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Research paper

Prediction maps of land subsidence caused by groundwater exploitation in Hanoi, Vietnam

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Abstract

The article presents study results of the land subsidence caused by groundwater exploitation in Hanoi, Vietnam. The study includes collection and analysis of data on geology, hydrology, soil properties and settlements observed at 10 monitoring stations as well as models of the time-dependent settlement. The calculated settlements are relatively close to actual monitoring data. The models were done for prediction of the land subsidence at 92 selected points by the finite element method. Prediction maps are made for prediction of the land subsidence in 2020 and 2030. Recommendations are proposed for potential zones of groundwater exploitation in Hanoi.

Keywords: Hanoi; Soils; Land subsidence; Settlement; Groundwater exploitation; Modeling

Hanoi, the capital of Vietnam, is one of the largest cities in Asia with a developed industry, infrastructure and high population density. After expansion of administrative boundary in August 2008, the New Hanoi has an area of 3324.9 m^2 and a population of 6.3 million people, groundwater exploitation for water supply of more than 1 million m^3 per day. Water consumption in the city is increasing annually. Continuous growth in groundwater exploitation from water supply stations created depression craters with decreasing groundwater levels in many areas: from 13 to 18 m at Thanh Cong, Ngo Si Lien, Don Thuy, Nga Tu Vong, etc.; from 18 to 32 m at Mai Dich, Ngoc Ha, Ha Dinh, Thuong Dinh, Dai Kim, Phap Van, etc. The city is located in an area with complicated natural conditions, dangerous geological processes caused by natural and man-made activities and widespread distribution of soft soils (equal to 30% of the area) that makes great difficulties in the construction and operation of engineering structures [1–3].

The land subsidence caused by intensive groundwater extraction is one of the most dangerous geological processes that occur in the Hanoi city, and accompanied by deformation and destruction of houses, buildings and objects.

Assessment and prediction of this phenomenon have great importance in the prevention and reduction of its damage to civil and industrial structures in Hanoi. Questions on the land subsidence in the Hanoi city caused by intensive groundwater extraction are answered in studies of Giao et al. [4]. One of the urgent tasks at the present time is to divide the Hanoi territory into zones with different levels of the land subsidence, and determine changes of future settlement areas.

Land subsidence due to large amounts of fluid withdrawal from an aquifer has occurred in many areas in the world, such as Venice, San Joaquin Valley, California, Mexico City, Shanghai, Bangkok etc., and has been extensively investigated both quantitatively and qualitatively. Many researchers have been dedicated to constructing mathematical models to predict the development of land subsidence and proposing measures to control land subsidence. The study results of the land subsidence caused by intensive groundwater extraction are also shown in studies of Giao and Phien-wej [5], Giao [6], Nguyen [7], Poland [8], and Terzaghi [9].

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The purpose of the article is prediction of the land subsidence in the Hanoi city and establishment of prediction map of the land subsidence caused by the groundwater extraction.

The main difficulty in achieving this goal is necessary to solve two independent groups of tasks. The first group includes hydrogeological problems for assessment and prediction of changes in groundwater levels. The second one is engineering–geological problems for assessment and prediction of the land subsidence in the geological environment with different compositions, structures and properties of soil strata. The study on the land subsidence caused by groundwater extraction was carried out by collecting and analyzing data on the geology, hydrogeology, soil properties and the observed settlements and modeling values of the land subsidence in process of groundwater exploitation. When processing, analysis and interpreting the observed data programs «MS Excel», «AutoCad», «Visual ModFlow», «Mapinfo» and others were used.

1. Analysis of data on the geology of the Hanoi area

In the profile of the Quaternary sediments in Hanoi, they can be divided into five formations according to age and origin, from bottom to top, as follows: Early Pleistocene alluvial deposits (Le Chi Formation – *a*I*lc*); Middle–Late Pleistocene alluvial and alluvial–proluvial deposits (Ha Noi Formation – *a*,*ap*II-III^{1}*hn*); Late Pleistocene alluvial, lacustrine, and lacustrine–bogged deposits (Vinh Phuc Formation – *a*,*l*,*lb*III^{2}*vp*$_{1,2,3}$); Early–Middle Holocene lacustrine–bogged, marine, and bogged sediments (Hai Hung Formation – *lb*,*m*,*b*IV$^{1-2}$*hh*$_{1,2,3}$); Late Holocene alluvial and alluvial–lacustrine–bogged deposits (Thai Binh Formation – *a*,*alb*IV^{3}*tb*$_{1,2}$).

Analysis of physical and mechanical properties of the Quaternary sediments in the Hanoi city [3] allowed dividing them into 24 layers (from top to bottom):

- **Man-made soils (*tH*):** *Layer 1* – sands, sandy clay, and clayey sand with an admixture of construction debris (fragments of brick, stone, limestone, construction mortar, etc.);
- **Upper part of Thai Binh formation (*a*IV^{3}*tb*$_{2}$):** *Layer 2* – very soft sandy clay with organic matters (bottom sediments of lakes and ponds); *Layer 3* – brown and pinkish-brown firm sandy clay, interstratified with clayey sand; *Layer 4* – saturated brownish-grey fine-grained and loose sand, some places with gravel;
- **Bottom part of Thai Binh formation (*alb*,*a*IV^{3}*tb*$_{1}$):** *Layer 5* – yellowish-grey stiff to firm clay; *Layer 6* – yellowish-grey and brown stiff to firm sandy clay; *Layer 7* – saturated brownish-grey very soft to soft sandy clay with organic matters; *Layer 8* – brownish grey firm sandy clay, interstratified with clayey sand and sand; *Layer 9* – saturated greenish-grey fine-grained medium dense sand; *Layer 10* – brownish grey firm sandy clay, interstratified with clayey sand and sand;
- **Upper part of Hai Hung formation (*amb*IV$^{1-2}$*hh*$_{3}$):** *Layer 11* – saturated dark grey very soft to soft sandy clay with organic matters;
- **Middle part of Hai Hung formation (*m*IV$^{1-2}$*hh*$_{2}$):** *Layer 12* – green grey stiff to firm clay;
- **Bottom part of Hai Hung formation (*lb*IV$^{1-2}$*hh*$_{1}$):** *Layer 13* – dark grey very soft sandy clay with organic matters;
- **Upper part of Vinh Phuc formation (*a*,*am*III^{2}*vp*$_{3}$):** *Layer 14* – light grey and yellowish-grey stiff clay; *Layer 15* – multi-coloured (brown, yellow, red) very stiff to stiff sandy clay;
- **Middle part of Vinh Phuc formation (*alb*II^{2}*vp*$_{2}$):** *Layer 16* – dark grey very soft to soft sandy clay with organic matters;
- **Bottom part of Vinh Phuc formation (*a*III^{2}*vp*$_{1}$):** *Layer 17* – yellowish-grey plastic clayey sand, interstratified with sandy clay or sand; *Layer 18* – saturated brown and yellowish-brown fine-grained medium dense to dense sand; *Layer 19* – saturated yellowish-grey and light grey medium- and coarse-grained dense to very dense sand, some places with gravel and pebbles;
- **Ha Noi Formation (*ap*,*a*II–III^{1}*hn*):** *Layer 20* – brownish-grey firm sandy clay, some places with organic matters; *Layer 21* – grey plastic clayey sand, some places with gravel; *Layer 22* – saturated gravel and pebbles, some places with grey and yellowish-grey very dense coarse-grained sand;
- **Le Chi formation (*a*I*lc*):** *Layer 23* – grey and brown plastic clayey sand, some places with gravel; *Layer 24* – saturated gravel and pebbles, fine-grained and coarse-grained brownish-grey and yellowish-grey very dense sand with sandy clay.

Summary of physical and mechanical properties of the Quaternary sediments in the Hanoi area according to study results of Phi H.T. is presented in Table 1.

Sediments of the upper part of the profile (Vinh Phuc, Hai Hung, Thai Binh formations) are soft soils with low bearing capacity and high compressibility ($R_0 < 100$ kPa and E_0 (0.1–0.2) < 5 MPa, respectively). Their thickness varies from 0.2 to 43.0 m; Their depth varies from 0 to 37.8 m. They are widely distributed in the central and southern parts of the city.

2. Analysis of data on hydrogeology and observed settlements in the city

According to the Hanoi Groundwater Extraction Company [10] the city has three main forms of groundwater extraction: public, industrial and private well fields. In Hanoi there are 10 major well fields (called water supply stations) and 11 small well fields to supply groundwater for domestic and industrial needs. They consist of 164 wells drilled in the Pleistocene complex, with an average capacity of 667,804 m^3/day in 2008. For supplying groundwater for industrial needs there are about 513 wells in total. Wells were drilled in the Pleistocene complex to a depth of 32–85 m, with an average capacity of 152,000 m^3/day in 2008. Private domestic wells consist of about 110,902 with shallow depth that use groundwater from the Holocene complex or upper part of the Pleistocene complex. The total groundwater extraction from these wells was 110,900 m^3/day in 2008.

The total groundwater extraction was 930,704 m^3/day in 2008. In the future, the daily water consumption will increase