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Influence of groundwater extraction on land subsidence in Jakarta

H. Hendarto
Imperial College, London, UK

Ministry of Public Works and Housing, Jakarta, Republic of Indonesia

J.R. Standing
Imperial College, London, UK

ABSTRACT: Major groundwater extraction in Jakarta, combined with other environmental issues, has caused severe land subsidence in areas of this teeming metropolis. Based on geodetic and PS-InSAR measurements, the current maximum rate of subsidence is more than 20 mm/year which has led to more than 3 m of settlement in northern parts of the city. Potential causes of the land subsidence are excessive groundwater extraction, urban development (e.g. high-rise building and tunnelling) and ongoing natural behaviour of the Jakarta soils. Groundwater pumping is thought to be the primary cause of the land subsidence. Records from groundwater levels, conventional monitoring and remote sensing using PS-InSAR indicate a strong relationship between pumping and land subsidence. Compiled data from more than one century's measurements indicate that groundwater levels have dropped significantly, by up to 25 m, in central Jakarta. A schematic diagram of historic pore pressure changes resulting from the decreasing groundwater levels has been developed to help explain the situation.

Keywords: land subsidence; PS-InSAR; monitoring; groundwater extraction

1 INTRODUCTION

Cases of urban development-induced land subsidence have been reported for several major cities throughout the world. In the case of Jakarta, (Abidin *et al.*, 2011) described four possible factors triggering land subsidence, namely: a) excessive groundwater extraction; b) urban development in the form of building and construction loading; c) natural consolidation of alluvium soil; and d) tectonic activity. The first two factors are related to urban development and thought to have a significant contribution to land subsidence in Jakarta. An emphasis on the excessive groundwater extraction as the potential factor causing land subsidence is given by (Abidin, *et al.*, 2011). Natural consolidation of alluvium soil should be complete given the geological age of the deposits (conditions have not changed geologically, for several millennia). While tectonic activity is considered as the least dominant because Jakarta is located more than 300 km from the Java subduction zone and so far there has been no significant shallow seismic activity near Jakarta.

Even though land subsidence has become a real threat to the city, for example northern parts of the city near the shoreline have ended up underwater, so far no comprehensive analysis from a geotechnical perspective has been undertaken concerning which soil strata beneath Jakarta primarily influence the land subsidence in the city. As Jakarta is close to the Java Sea and located in the estuary areas of thirteen rivers, there is a necessity to explore the potential effects of saline water, organic contents and the presence of carbonates on land subsidence in Jakarta. All of these influence the index properties and consolidation characteristics of soils. Bjerrum (1954) investigated the effects of salt concentration in the pore water of Norwegian marine clays and found that they have a significant influence on activity and the Atterberg limits. An increase in the compressibility of the Norwegian marine clays was observed as salt concentration decreased. Atterberg limits and compressibility also increase with the presence of organic content in soil (Mitchell & Soga, 2005).

To gain a better understanding of the ground conditions beneath Jakarta, site investigations were conducted at several locations under Imperial College supervision. This paper explores the mechanism of land subsidence due to groundwater extraction using evidence from one of these locations at Tongkol Street, as shown in Figure 1. This site is less than 1 km away from Jakarta Bay and within the grounds of the Groundwater Conservation Agency Office (Balai Konservasi Air Tanah – BKAT), Ministry of Energy and Mineral Resources of the Republic of Indonesia. Monitoring wells with various screen depths and a settlement monitoring pile were installed on the site by BKAT. The ground surface at the site is relatively flat with a level of 1-2 m above sea level (m asl).

2 GEOLOGICAL CONDITIONS

Jakarta is located in a low-land area on the northern coast in the western part of Java Island. The terrain is relatively flat in northern and central Jakarta, while the topography slopes in the upwards towards the south by up to 5º. The highest altitude located in the most southern part of Jakarta is about ~70 m asl.

According to Van Bemmelen (1949), the lowland area which extends from Serang-Rangkasbitung in Banten to Cirebon in West Java is about 40 km wide and is made up of geological formations of alluvial deposits and mud flows from surrounding volcanoes, with intermittent exposures of slightly folded marine tertiary sediments.

Geological cross-sections of the western and northern parts of the surface geological map of Jakarta & Kepulauan Seribu indicate that the under-lying bedrock is potentially a part of the Bojongmanik Formation, unit Tmb (Turkandi *et al.*, 1992). This formation consists of alternating claystone and sandstone layers with limestone intercalations of Miocene age and the top of this formation is several hundred metres below ground level (m bgl) in the northern areas, close to the coast. In the west, above this layer, the early Pliocene Genteng Formation (Tpg), consisting of pumice tuff, tuffaceous sandstone, andesite breccia, conglomerate and tuffaceous claystone is overlain by the Pleistocene Banten Tuff (QTvb), comprising tuff, pumice tuff, and tuffaceous sandstone. The Banten Tuff Formation is overlain by superficial deposits deposited during the Quaternary period.

These superficial strata consist of the Alluvial Formation (Qa) and the Alluvial Fan Formation (Qav). Typical materials of the Alluvial Fan Formation are beds of fine tuff, sandy tuff interbedded with conglomerate tuff, whereas the alluvial deposits (Qa) consist of clay, silt, gravel, cobbles and boulders. Another superficial deposit, the Beach Ridge Formation (Qbr) consisting of well-sorted coarse sand with mollusc shells overlies the Banten Tuff at other locations in Jakarta especially in the western and northern part near to the shoreline. A study of the cities subsurface conditions conducted by Fachri *et al.* (2002) classifies subsurface soils similar to the Qav as the Citalang Formation, which is found extensively in their borehole database, with a thickness varying from 80 to 110 m in northern Jakarta.

In terms of hydrogeological units, Jakarta has a complex aquifer-aquiclude system. However, for practical purposes, the aquifer zones in this paper are divided into three, following Soekardi (1986). The three aquifer zones are an unconfined aquifer (0-40 m), upper-confined aquifer (40-140 m) and lower-confined aquifer (140-250 m).

In this study, all samples were collected from a maximum depth of 60 m and so are within the Quaternary deposits or the Citalang Formation and within the unconfined and top-confined aquifers. The age of this formation is late Pliocene – early Pleistocene (Martodjodjo, 1984).

3 SITE DESCRIPTION

The extent of the city of Jakarta is presented in Figure 1. Imperial College (IC) organised two phases of site investigation (SI) at various locations of interest in the city from May to June 2017 and in April 2018.

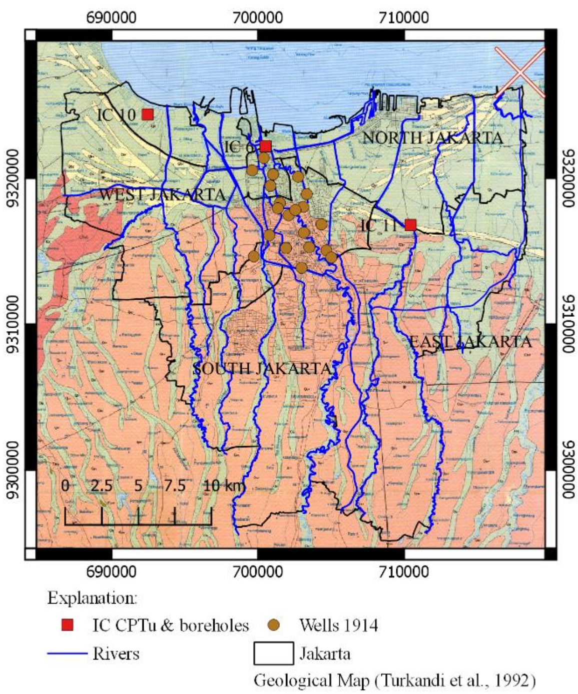

Figure 1. Layout of monitoring wells and site investigation at IC 6 superimposed onto the geological map.

Information from these SIs and subsequent laboratory tests, with a focus on consolidation characteristics (c_v, m_v, and k), has been gathered and synthesised along with subsurface data from other projects in Jakarta to assist with the prediction of magnitudes and rates of settlement from water extraction in the city.

Phase 1 of the SI, along the corridor of the north-south (NS) line of the Jakarta Mass Rapid Transit (MRT) project and at three locations where severe land subsidence has occurred, was conducted by Fugro Indonesia and supervised by the first author. Phase 2, conducted by a local company, was located in Pantai Indah Kapuk (PIK) in north Jakarta. Figure 1 shows only three SI locations from Phase 1 where piezocone penetration testing with pore pressure measurements (CPTu) were performed and geotechnical boreholes sunk, denoted IC 6, IC 10 and IC 11.

4 HISTORICAL PORE PRESSURE PROFILES

An expected consequence of the drawdown is the reduction in pore pressure both in permeable aquifers (sand layers) and aquicludes (clay layers) resulting in increases in effective stress. It is instructive to plot historical pore pressure profiles within the Jakarta Basin as shown in Figure 2. Results from the SI at IC 6 are plotted together with pore pressure distributions at three different times: 1914, 1989 and 2017. Soil classification charts proposed by Robertson (1990), known as the normalized soil behaviour type classification charts (SBT_n), are used to identify the stratigraphy beneath the site. This method is based on: normalized cone resistance, Q_{tn}, and normalized friction ratio, F_R, and pore pressure ratio, B_q. The $Q_{tn} – F_R$ chart is usually used for basic CPT data, i.e. when only cone resistance, q_c, and sleeve friction resistance, f_s, data are available. However, for soft saturated fine-grained soils where the value of q_c could be small and pore water pressure could be large, the $Q_{tn} – B_q$ chart is favoured. Results from the SBT_n analysis together with core logs from the boring activity have been interpreted to classify aquifer and aquiclude layers. Proposed SBT_n zones of 5 to 8 (described as sand mixtures to over consolidated or cemented clayey sand) are classified as aquifer layers whereas the other SBT_n zones (1, 2, 3, 4 and 9) are taken to be aquiclude layers.

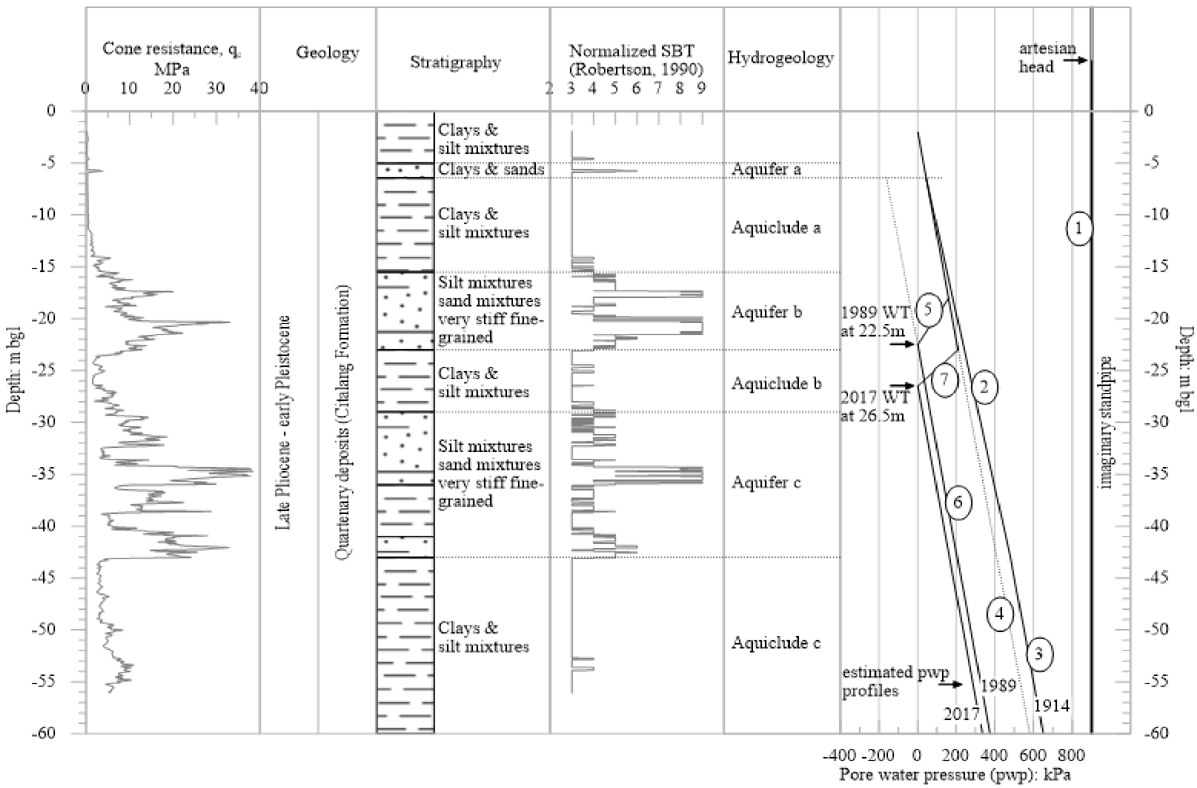

Figure 2. Reconstruction of natural pore water pressure distribution with depth at IC 6 site plotted with geological stratigraphy, cone resistance, normalized soil type and hydrogeology conditions at three time periods.

The CPT trace, geology, simplified stratigraphy, normalized SBT and the assigned aquifers and aquicludes are plotted against depth in Figure 2. Note that a more detailed breakdown of aquifers and aquicludes has been made here compared with Soekardi's scheme. The historic pressure head at depth (> 60 m bgl) at the location of IC 6 in northern Jakarta is recorded as being artesian in 1914 and, in the absence of accurate records, is arbitrarily taken to be 5 m above ground level. This artesian head is illustrated using a standpipe analogy in Figure 2 (marked 1). The groundwater level in the upper aquifer *a*, was recorded at a depth of 3 m bgl during the SI while monitoring results from shallow wells surrounding IC 6 from 2013 to 2017 indicate an average groundwater level at 2 m bgl. The level of this water table varies depending on the season and rainfall. It seems reasonable to assume that the pore water pressure distribution in aquifer *a* is hydrostatic from 2 m bgl for both the present and historic conditions. This pressure distribution is extrapolated downwards below aquifer *a* in Figure 2 (marked 4). Historically, below aquiclude *c* the distribution is 7 m in excess of hydrostatic (marked 3 in Figure 2). For simplicity, a straight line has been drawn connecting the hydrostatic profile in aquifer *a* to the base of aquifer *c* (marked 2 in Figure 2).

A major campaign of groundwater level monitoring started in 1982 and the resulting data, in conjunction with findings from the IC 6 borehole, have been analysed. A significant drawdown had developed by 1989 with the water table (WT) being observed at 22.5 m bgl. A hydrostatic profile distribution is drawn for all layers below this 1989 level (marked 6 in Figure 2). The hydrostatic pore water pressures in aquifer *a* is unaffected by this because the IC 6 location is close to rivers and canals (~200 m from Kali Besar and

~125 m from Kali Ciliwung Gajahmada). An arbitrary line has been drawn to connect the upper and lower hydrostatic pressures (marked 5 in Figure 2) although the position where it meets the upper distribution is uncertain. If aquiclude *a* prevents any significant downward water flow from aquifer *a* above it, aquifer *b* could have negative pore water pressures and cavitation is likely to occur. However, in reality, another process that could occur is an incursion of seawater from the nearby bay.

The groundwater level at the IC 6 - Tongkol site had reduced by a further 4 m by 2017. The 2017 pore water pressure profile is assumed to be similar to that of the 1989 profile but with the WT now at 26.5 m bgl. Another arbitrary line joining the two hydrostatic profiles has again been drawn (marked 7 in Figure 2). It is important to note that for the two lines marked 5 and 7 in Figure 2, there is uncertainty about their gradient and where they connect with the upper hydrostatic profile. As described above, this could lead to negative pore water pressures and cavitation.

The pore pressure reductions shown in Figure 2 (resulting from groundwater pumping), under conditions of constant total stress, essentially reflect equivalent increases in mean effective stress. In the fine-grained layers (aquicludes), the effective stress changes lead to consolidation which takes place with time because of their low values of permeability. Within the more granular aquifers, the consequent compression that occurs is relatively small and occurs rapidly.

5 GROUNDWATER CHANGES

Water demand has increased tremendously due to increases in the population size and industrial activities in Jakarta. Water supplies from the water companies in the city seemingly do not meet the water demand. In order to overcome this demand, private groundwater extraction has significantly increased since the 1980s with the number of registered private wells being just below 4000 in 2007 (Kagabu *et al.*, 2013). The exact number of total wells in Jakarta is hard to estimate. However, the major groundwater extraction from these wells combined with environmental effects, such as land conversion and the degradation of water recharge areas, create another environmental problem in several places in Jakarta: land subsidence, (Abidin *et al.*, 2015).

Records of deep wells from the colonial period (Houwink, 1914) indicate that the groundwater from deep wells (Jakarta's lower-confined aquifer) constructed from 1873 to 1916 had artesian pressure 4–16 m asl. According to spatial analyses of groundwater levels based on recent monitoring data from deep monitoring wells (up to 2014), groundwater levels have dropped significantly, by 20–25 m in central Jakarta and even deeper in western and eastern Jakarta as can be seen in section A-A' and B-B' in Figure 3.

Piezometric head contours from both 1914 and 2014 data indicate that the groundwater generally flows northwards. In southern parts of Jakarta at altitudes of 50–60 m asl, the head was about 40–60 m asl, while in northern parts was about 10–40 m below sea level. Cones of groundwater depression are evident in western and eastern Jakarta based on the 2014 data as seen in the piezometric head sections in Figure 3. These may result from pumping activities in these areas.

6 EVIDENCE OF LAND SUBSIDENCE

Two methods of monitoring land subsidence at the IC 6, Tongkol site, are presented in this paper. The first is based on a conventional monitoring technique using a deep datum point, the base of which is assumed to be fixed. The second relies on remote sensing using Persistent Scatterer Interferometry Scattered Image (PS-InSAR) techniques.

For the conventional monitoring, the deep datum comprises a steel rod which was installed at a depth of 300 m in 1990. The rod is sleeved with a steel casing. Both the rod and casing were set at the same level about 1 m above the ground at the time of installation. The casing tends to settle with the vertical ground displacements while the rod remains stable. The difference between the tops of the rod and the casing is taken to represent the magnitude of land subsidence magnitude in the Tongkol area.

Groundwater levels in three monitoring wells at the BKAT office have been monitored since 1985. These wells are located near to IC 6 as shown in Figure 4. Historical records from these wells, namely TKL5, TKL 6 and TKL 8 have been analysed and are presented in Figure 5a. It is evident that up to 44.2 cm of land subsidence has occurred from 1990 to 2018. The relationship between land subsidence and a decrease in groundwater levels of two wells with screens installed within aquifer 40-140 m (TKL 5) and 140-250 m (TKL 8) is clearly visible.

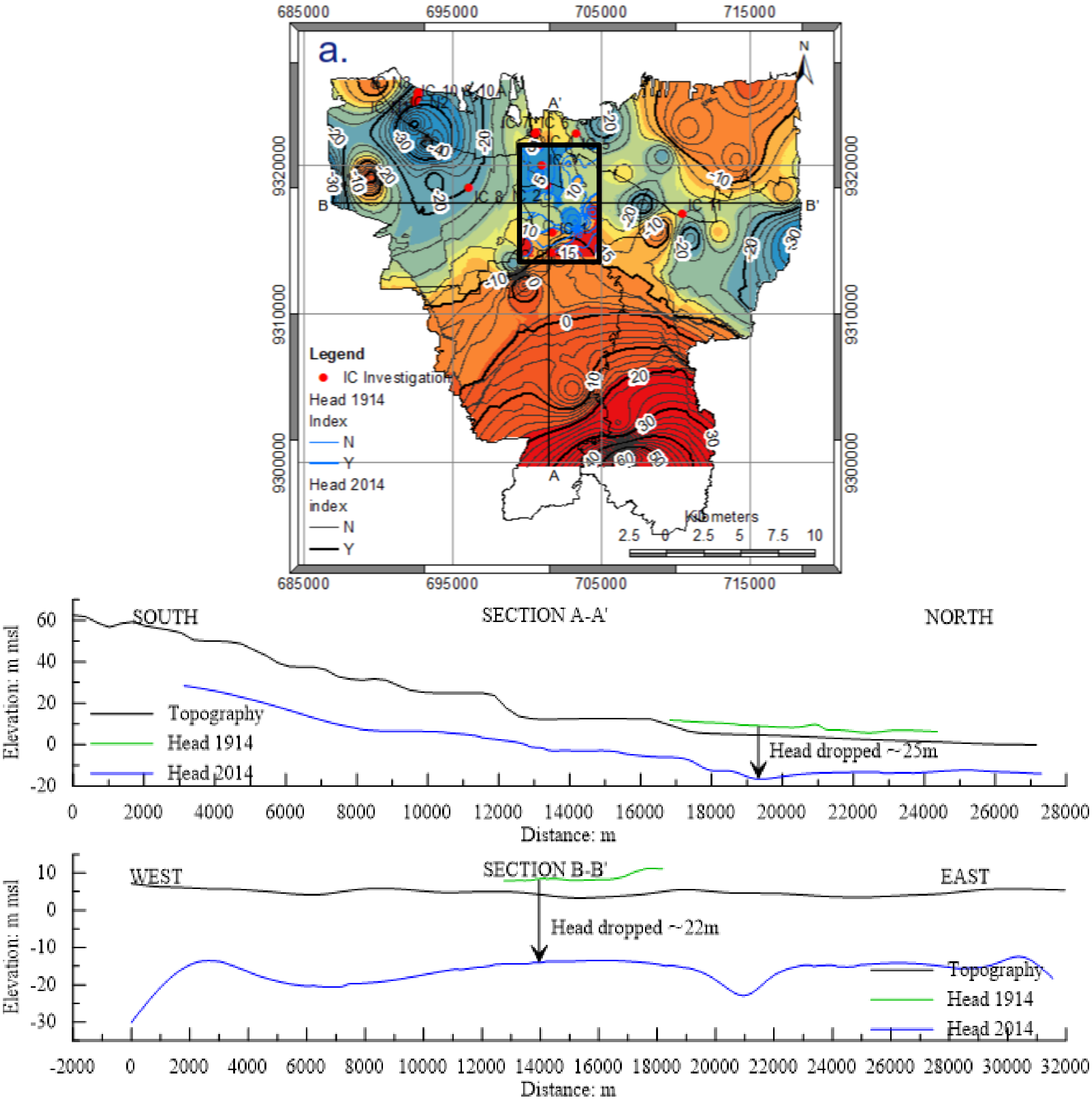

Figure 3. Groundwater levels of 1914 (within a rectangular box) superimposed on those of 2014 and cross-sections of groundwater levels in south-north (A-A') and west-east directions (B-B').

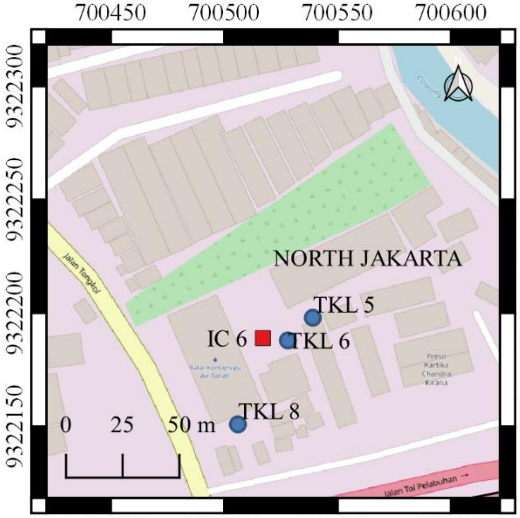

Figure 4. Plan showing IC 6 site and monitoring wells (TKL 5, TKL 6 and TKL 8) in IC 6, Tongkol site, north Jakarta

An average land subsidence rate of 18 mm/year was observed from 1990 to 2007. The rate was increased to 21- 23 mm/year in 2009 and 2010, respectively. These were potentially triggered by significant water extraction from confined aquifer 140-250 m in surrounding areas near Tongkol site, as represented in TKL 8. Nonetheless, the land subsidence rate was slowing down (10 mm/year) when aquifers: 40–140 m and 140–250 m were recharged from 2011 to 2017 as presented in Figure 5(a).

Yuen (2018) performed PS-InSAR analysis to verify land subsidence and its rate in Jakarta. A set of satellite images was used in this analysis from October 2014 to September 2017. Figure 5b shows a total vertical displacement at the IC 6 site of 40 mm relating to a rate of 13.5 mm/year. A clear message from both monitoring is that land subsidence is still taking place. Further investigation is needed to confirm the potential causes of this settlement and also to develop efficient counter measures against this worsening scenario of land subsidence in the city.

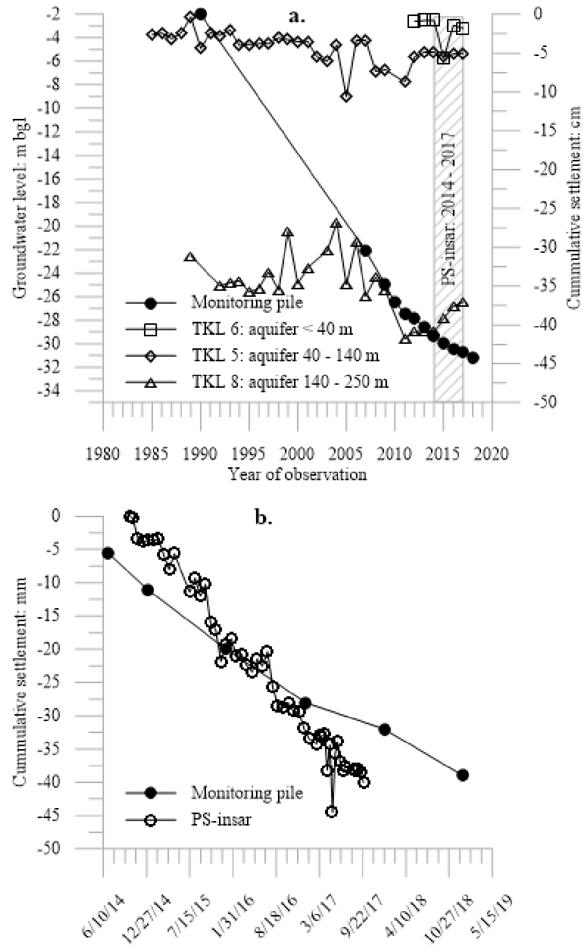

Figure 5. Evidence of land subsidence at the IC 6, Tongkol site: a) settlements from deep datum monitoring plotted with groundwater levels from monitoring wells; b) settlements from PS-InSAR analysis from October 2014 to September 2017

7 CONCLUSIONS

Jakarta has been subjected to groundwater extraction from well pumping for more than a century. By comparing data from1914 and 2014, it is evident that groundwater levels have dropped significantly, by as much as 20–25 m under central Jakarta and even more in western and eastern Jakarta.

Land subsidence has occurred because of the reduction in pore water pressures (as presented in

Figure 2) leading to increases in effective stress and consequent consolidation in the compressible soils/aquiclude layers (very soft to soft clay layers) within Citalang Formation.

The current rate of land subsidence at the IC 6, Tongkol site, based on conventional and remote sensing measurements is 10–13.5 mm/year.

There is a strong relationship between groundwater pumping and land subsidence at the Tongkol location, especially from 2003–2011. The process is largely irreversible, as would be expected, as despite lower confined aquifers being recharged from 2011–2017, subsidence at the IC 6, Tongkol site, still took place but by lower magnitudes.

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