Modeling the damming effect of pile foundations (Tomsk city)

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Abstract. The authors have considered the impact of pile foundations on the structure of filtration flows in the conditions of urban development. Hydrodynamic simulation methods have shown that a groundwater level rise might occur due to the damming effect that can be created by pile fields in semipermeable rocks. This phenomenon can intensify anthropogenic waterlogging processes in urbanized territories.

1. Introduction

The interest in studying the damming effect of pile foundations in urbanized territories is caused by the need to forecast changes in hydrogeological conditions under the influence of the construction development of the geological environment. The underground hydrosphere reacts to man-induced impact most dynamically. Directional groundwater level rise, i.e. waterlogging, occurs as the result of distortions in the water regime and balance of territories. This complex hydrogeological and engineering-geological process distorts the required conditions of construction and operation of specific structures and demands the application of protective measures. Waterlogging caused by different reasons is registered in many cities of the world in Brazil, Great Britain, Germany, Egypt, India, China, USA, France, etc. Tomsk is not an exception in this respect. We have been studying the problem of changes in the hydrogeological conditions in the territory of this Siberian city for a long time [1- 4].

It is found that the hydrogeological conditions of the city territory are predetermined by the peculiarities of a geological structure. There are two structural levels in the cross section. The foundation is composed by the compact dislocated fractured rocks of the Paleozoic era that is covered by the loose sand-clay deposits of the Meso-Cenozoic age. The role of the separating layer between them is played by the clay weathering mantle of the Cretaceous-Paleogene age characterized by varying thickness and composed by seat clays. The dense rocks of the foundation contain fracture, predominantly head waters that are partially used for the utility and drinking water supply of the city. The loose rocks of the sedimentary mantle are characterized by almost horizontal bedding, in compliance with which one can identify aquifers on the basis of the lithostratigraphic principle. The special conditions of groundwater occurrence are typical of the complex of alluvial deposits of the rather well-developed hydrographic network. The groundwater of the upper part of the hydrogeological section is exposed to the strongest anthropogenic impact and, in its turn, has a significant influence on the living environment of the city. The groundwater is recharged locally due to the infiltration of precipitated waters and leaks from water-bearing utility systems [1, 2, 3, 5, 6].

2. Hydrodynamic simulation

The need to apply mathematical simulation methods to study changes in the hydrogeological conditions under the influence of anthropogenic waterlogging processes in local areas is explained by the complexity of schematizing and assigning boundary conditions within the framework of analytical solutions to forecast geofiltration problems [7,8,9]. Within the territory of the city, waterlogging development schemes are difficult to forecast due to the damming effect of pile foundations [7].

As the interaction between groundwater and an artificial barrier implies the distortion of flow lines and forming a complex shape of filtration flow, it is expedient to use numerical methods of hydrogeological condition simulation to assess changes in levels. In this case, it is offered to perform simulation with a multiple-path approach for a local area having a standard size and typical conditions of a filtration section when locating pile foundations of different shapes within the boundaries of the area under study [6, 7].

We have used the ***Processing Modflow*** software complex as a tool for simulating local models. The peculiarity of this programming environment is a simplified user interface that has only the essential set of capabilities to prepare initial data with due account for the immediate setting of filtration parameters and boundary conditions for the space of the finite-difference grid. Along with that, the software complex uses ***modflow96,*** which is the core of the most popular hydrodynamic simulation programs, such as ***Groundwater Modeling System*** or ***Visual Modflow***.

For local models, we have used a square finite-difference grid with the permanent size of 21×21 computational cells. The same size of the cells (10×10 m) is selected, on the one hand, to minimize the number of computational cells and, on the other hand, to have a possibility to approximate the shape of file foundations satisfactorily [8,9].

All local models have a three-layer structure to the depth of 21 m by analogy with the structure of typical filtration sections. However, the model implies the more exhaustive division of the water-saturated and semipermeable layers to set water-bearing utility systems at the depth of 3 m and piles having the length of 9 m from the surface. Thus, to simulate the conditions of interaction between a typical filtration section and a pile foundation, it is offered to use a five-layer numerical model where layers 1 and 2, 3 and 4 pairwise have similar filtration parameters, as they represent the same lithologic layer of the cross section (Figure1).

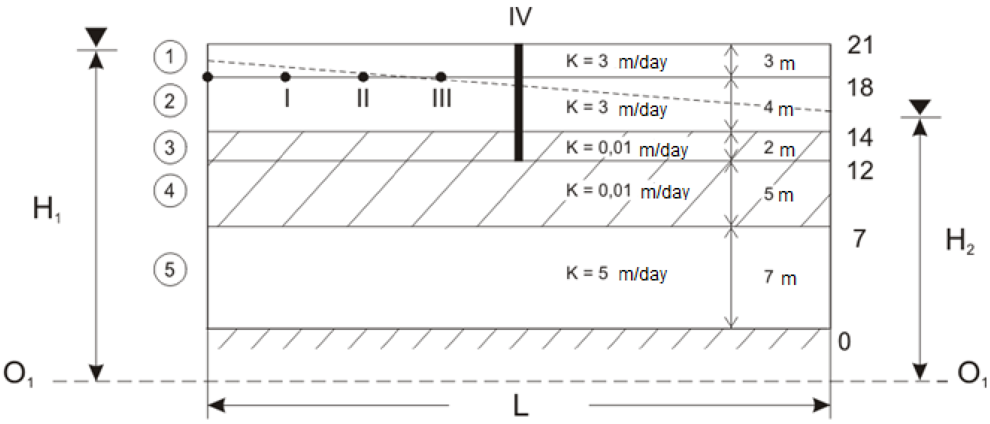


Figure 1. Boundary conditions in the numerical model of a typical filtration section:
1-5 – number of layers in the numerical model; I-III – configuration of the linear source of additional recharge at different distances from the pile field; IV – pile field acting as an impermeable groundwater cutoff wall; H1 and H2 – heads on the boundary of the filtration area; L – filtration area length (square numerical model size); ▼ – groundwater level.

Constant heads are set on the opposite boundaries of the filtration area, filtration heterogeneity is restricted by the different degrees of permeability of the layers, spatial heterogeneity is absent.

To register levels, we have set observation wells to ensure that there is a possibility to compare groundwater levels in different layers of the numerical model and in terms of the direction of a filtration flow (Figure 1). The observation wells are located on a single common beam pairwise in each layer of the numerical model. Their location is selected in such a way that two control points are before the filtration barrier on the side of the recharge area, and two more points of observation are behind the pile field on the side of the discharge area. Such an approach allows comparing groundwater levels in the conditions of natural and distorted filtration flows for similar points. In this case, it is noteworthy that the quantitative measure of anthropogenic impact might be the difference between the reference level surface of groundwater in the current simulation option and the basic surface taken as the natural field of heads obtained in the first simulation option without the impact of the damming effect.

Initial heads are determined on the model as the result of solving a stationary problem for the filtration area without regard to urban development (piles are absent).

The calculated values of the heads are used for the comparative assessment of the influence of the geometrical configuration of impermeable barriers on the structure of the filtration flow.

3. Hydrogeological conditions

To predict the development of anthropogenic temporary waters, we have schematized the upper portion of the cross section to the averaged depth of the area of interaction between aquifers and engineering systems and the geological environment. We have determined typical cross sections and mapped them in the area of the city [3, 4, 7]. In the area of the city, we have localized filtration areas with the single-, two- and three-layer structure of filtration sections that differently react to the supply of an additional infiltration recharge. The analysis of the spatial arrangement of these types of filtration sections has allowed zoning the territory of the city and qualitatively characterizing it in terms of the degree of potential waterlogging.

We have presented the materials of hydrogeological studies conducted in different years in the form of a multilayer electronic map. It gives a possibility to use them within the framework of comprehensive analysis with additional updated information. We have suggested a concept of a municipal geographic information system for Tomsk. It allows using the address of an object to determine the qualitative and quantitative characteristics of the hydrogeological environment (type of filtration section, additional infiltration recharge determined on the basis of the averaged value of per-capita water consumption for this portion of the territory, depth of temporary waters and groundwater). It allows promptly assessing the degree of the potential waterlogging of a specific object.

Forecasting the influence exerted by the pile foundations of buildings on the structure of filtration flows is essential for the territory of Tomsk. First, the analysis of hydrogeological conditions shows that the upper portion of the cross section composed by the bedded formation of semipermeable loose deposits tends to develop anthropogenic waterlogging in case of excessive additional infiltration recharge. Second, overmoistening is caused by the non-ideal conditions of the relatively old water-bearing utility systems. Third, in the conditions of the current urban development, the prevailing type of civil buildings foundation is pile foundation with the length of piles usually exceeding 9 meters that forms practically impermeable barriers to natural filtration flows. The maximum effect of this impact on groundwater is expected in transit zones.

The analysis of the developed areas of the city territory with high-rise modern buildings that drastically differ from the districts with private houses allows systematizing the planned configuration of pile foundations for the quantitative assessment of the damming effect. We suggest six main shape-based types of pile foundations in plan view in terms of their impact on natural filtration flows (Figure 1).

Due to the limited range of the typical shapes of pile foundations in plan view there is a whole family of computational models in case of different orientations of foundation contours in relation to the direction of the filtration flow (Figure 2). Their diversity grows with the joint inter-quarter arrangement of single-type or different-type foundations.

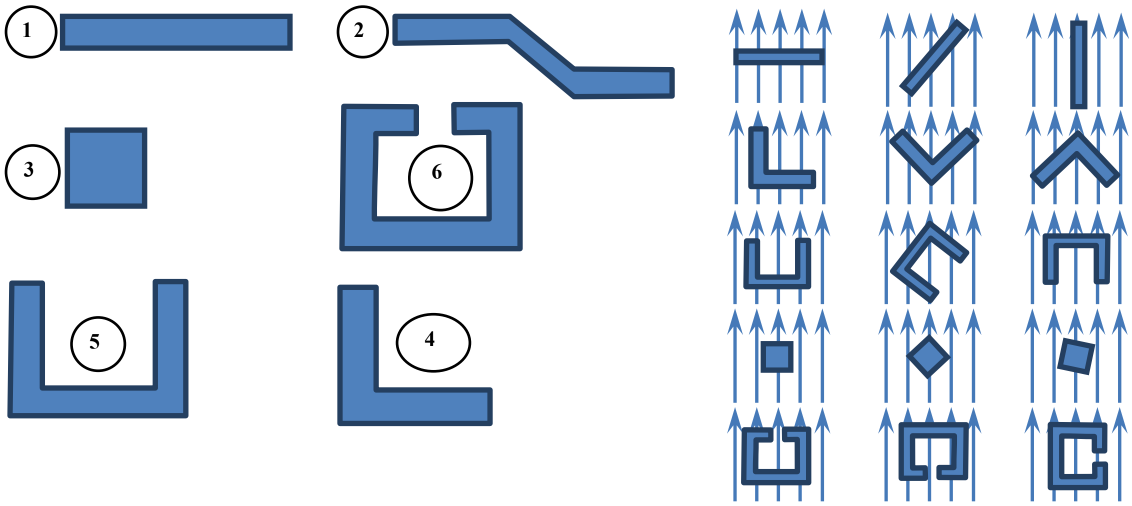
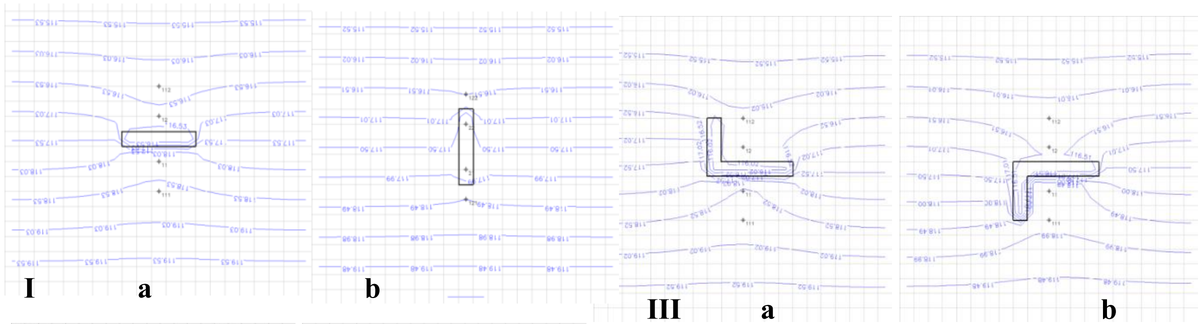


Figure 2. Shape-based types of pile foundations in plan view: 1 – linear; 2 – linear with peculiarities; 3 – isometric continuous; 4 – L-shaped; 5 – U-shaped; 6 – closed U-shaped foundation and their orientations vs. the direction of a natural filtration flow.

4. Results and discussion

For illustrative purposes, Figure 3 presents the results of the numerical simulation of the influence exerted by specific types of pile foundations.



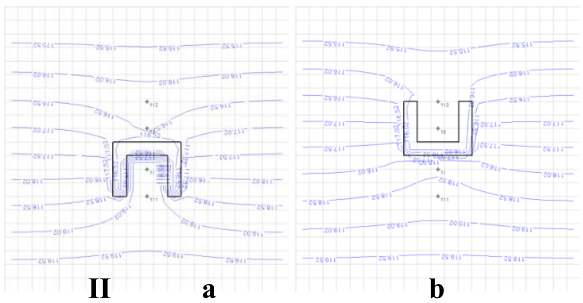


Figure 3. Solving stationary problems of assessing the impact of different types of pile foundations on the structure of a filtration flow: I – linear type (*a* – long side against the flow; *b* – short side against the flow; II – U-shaped foundation (*a* – protrusion against the flow; *b* – protrusion along the flow); III – L-shaped foundation (*a* – protrusion against the flow; *b* – protrusion along the flow).

To be definite, the model arrangement of the hydroisohypses is shown for the second layer of the model located above the surface of the separating semipermeable horizon.

It is possible to perform the quantitative assessment of damming effect manifestation by comparing the structural plans of hydroisohypses for a distorted filtration flow in different typical conditions or by comparing heads for observation wells (Table 1). To obtain more credible comparative assessment results, we have used the fixed spatial arrangement of observation wells for all simulation options, including the reproduction of a natural head field.

Table 1. Model values of heads in observation wells.

Well No.	No piles	Shaped-based types of pile foundations in plan view							
		linear		U-shaped		L-shaped			
		Length against the flow	Length along the flow	Protrusion against the flow	Protrusion along the flow	Protrusion along the flow	Protrusion against the flow	Vertex against the flow	Vertex along the flow
11	117.87	118.40	116.96	119.08	118.49	118.54	118.77	117.80	119.20
12	117.13	116.60	116.96	116.51	115.92	116.23	116.46	116.00	116.46
21	117.86	118.39	116.12	119.07	118.48	118.53	118.76	117.36	119.20
22	117.12	116.60	115.94	116.51	115.92	116.23	116.45	116.00	116.40
31	113.58	113.82	113.91	114.08	113.86	113.89	113.97	113.87	114.02
32	113.20	112.87	113.90	112.82	112.43	112.64	112.79	112.49	112.81
41	111.58	111.58	111.58	111.58	111.58	111.58	111.58	111.58	111.58
42	111.27	111.27	111.27	111.27	111.27	111.27	111.26	111.26	111.26
51	111.15	111.15	111.15	111.15	111.15	111.15	111.15	111.15	111.15
52	110.86	110.86	110.86	110.86	110.86	110.86	110.86	110.86	110.86
111	118.37	118.65	118.50	119.09	118.72	118.76	118.90	118.85	119.22
112	116.63	116.35	116.50	116.28	115.91	116.10	116.24	115.94	116.22
121	118.36	118.64	118.69	119.08	118.72	118.75	118.89	118.84	119.21
122	116.63	116.35	116.30	116.27	115.91	116.10	116.24	115.94	116.18
131	113.63	113.76	113.65	113.90	113.79	113.81	113.85	113.82	113.87
132	112.74	112.57	112.59	112.53	112.26	112.40	112.51	112.29	112.51
141	111.73	111.73	111.73	111.74	111.74	111.74	111.74	111.74	111.73
142	111.02	111.01	111.02	111.01	111.01	111.01	111.01	111.01	111.00
151	111.34	111.34	111.34	111.34	111.34	111.34	111.34	111.34	111.34
152	110.6	110.66	110.66	110.66	110.66	110.66	110.66	110.66	110.66

The results of the comparative assessment of groundwater levels for observation wells are given in Table 2.

Table 2. Stratigraphic throw of groundwater levels on different sides of a filtration barrier (for the second model layer).

Layer	Well No.	Shaped-based types of pile foundations in plan view							
		linear		U-shaped		L-shaped			
		Length against the flow	Length along the flow	Protrusion against the flow	Protrusion along the flow	Protrusio n along the flow	Protrusion against the flow	Vertex against the flow	Vertex along the flow
2	21	0.53	-1.75	1.20	0.62	0.67	0.89	-0.50	1.33
	22	-0.53	-1.18	-0.62	-1.20	-0.89	-0.67	-1.13	-0.73
	121	0.28	0.33	0.72	0.36	0.39	0.54	0.48	0.86
	122	-0.28	-0.33	-0.36	-0.72	-0.53	-0.39	-0.69	-0.45
Stratigraphic throw		1,06	1.06	0.66	1.82	1.82	1.56	1.56	1.61

Note: the color marking shows cells used for calculating the stratigraphic throw with due account for the pile foundation shape.

The simulation results allow making substantiated conclusions about the peculiarities and differences of changes in hydrogeological conditions that accompany construction of buildings on different types of pile foundations.

In the conditions of a three-layer filtration hydrogeological section, when the depth of the pile field does not exceed the bounds of semipermeable separating layer, no changes in the groundwater level occur in the lower aquifer. This fact is testified to by the absence of difference in heads in the conditions of natural and artificial flows for all types of pile foundations (wells Nos. 51, 52, 151, 152).

The peculiarity of damming effect is not only an increase in the groundwater level from the side of oncoming flow, but also a simultaneous drop in the levels behind the impermeable barrier vs. natural conditions (Table 2). Almost in all the cases under study, the amplitude of such changes is over one meter with the maximum value of over two meters. Such types as U-shaped and L-shaped foundations have the strongest impact on the filtration flow among all shapes of pile foundations under study. They can cause the growth in the level by 1.2 and 1.3 m, respectively, even in permeable rocks with the filtration coefficient of 3 m/day. The simulation results show that a predicted level rise can be decreased by almost 50% down to 0.62 m and 0.67 m, respectively, only by choosing the optimal orientation of the pile field vs. the direction of filtration flow (Table 2).

5. Conclusion

The simulation materials allow concluding that filtration barriers with a rectilinear axis in plan view have the minimum impact on the structure of filtration flow. The maximum growth in groundwater levels can be caused by filtration barriers with one and two changes in the direction of their longitudinal axis at the angle of 90 degrees forming a semi-closed shape.

These changes can only give a general idea about the possibilities of predicting changes in groundwater levels. We should note that we can significantly change the assessments of groundwater level rise by taking additional recharge into consideration. However, these examples are quite sufficient to substantiate the need for taking into account the regional direction of filtration flows at all stages of area planning for urban quarters.

References

[1] Pokrovsky V D, Dutova E M, Nikitenkov A N, Kuzevanov K I and Pokrovsky D S 2015 Methodological approaches to the assessment of the degree of drainability of the urbanized territories *Modern problems of science and education* 1 URL:http://www.science-education.ru/125-20130

[2] Pokrovskiy V, Pokrovskiy D, Dutova E and Nikitenkov A 2014 The research underflooding processes of architecture monuments on the territory of tomsk with using gis-technology. *Paper presented at the International Multidisciplinary Scientific GeoConference Surveying Geology and Mining Ecology Management, SGEM*, 935 – 941.

[3] Pokrovsky V, Pokrovsky D, Dutova E, Nikitenkov A and Nazarov A 2014 Degree of areal drainage assessment using digital elevation models *Paper presented at the IOP Conf. Ser.: Earth Environ. Sci.* **21**(1)

[4] Pokrovsky V, Dutova E, Kuzevanov K, Pokrovsky D and Nalivaiko N 2015 Hydrogeological Conditions Changes of Tomsk, Russia *IOP Conf. Ser.: Earth Environ. Sci.* 27 012031 (http://iopscience.iop.org/1755-1315/27/1/012031)

[5] Adam A M, Novoselov A L, Chepurnykh N 2000 *In. Environmental problems of Russian regions. Newscast. The Tomsk region*. No. 6

[6] Olhovchenkov V E 2015 *Hazardous natural and anthropogenic processes on the territory of Tomsk and their influence on the stability of natural-technical systems* (Tomsk) p141.

[7] Sologaiev V I 2002 *Filtrational calculations and computer modeling at protection against flooding in city construction: Monograph* (Omsk: Publishing house SibADI) p 416

[8] Nazarenko I A 2010 *GIS in hydrogeological studies* (on the example of JSC "AVTOVAZ"). *Geography and Geology. Hydrology and water resources*. SSC RF research Institute "VODGEO", Moscow. [Electronic resource]. URL: http://www.rusnauka.com/10_NPE_2010/Geographia/62643.doc.htm. free

[9] Bukaty M B 2002 *Development of software for solving hydrogeological problems* // News of TPU Geology prospecting and exploration of mineral resources of Siberia (Tomsk: Izd. TPU) T 305 **6** 348 – 365