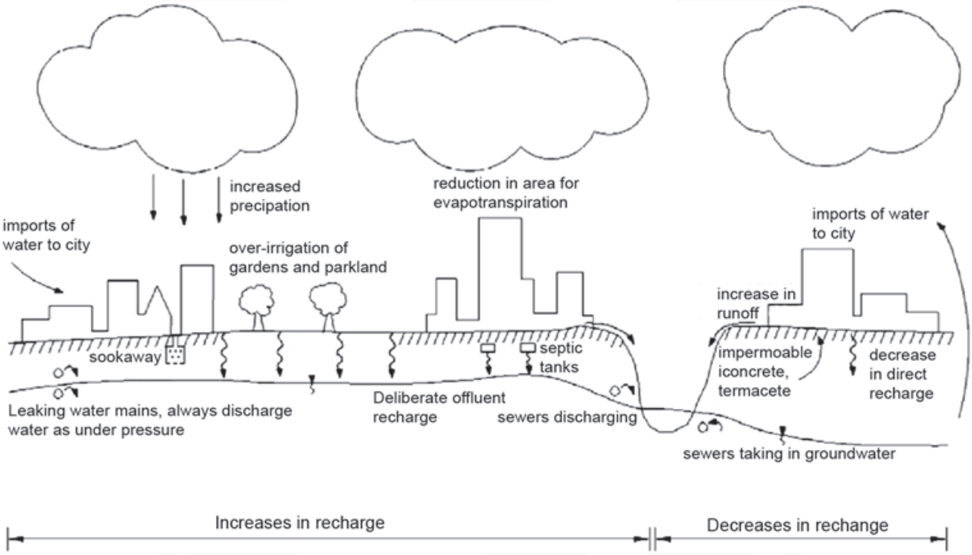


Fig. 1. Water circulation scheme in urban areas [19]

The contribution and influence of anthropogenic elements depends on many factors, such as grade of field coverage with impermeable layer, underground technical pipelines (sewage, water supply, heating, etc.) leakiness scale, or level of groundwater exploitation for communal or industrial purposes [28]. In addition to elements participating in water circulation, other elements of possible significant influence on groundwater-soil conditions also occur in urban areas. Buildings with deep foundations that partition groundwater horizons may disrupt the natural directions of groundwater flow, which can happen not only during their execution (excavation drainage, often simultaneous execution of several buildings), but also during exploitation. Thoughtless action or a lack of urban infrastructure maintenance may result in failure, varying in range and scale.

Elements that influence the groundwater-soil environment in extensively urban areas, include:

- deep foundations,
  - cavity walls,
  - tunnels (excavated using mining techniques and TBM),
- construction drainage (pumping water to and from the soil),
- leaking of underground technical pipelines (water supply, heating, etc.),
- anthropogenic bottom,
- impermeable field coverage,
- drainage systems.

The phrase “anthropogenic bottom” refers to constructional, industrial or communal waste built into the ground to fill the field depressions, e.g. to assure an appropriate construction level. In Warsaw, it was common to construct on ruins buried after the Second World War. The bottom of such material may be of hydraulic conductivity significantly higher than the surrounding material and develop a certain privileged flow pathway or, if of low permeability, may cause flow to be restricted to the groundwater bearing horizon or create a barrier that restricts the water inflow to the soil.

The extent of impermeable layers has a driving influence on the character of urban catchment. The participation of basic processes in the hydrological cycle changes with the spread of solidified (hardened) surfaces (Fig. 2.). Impermeable coverage, compared to direct

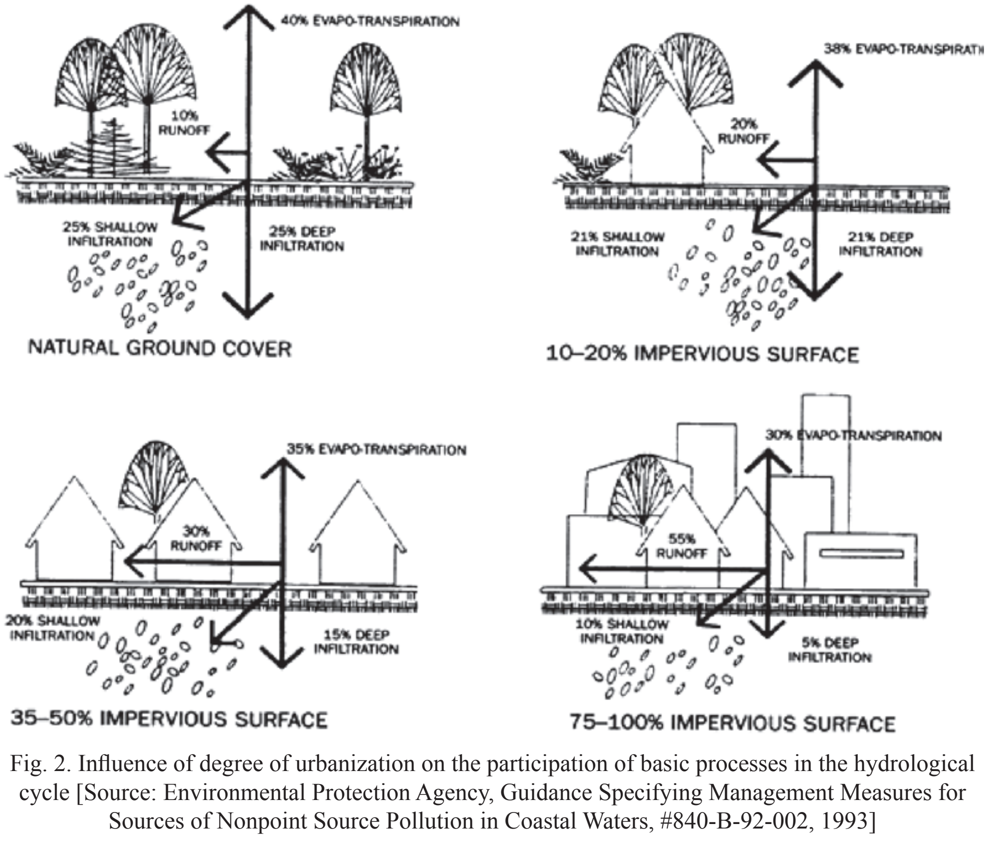


Fig. 2. Influence of degree of urbanization on the participation of basic processes in the hydrological cycle [Source: Environmental Protection Agency, Guidance Specifying Management Measures for Sources of Nonpoint Source Pollution in Coastal Waters, #840-B-92-002, 1993]

infiltration, causes a significant increase in surface runoff. However, a decreased inflow of rainwater to the soil is often compensated for by leakages from underground technical installations (e.g. water supply pipelines). In some cases, water inflow from such leakages may constitute the main source of groundwater supply. Such a situation frequently occurs in ecosystems with low annual rainfall, where water inflow from leaking pipelines can reach 90% of total inflow (e.g. Lima, Peru) [28]. Moreover, uncontrolled outflow of pressurized water, e.g. from a damaged water supply main, may lead to leach of soil and a following local field collapse.

In 2004, a heating pipeline failure occurred, resulting in the collapse of Złota Street in Warsaw. Two cars fell into a hot water filled breach in the asphalt. Another such failure occurred in 2011, when Koszykowa Street collapsed due to leach of soil by water from a damaged water supply main (Fig. 3). Similar damage occurred from infiltration of groundwater into a sewer collector under Krakowska Avenue, causing soil erosion in the collector's surroundings.

Fig. 3. Subsidence on Koszykowa Street in Warsaw (source: TVN24 publication)

Deep foundations are becoming one of the key geo-engineering problems. Urban development results in new investments, usually with a leveled basement, occurring in city centres with dense and often historical infrastructure. Such objects not only influence the surface infrastructure, but also underground facilities like subway tunnels and stations. Urban areas are characterized by high "saturation" in the underground infrastructure, which is often sensitive to displacements due to buildings with foundations at considerable depths. [30] Moreover, deep foundations influence the groundwater flow conditions by partitioning natural flow directions, or through complete change of the water regime due to water pumping from/to the soil (not only during construction, but also exploitation). Damming of water flow or its concentration in between deeply founded buildings may result in the initiation of filtration phenomena in areas of respectively high velocity and hydraulic gradient values. For the soils susceptible to such phenomena (granulometric composition, compaction, flow direction), even a relatively low increase in the gradient may initiate leaching of fine soil grains and, as a result, an increase in soil porosity and decrease in its bearing capacity. In extreme situations, this process may lead to damage or failure of a building founded on such soil.

In some cases, the influence of external factors is so strong that soil degradation occurs regardless of its parameters. In 1998 in Moscow, a soil collapse occurred that caused damage to a two-stage building. (Fig. 4). The collapse occurred when water-saturated sand was removed to a tunnel that was excavated below (Fig. 5). The amount of soil used during repair actions necessary to fill the subsidence was estimated to be over 1000 m^3.

Fig. 4. A building destroyed due to ground uplift from under the foundation to a tunnel executed below, Moscow 1998 [15]

In 2012 in Warsaw, during execution of a tunnel connection for two parts of the subway station Warsaw-Centrum Nauki Kopernik, hydraulic heave occurred at the tunnel front, resulting in flooding and soil inflow into the station platform chamber, in the station western section [11] (Fig. 5). The executed tunnel was localized under an existing tunnel of the Wisłostrada freeway. A vein under the Wisłostrada tunnel occurred due to soil displacement into the station interior (Fig. 6), and tunnel channel constructions underwent displacement (settlement), most probably subsequently wedging at the cavity walls and in dilatations between themselves [9]. The space under the Wisłostrada filled with water to the level of c.a. 2 m under the tunnel slab bottom [24]. The loss of soil from under the Wisłostrada tunnel was estimated to be of c.a. 6500 m^3.

Groundwater related hazards linked to deep foundation execution that may lead to soil displacement are caused by changes in the groundwater table level and filtration processes in the excavation area (Fig. 7). These processes include: flow through leakages in excavation walls, filtration along the contact of wall and soil, filtration below (around) the wall, inflow from a suspended layer to the excavation, as well as changes in groundwater table level due to drainage [30].

Fig. 5. Initial phase of soil liquefaction after the heave of excavation work ceiling [11]

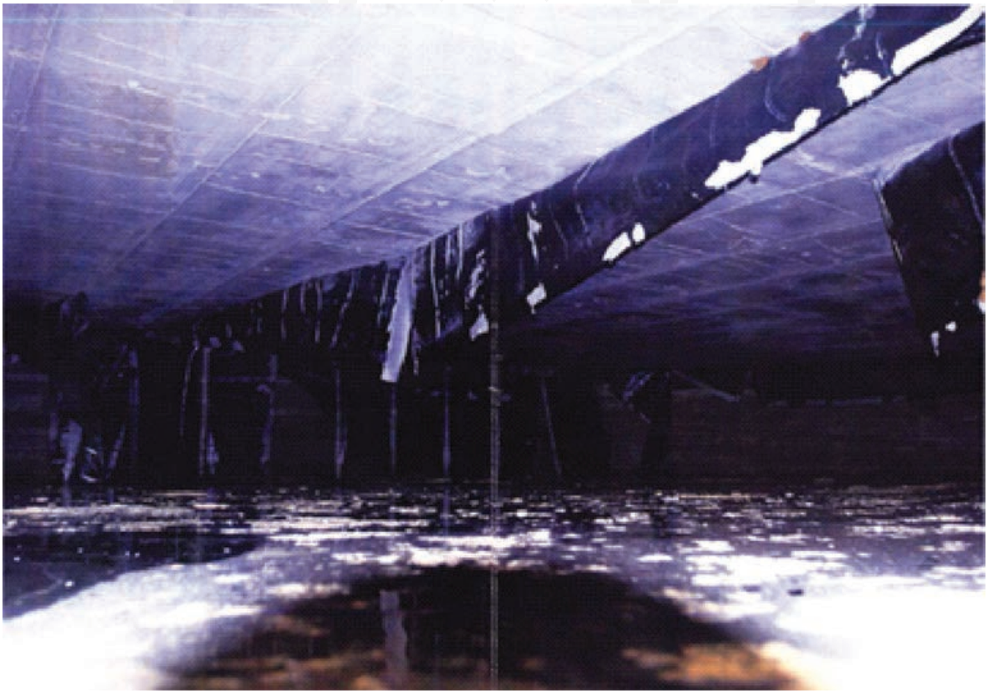


Fig. 6. A view from inside the vein under the Wisłostrada tunnel (materials of AGP) [9]

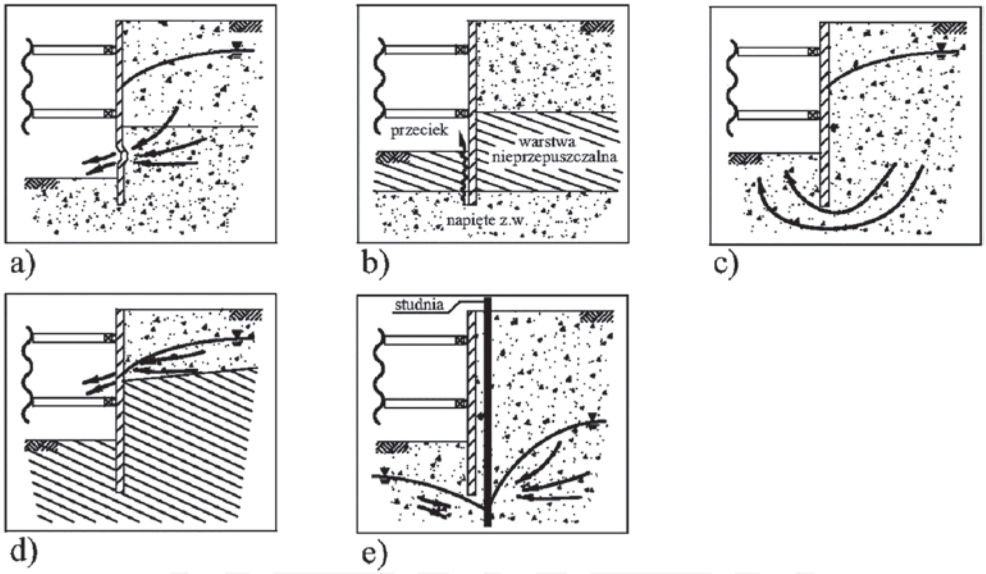


Fig. 7. Groundwater related hazard cases, which may cause changes in the bottom during execution of deep foundations [Clough G., O'Rurke T. 1990]: a) flow though wall leakages, b) flow along the wall and soil contact, c) flow below (around) the wall, d) suspended water inflow, e) drainage-caused flow [30]

The interference of deeply founded buildings with groundwater-soil conditions may result in [30]:

- change in level of groundwater table,
- change in flow direction (sometimes, local direction diversion),
- change in pressure gradient and groundwater flow velocity,
- change in soil parameters (changes of humidity, porosity, suffusion, internal and external erosion, colmatation).

To minimize the negative influence of deeply founded buildings, it is important to execute appropriate design and impact assessment on the groundwater-soil environment during both construction and further exploitation.

2. Suffusion

Suffusion is a phenomenon that belongs to the group of so called filtration deformations. It is based on finer particle or grain removal from the soil or their movement within its mineral structure, due to groundwater flow through that soil [16]. The process may be chemical or mechanical in nature.

Mechanical suffusion is a phenomenon in which soil skeleton elements are under the pressure of flowing water mass, which is referred to as seepage pressure. That pressure mechanically impacts respective elements of the soil skeleton (depending on structure, soil granulometric composition and velocity of filtrating water), causing leaching of soil grains

[5]. Enlargement of soil pores results in an increase in the filtration coefficient and flowing water velocity. The water of higher velocity may move respectively bigger soil grains, causing further development of the suffusion process. An increase in soil porosity decreases its strength and might cause sudden settlement or displacement, or occurrence of channels or hydraulic heave within.

The phenomenon of leaching fine grains from the soil skeleton can progress in various ways, depending on the place of its occurrence in the soil. Those distinguished are: internal erosion, occurring within a certain type of soil; external erosion (also known as backward erosion), occurring in the near-surface zone of bottom and at the contact surface between two different soil layers, when water flow direction is perpendicular to that contact surface; as well as contact erosion, occurring at the contact surface between two different soil types when the water flow direction is parallel to the contact surface (Fig. 8) [29].

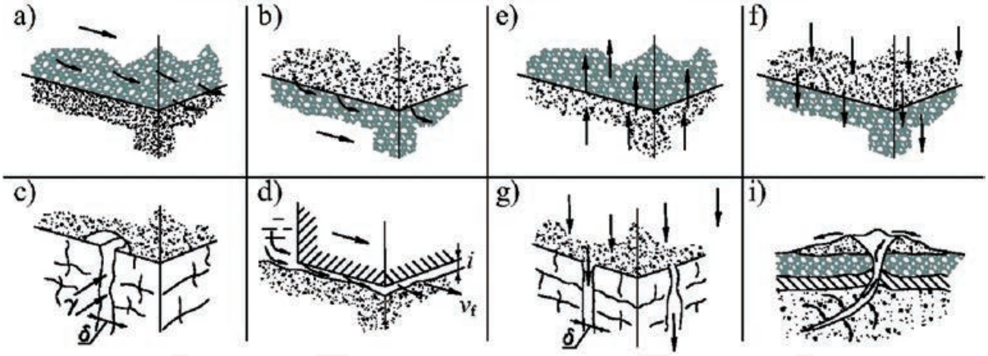


Fig. 8. Forms of soil medium destruction by filtrating water: a) b) c) d) contact erosion, e) f) g) external erosion (backward erosion), i) hydraulic heave [30]

To determine the susceptibility of soil to suffusion, geometrical or hydraulic criteria may be employed. Geometrical criteria refer to soil grain size and the granulometric composition. From the geometrical criterion perspective, two conditions must be met for suffusion to occur:

- the fine grain size in the soil must be smaller than the soil skeleton material pores (a fine soil particle/grain is understood as a grain of diameter smaller than 0.075mm and will be referred further to as such) [4], therefore soil with equal grains will not be susceptible to suffosion, as the dimensions of free spaces in between soil particles are smaller than the size of soil skeleton grains, even if distributed more loosely [7],
- the soil must contain fine particles amount smaller than is necessary to fill the spaces between the coarse, skeleton-forming particles (in the case of finer particle occurrence, the coarse particles will be “borne” in a skeleton of fine-grained soil and suffosion will not occur) [4].

Moreover, for suffusion to start, the forces causing the leach of soil particles must overbear the forces of soil resistance – the hydraulic criterion. Grain resistivity forces depend on the soil type (cohesivity), resulting mainly from their weight and interactions with other particles (granulometric composition, shape of grains, compaction). The velocity of water flowing through must reach the appropriate value (critical velocity), or an appropriately high hydraulic gradient must occur (critical gradient). This dependence is often referred to as local (hydraulic) gradient difference, described as the critical value gradient for a given soil.

The geometrical criterion is based on soil granulometric composition analysis (grain size distribution curve). The soil is potentially unstable and susceptible to suffosion if its poorly graded or gap- graded (i.e. being of leap character – lack of medium diameter grains in the soil), or if it mainly consists of coarse grains with certain restricted percentile content of fine particles.

Many considerations on the geometrical criterion are still based on Terzaghi’s criterion, applied in the design of reverse filters (securing the construction against suffusion). According to this criterion, the following dependencies must be met for erosion not to occur:

$$D_{15}/d_{85} \leq 4 \tag{1}$$

and

$$D_{15}/d_{15} \geq 4 \tag{2}$$

where:

D_{15} – grain diameter of filter soil, whose content, including finer grains, is of 15%,

d_{15}, d_{85} – grain diameter of protected soil, whose content with finer grains is respectively of 15% and 85%.

The seepage pressure refers to hydraulic gradient, which in turn is related to the hydraulic forces that cause the movement of fine soil grains [4]. Terzaghi defined a critical hydraulic gradient for vertical flow, for a scenario of seepage pressure value exceeding the watered bulk density of soil skeleton and causing loss of stability in soil [14]:

$$i_{kr} = (1-n)\cdot(1-\rho) = \frac{\rho-\rho_w}{\rho_w} \tag{3}$$

where:

n – porosity,

ρ – soil volumetric density,

ρ_w – water volumetric density.

The value of the critical hydraulic gradient defined by the equation above, is equal to 1. For this value, the soil undergoes liquefaction. However, critical hydraulic gradients related to suffusion are often lower than those determined employing the equation above [14].

3. Numerical analysis

One of the possible means to evaluate the impact of deep foundations on groundwater-soil environment and the possibility of suffusion is numerical calculations. Such analysis has been performed for a zone in between Puławska, Dolna, Konduktorska and Belgijska streets, in the area of Morskie Oko Square in Warsaw (Fig. 9). The calculations were performed to investigate the possible influence of deep foundations on groundwater-soil conditions in the investigated area, through analysis of the changes in directions, velocities and gradients of water flowing through. The geological setting was prepared in numerical form (GIS). The model was built in the HydroGeo Builder software and subsequently the necessary parameters and boundary conditions were determined in Visual Modflow, with subsequent execution of the model.

The goal of the execution of the model was to investigate the deep foundation's influence on groundwater-soil conditions through:

- analysis of groundwater table changes,
- analysis of water flow directions,
- analysis of possible periodic humidification causes for surrounding buildings,
- analysis of groundwater gradients and flow velocities,
- identification zones of soil being potentially at risk of suffusion.

Fig. 9. The new deep foundation buildings are surrounded by a black line. The striped field depicts the area of existing buildings whose basements are damp [map source: geoportal.gov.pl]

The restriction of the model depth below ground level was assumed on the boundary of Pleistocene sediments, i.e. on the ceiling level of Pleistocene clays (on average, at 80 m b.g.l.). Quaternary deposits occurring in the investigated area are typical for continental glaciations.

The quaternary groundwater bearing horizon occurs in the whole city area. The high plain part of the investigated area breaks into the eastern and western part, from which the first is of multi-layer groundwater bearing horizon and the latter has one groundwater bearing horizon, mostly occurring in the eastern part. The two groundwater bearing horizons, locally three on the south-east, remain in hydraulic contact, with their possible transformation into one layer towards north. The quaternary groundwater bearing horizon generally lacks isolation from the surface.

To allow numerical modelling, conceptual soil conditions had to be developed, with certain assumed groundwater conditions. After analysis of the known geological cross-sections, the one near Belgijska street was selected (recommended by PGI-NRI) (Fig. 10).

As no water outflow from the scarp was observed in the investigated area (water-head area) [32, 33] it was assumed that hydraulic connection must exist between the surface and the sands overlaying the high plain, as well as these sands and the valley sands (PGI-NRI, ITB). Such a state entails the existence of hydrogeological windows, i.e. areas lacking in impermeable layers, which results in direct filtration. Moreover, a landslide occurred in the investigated area in the past, which could have led to mixing of soil layers. Therefore it was stated that permeable soils must occur in the area depicted with black line on Fig. 10.

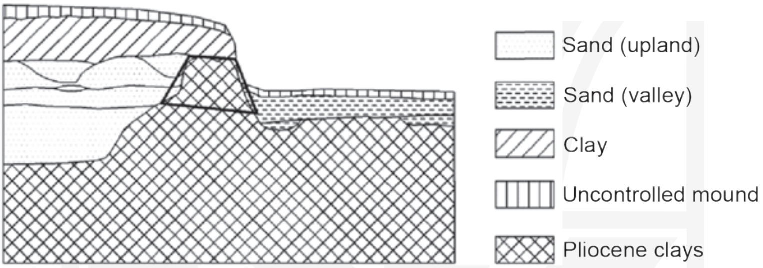


Fig. 10. A sketch geological cross-section of the investigated area [PGI,32,33]
The black line surrounds soil area of changes in filtration coefficient value, depending on the numerical calculations variant under consideration

The planar placement of permeable layers was changed in subsequent variants. An area was established at the scarp, in the contact zone of high-plain and valley sands, for which zones of changing filtration coefficient were determined (depending on calculation variant, the flow through the zone was enabled or disabled). The filtration coefficient value assumed for the permeable zones was of $1\cdot10^{-4}$ m/s, whereas for impermeable layers it was given at $1\cdot10^{-6}$ m/s.

The groundwater level was established on two model boundaries (left and right), according to the natural groundwater flow (from the scarp towards the Vistula river). Initial groundwater level was determined based on the map (Fig. 11) from PGI-NRI, depicting mean, multiannual values.

The average annual rainfall in Warsaw was taken at the level of 500mm/year. Filtration index was assumed at 0.25. On that basis, the determined amount of rainwater infiltrating to the soil was of 125mm/year.

Calculations in Visual Modflow were executed for five variants, varying in planar placement of changing filtration coefficient zone.

The building foundation depth was assumed according to the scheme in Fig. 12 below:

- new, deeply founded buildings (marked on fig. 10 with red line): 10 m b.g.l.,
- old buildings, with basements rising above the ground level: 2.5 m b.g.l. (two buildings by Ludowa Street),
- old buildings with basements below the ground level: 3.0 m b.g.l.,
- old buildings without basements: 1.5 m b.g.l.

Calculations for each variant were executed in two versions:

- Version 1 – taking deep foundation buildings into account,
- Version 2 – disregarding deep foundation buildings.

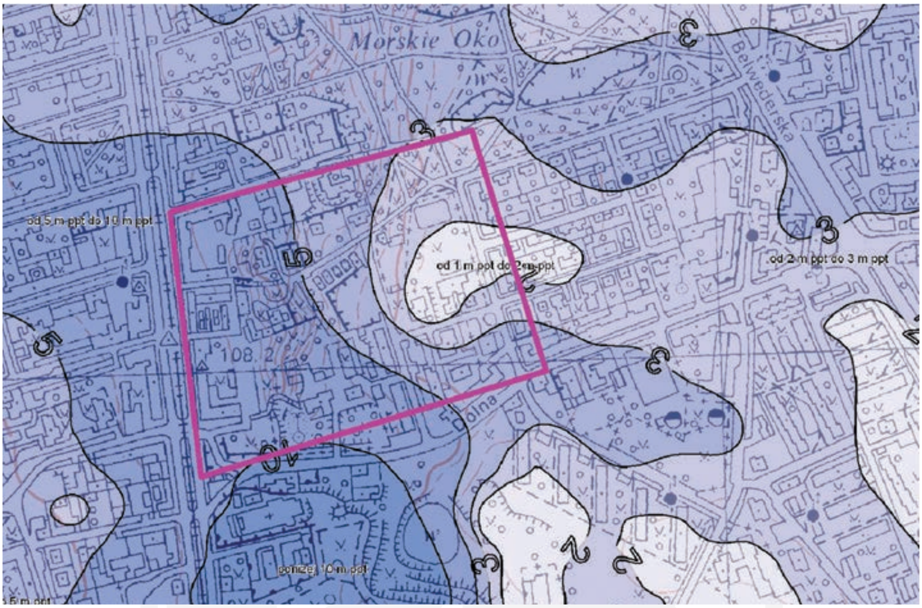


Fig. 11. The first groundwater table – multiannual average state [PGI-NRI]
The boundaries of the area investigated are marked with pink line. Isolines (black) depict the groundwater table depth below the ground level

To diversify the building foundation depth, the model space was divided in-depth into two layers. The foundations of deeply founded buildings partition the whole model height, as the cavity walls used for their construction were dipped into the upper surface of the impermeable layer, which constitutes the lower model boundary.

This paper presents the results for one variant (Fig. 14 to 16). Figures 14 and 15 represent the results for the version taking deep foundation buildings into account, whereas Fig. 16 – for the version without. The arrows visualize the velocity vectors of water flow. Also, groundwater level isolines (5m step) are marked, whereas the thick black line depicts areas of changing (depending on variant) filtration coefficient values. As can be observed, including deep foundation buildings into the model caused change in the direction of water flow. Due to the narrowed water outflow possibilities from the scarp towards the Vistula River and the partitioning of natural flow, an increase in gradients and flow velocities occurred, compared to the variant disregarding the deep foundations.

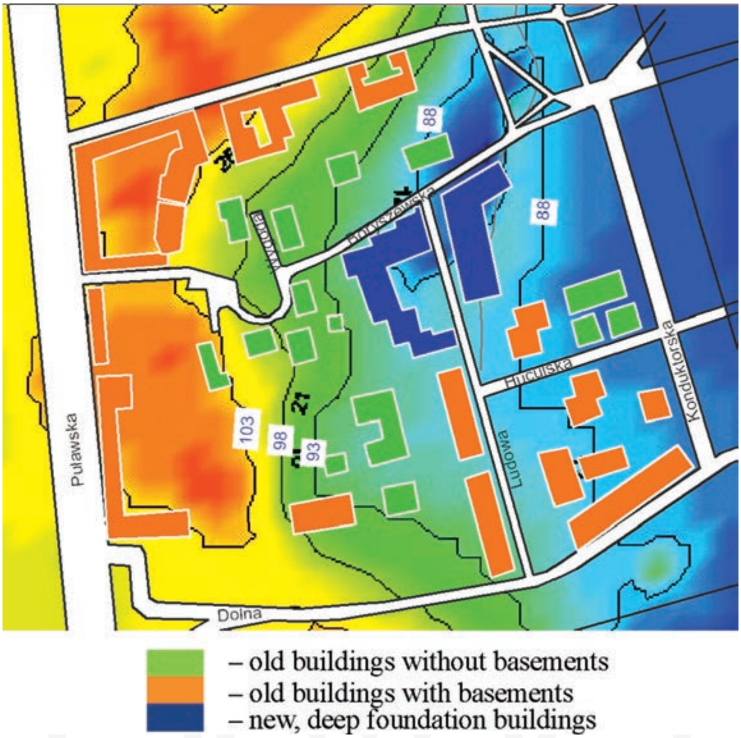


Fig. 12. Situational plan – upper model surface generated in HydroGeoBuilder software, with introduced localization of buildings and roads; levels are given in m a.s.l.

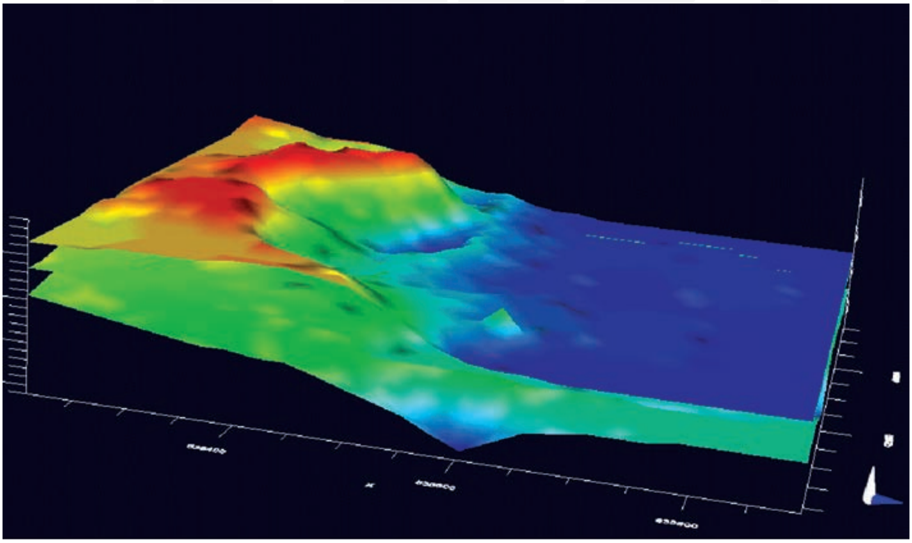
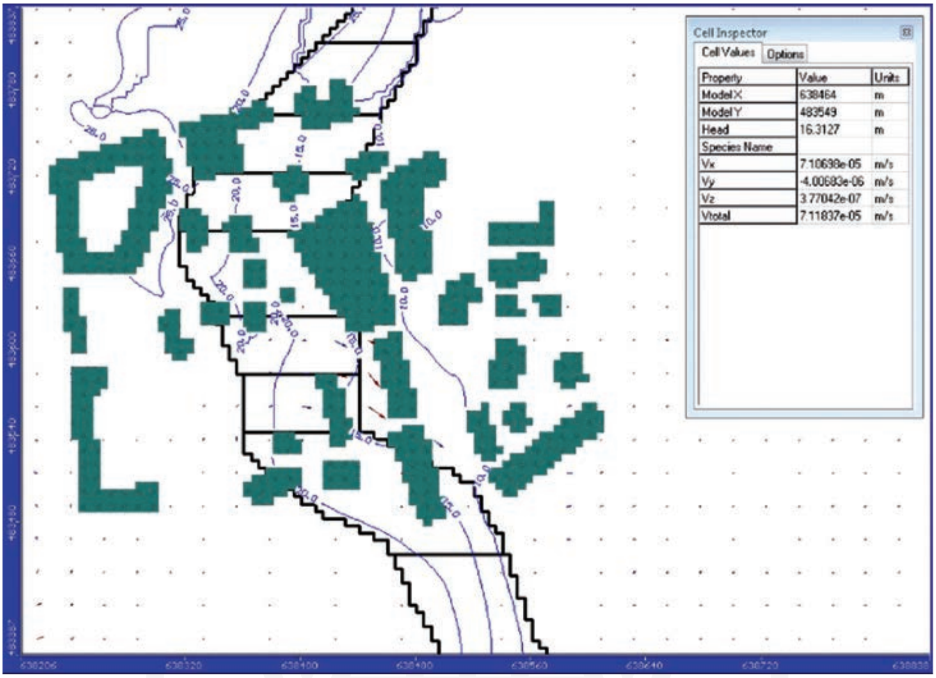
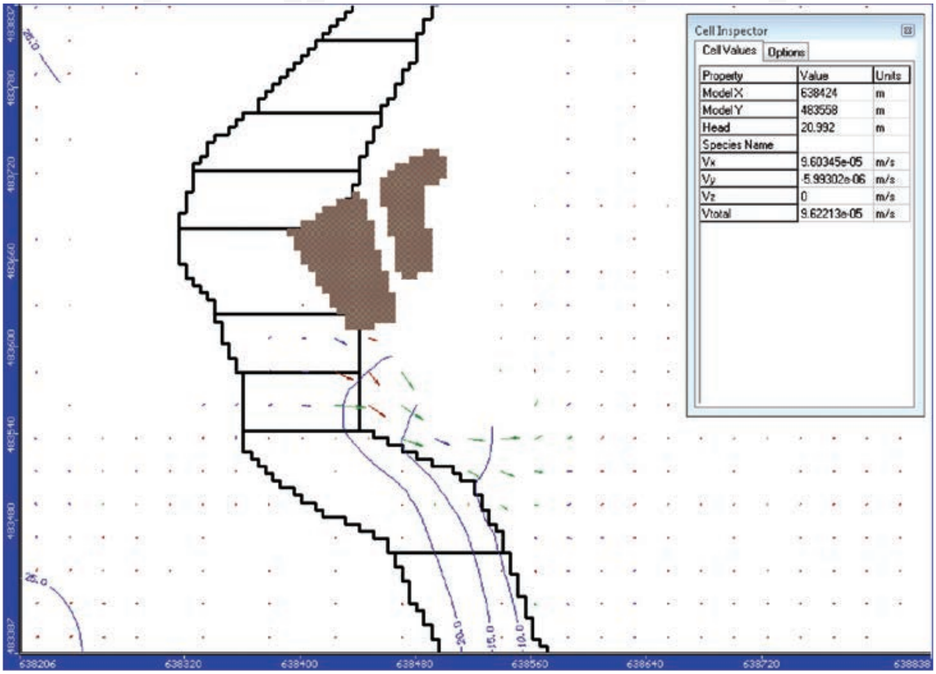


Fig. 13. A 3D view of the modeled area from Dolna Street perspective (HydroGeoBuilder)



Property	Value	Units
Model X	638464	m
Model Y	483549	m
Head	16.3127	m
Species Name		
Vx	7.10698e-05	m/s
Vy	-4.00683e-06	m/s
Vz	3.77042e-07	m/s
Vtotal	7.11837e-05	m/s

Fig. 14. Results for variant III – Version1 / Layer1



Property	Value	Units
Model X	638424	m
Model Y	483558	m
Head	20.992	m
Species Name		
Vx	9.60345e-05	m/s
Vy	-5.99302e-06	m/s
Vz	0	m/s
Vtotal	9.62213e-05	m/s

Fig. 15. Results for variant III – Version1 / Layer2

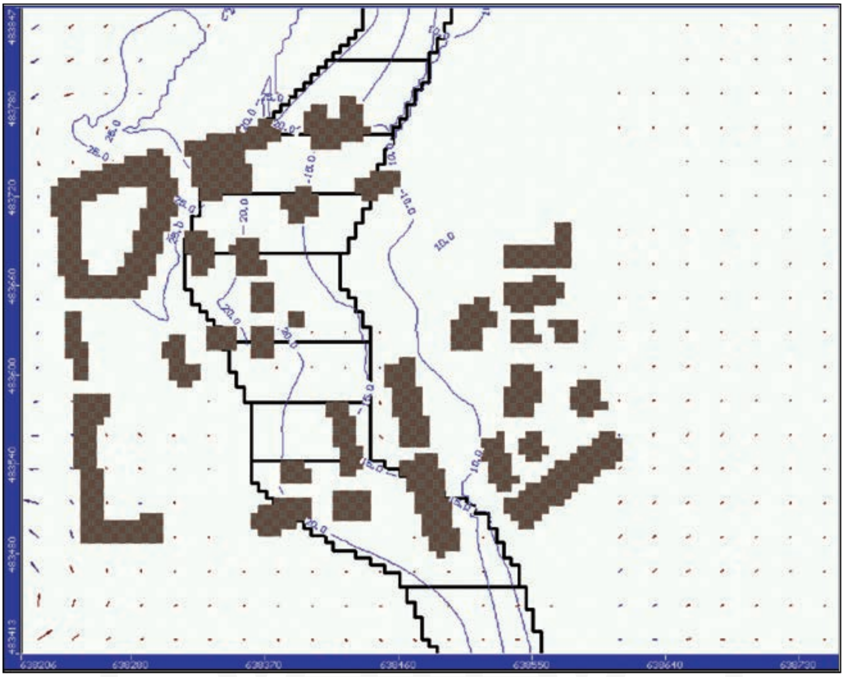


Fig. 16. Results for variant III – Version2 / Layer1

After the numerical analysis for all the variants, it was stated that there was noticeable influence of deep foundation buildings occurs on groundwater flow directions, velocity and gradient values, as well as groundwater table level. The deep foundation and narrowing of permeable space on the contact between high-plain and valley sands, caused flow concentration and uplift of the groundwater table.

In some calculation variants, the output gradients reached values considered sufficient to initiate suffusion under favourable geological conditions [14].

Following the analysis of possible causes for building basement humidification by Huculska Street, additional elements were pointed out that may contribute to periodic or constant uplift of groundwater level except rainwater infiltrating naturally in the area:

- periodic groundwater table uplift in the given area can be caused by rainwater exfiltrating from a leaking rain-pipeline or, if a field downslope occurs towards these buildings – additional water infiltrating in the area, originating from surface runoff,
- additional factor for the potential increase in basement humidification are, as mentioned above, leaking water pipelines, water from which exfiltrates to the soil constantly, supplying the groundwater bearing horizon. The condition of water and sewage infrastructure in the described area should be verified in the field,
- after the performance of numerical modelling it was observed that groundwater table uplift occurred in some variants after execution of deep foundation buildings, being additionally strengthened by narrowed groundwater outflow from the high plain towards the Vistula river. The above may be the next factor influencing the humidification of basements after rainfall, as an element causing constant uplift of the groundwater table.

4. Summary

In 1946, Terzaghi compared the importance of means to be assured by a designer to prevent external suffusion to the importance of anti-corrosion means in steel constructions, or means protective against biological degradation in wooden constructions [30].

Sufussion and external erosion issues have been addressed since 2004 by the ICOLD working group (International Commission of Large Dams). The final stage of Group work is the preparation of a report – a set of data and practical guidance to prevent internal erosion. The first part of the report was edited in 2013 [30].

In the document Eurocode 7 (PN-EN 1997-1:2008), bottom deformations that may result in loss of stability were raised up to a range of critical soil state, which justifies the necessity of in-depth analysis for that phenomenon. However, assessment criteria for suffusion of soils were not determined in the abovementioned standards. Hence, developing adequate tools and determining appropriate action schemes for soil analysis of this phenomenon are of crucial importance in the short term. Suffusion is now not only considered a marginal phenomenon occurring in the soil, but a real hazard deciding on ground stability.

Taking the aforementioned, it seems necessary that Warsaw, as a developing urban agglomeration, undergo a thoroughgoing analysis to assure construction safety not only for existing buildings, but also for objects currently planned or in construction. Performing numerical analysis for the urban part is necessary, with a set of laboratory tests aimed at determining the susceptibility of soils in Warsaw to suffusion. Based on the numerical and geotechnical research given above, adequate tools can be determined that take geometrical and hydraulic criteria for soil suffusion into account, with simultaneous consideration of effective stress influence. The research may lead to identification of areas in central Warsaw that are particularly at risk of changes in groundwater-soil conditions due to deep foundations. Establishing appropriate criteria, assisted by numerical calculations at the investment planning & design stage, would appear to be a necessary element in identifying and undertaking appropriate preventive measures to eliminate the negative impact of suffusion. Such action will ensure the sustainable and safe development of urban areas.

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