Studying Land Subsidence in Semarang (Indonesia) Using Geodetic Methods

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Key words: Semarang, Land Subsidence, GPS, InSAR, Levelling, Microgravity

SUMMARY

Type the English summary here (about ½ page) Semarang is the capital of Central Java province, located in the northern coast of Java island, Indonesia, with an area of about 374 km² and population of about 1.4 million. It has been reported for some time that locations in Semarang are subsiding at different rates. This subsidence is mainly due to natural consolidation of alluvial, coupled with excessive groundwater extraction and load of constructions. During the high tide periods, these subsiding areas used to experience flooding. Land subsidence phenomena in Semarang has been studied using several geodetic monitoring methods, i.e. levelling surveys, InSAR (interferometric Synthetic Aperture Radar) technique, GPS surveys, and microgravity surveys. Based on the levelling, InSAR and microgravity data, the subsidence with maximum rate of up to about 15 cm/year were observed during the period of 1979 up to 2006. Largest subsidence occurred at areas along the coast. This paper mainly describes and discusses the results obtained by GPS surveys that have been conducted in 2008 and 2009, and InSAR using ALOS/PALSAR images of 2007 and 2008. Paper is sum up with some concluding remarks.

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1. INTRODUCTION

Semarang is the capital of Central Java province, located in the northern coast of Java island, Indonesia (see Figure 1). It is centred at the coordinates of about -6º58' (latitude) and +110º25' (longitude), and covers an area of about 37,366.8 hectares or 373.7 km^2, with the population of about 1.43 million people in 2006 [*Semarang City,* 2009].

Topographically, Semarang consisted of two major landscapes, namely lowland and coastal area in the north and hilly area in the south. The northern part, where the city centre, harbour, airport and railway stations are located, is relatively flat with topographical slopes ranging between 0 and 2^o, and altitude between 0 and 3.5 m; while the southern part have slopes up to 45^o and altitude up to about 350 m above sea level. The northern part has relatively higher population density and also has more industrial and business areas compared to the southern part. The land use of southern part is usually consisted of residential, office, retail, public use and open space areas. Two rivers run through the city, one on the east side and another on the west which essentially dividing the city into three parts.

Figure 1. Geographical location of Semarang.

Geologically, Semarang has three main lithologies, namely, volcanic rock, sedimentary rock, and alluvial deposits. According to *Sukhyar* (2003), the basement of Semarang consists of Tertiary Claystone of the Kalibiuk Formation. Overlying this Formation is the Notopuro Formation which consists of Quaternary volcanic material. The two formations crop out in the southern part of the Semarang area. The northern part of the Semarang area is covered by Kali Garang deltaic alluvium up to a depth of 80 to 100 m in the coastal area. Aquifers are found at depths ranging from 30 to 80 m in this alluvium.

The northern part of Semarang is composed by very young alluvium with high compressibility. Several researches [*Van Bemmelen,* 1949; *Marfai et.al.* 2008] reported that the shoreline of Semarang progresses relatively quick toward the sea, namely about 2 km in 2.5 centuries or about 8 m/year. Therefore it can be expected that natural consolidation process still occurred until now, causing land subsidence in the northern part of Semarang. Increases in the population and urban development in the area, has accelerated land subsidence through excessive groundwater extraction, and load of building and construction.

Land subsidence is not a new phenomenon for Semarang, which has experienced it since more than 100 years. The impact of land subsidence in Semarang can be seen in several forms, such as the wider expansion of (coastal) flooding areas, cracking of buildings and infrastructure, and increased inland sea water intrusion. It also badly influences the quality of living environment and life (e.g. health and sanitation condition) in the affected areas.

In the case of Semarang, comprehensive information on the characteristics of land subsidence is applicable to several important planning and mitigation efforts (see Figure 2), such as effective control of coastal flood and seawater intrusion, spatial-based groundwater extraction regulation, environmental conservation, design and construction of infrastructure, and spatial development planning. Considering the importance of land subsidence information for supporting development activities in the Semarang area, monitoring and studying the characteristics of this subsidence phenomenon becomes more valuable.

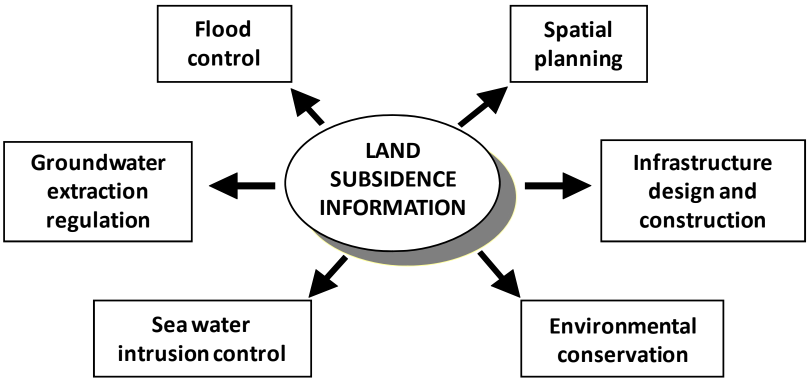

Figure 2. The importance of land subsidence information.

Some subsidence study has been conducted in Semarang city using several geodetic methods, such as Levelling [*Sutanta et al.,* 2005; *Marfai and King,* 2007], GPS surveys, Gravity [*Sarkowi et al., 2005; Fukuda et al.,* 2008] and InSAR [*Murdohardono et al.,* 2009; *BGR,* 2009]. This paper describes and discusses the results obtained by GPS surveys that have been conducted in 2008 and 2009.

2. LAND SUBSIDENCE IN SEMARANG

Land subsidence in Semarang has been widely reported and its impacts can be seen already in daily life. It can be seen in the forms of coastal flooding (it is called rob by the locals) that its coverage tends to enlarge by times. Figure 3 shows the severity of coastal flooding in coastal areas of Semarang. This frequent and severe rob not just deteriorate the function of building and infrastructures. It also badly influences the quality of living environment and life (e.g. health and sanitation condition) in the affected areas (see Figure 4). Cracking of buildings and infrastructure, and increased inland sea water intrusion, are also other impacts of land subsidence.

The economic losses caused by land subsidence in Semarang are enormous; since many buildings and infrastructures in the industrial zone of Semarang are severely affected by land subsidence and its collateral coastal flooding disasters.

Many houses, public utilities and a large number of populations are also exposed to this silent disaster. The corresponding maintenance cost is increasing by year. Provincial government and communities are required to frequently raise ground surface for keeping roads and buildings dry. The living conditions of population affected by the land subsidence are in general decreasing.

Figure 3. Coastal flooding in Semarang on mid April 2009; courtesy of Kompas photo, 2 July 2009.

Figure 4. Examples of subsidence impacts in Semarang.

Based on the levelling surveys conducted by the Centre of Environmental Geology from 1999 to 2003 it was found that the relatively large subsidence were detected at around Semarang Harbor, Pondok Hasanuddin, Bandar Harjo and around Semarang Tawang Railway station, with the rates ranging from 1 to 17 cm/year [T*obing and Murdohardono, 2004*; *Murdohardono et al.,* 2007].

Levelling derived subsidence zones in Semarang is given in Figure 5. The zoning is derived based on the height changes of 29 levelling points. It should be noted in this case that the zoning is highly generalized and maybe in accurate in detail. This Figure shows that the northern coastal areas of Semarang are subsiding with the rates larger than 8 cm/year. These areas are generally composed by swamp deposit of soft clay soil.

The estimation based on the PS InSAR technique also revealed that the areas close to shoreline have subsidence rates of more than 8 cm/year [*Murdohardono et al.,* 2009; *Kuehn et* *al.,* 2009], as shown in Figure 6. The contour lines in this Figure are based on the PS InSAR based velocity data derived from 28 ERS-2 and ENVISAT-ASAR radar scenes recorded between 27 November 2002 and 23 August 2006.

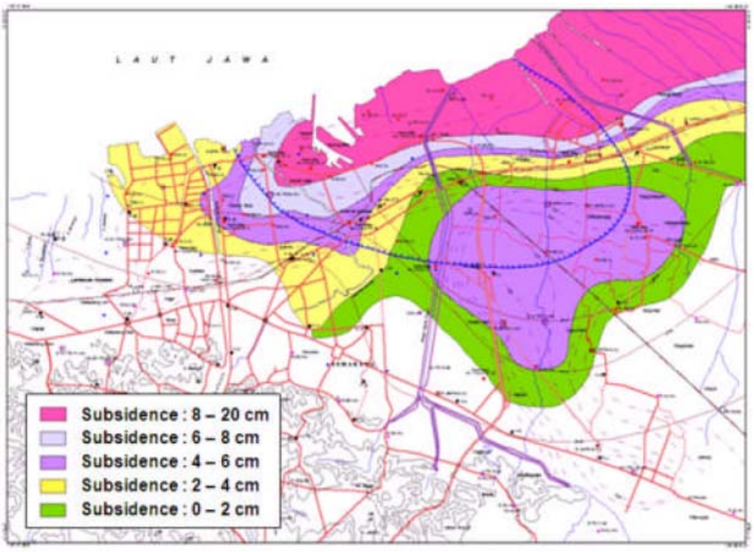

Figure 5. Levelling derived subsidence in Semarang in the period of 2000 to 2001; courtesy of Geological Agency Bandung, after [*Murdahardono et al.*, 2007].

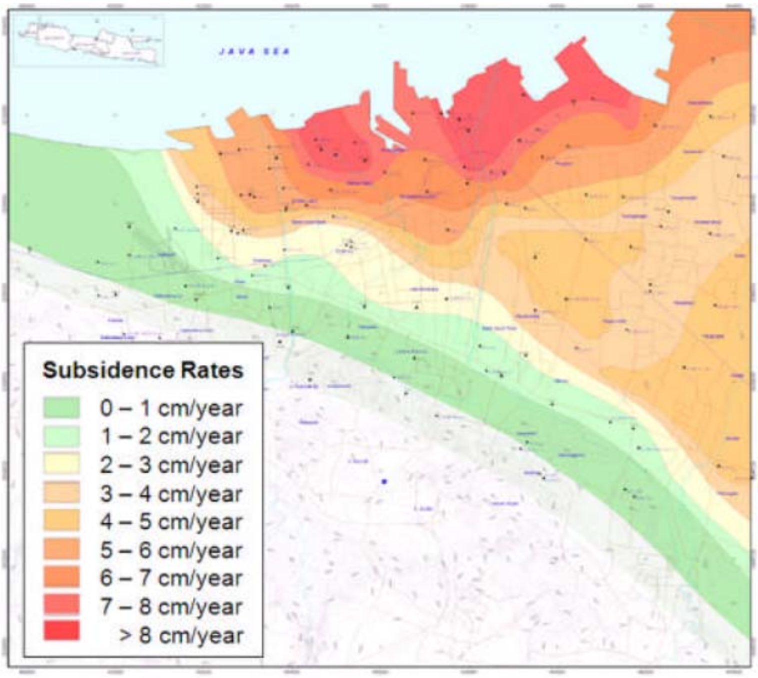

Figure 6. PS InSAR derived subsidence rates in Semarang; courtesy of Geological Agency Bandung, after [*Murdahardono et al.*, 2009; *Kuehn et al.*, 2009].

Subsidence in Semarang has also been studied using the microgravity method since 2002 by the research group from the Department of Geophysics of ITB. Based on this method, it is found that during September 2002 to November 2005, a maximum subsidence of about 48 cm occurred in the northern region of Semarang (see Figure 7). It corresponds to a maximum rate of about 15 cm/year.

Based on the results from Levelling, PS InSAR and Microgravity methods, shown in Figures 5 to 7, suggested that during the period between 2000 and 2006, subsidence process in Semarang is going on with the rates that can be up to about 15 cm/year. The higher subsidence rates always occur in the northern coastal areas and getting generally smaller to the south direction.

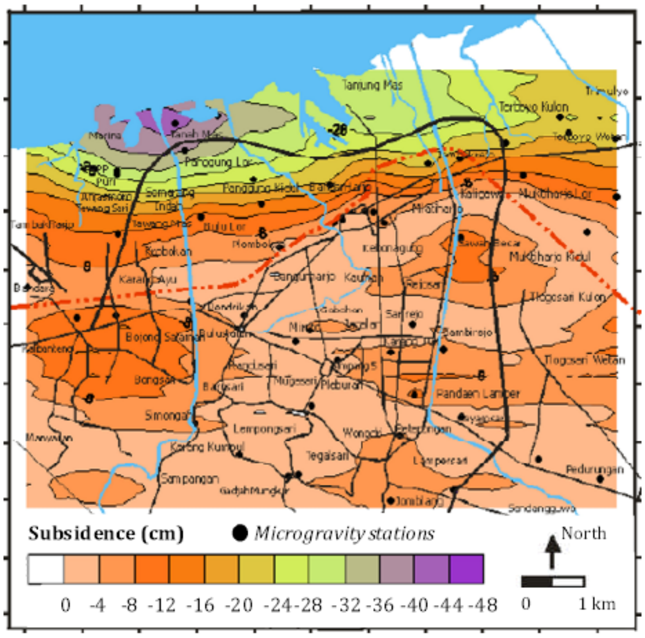

Figure 7. Microgravity derived subsidence in Semarang from Sept. 2002 to Nov. 2005; after [*Supriyadi,* 2008].

Since 2008, the Geodesy Research Division of ITB started to study land subsidence in Semarang by using GPS surveys and InSAR methods. The results are presented in the following sections.

3. LAND SUBSIDENCE MEASURED BY GPS

GPS (Global Positioning System) is a passive, all-weather, satellite-based navigation and positioning system, which is designed to provide precise three-dimensional position and velocity, as well as time information on a continuous worldwide basis [*Wells et al.,* 1986; *Hofmann-Wellenhof et al.,* 2007; *Abidin,* 2007].

With GPS survey method several monuments, which are placed on the ground covering the Bandung Basin and its surroundings, are accurately positioned relative to a certain reference (stable) point, using the GPS survey technique. The precise coordinates of the monuments are periodically determined using repeated GPS surveys at certain time intervals. By studying the characteristics and rate of change in the height components of the coordinates from survey to survey, the land subsidence characteristics can be derived.

For monitoring land subsidence, when the expected subsidence is of very small magnitude, the ideal positioning accuracy to be achieved is at the mm level. In order to achieve this level of accuracy the GPS static survey method based on dual-frequency carrier phase data processing should be implemented, with stringent measurement and data processing strategies [*Abidin et al.,* 2002; *Leick,* 2004].

GPS surveys for studying land subsidence in Semarang have been conducted on 7-13 July 2008 and 5-11 June 2009. The number of observed points was 48 at first survey and 52 points at second survey. The location and distribution of the points are shown in Figure 8. Station SMG1 is the southernmost point in the network and considering its relatively stable location is used as the reference point for this subsidence study.

The GPS surveys exclusively used dual-frequency geodetic-type GPS receivers. The length of surveying sessions was in general between 9 to 11 hours. The data were collected with a 30 second interval using an elevation mask of 15^0. The surveys were mainly carried out by the staffs and students from the Department of Geodesy and Geomatics Engineering of ITB (Institute of Technology Bandung). Example of some GPS stations is shown in Figure 9.

The data were processed using the software Bernese 5.0 [*Beutler et al.,* 2007]. Since we are mostly interested in the relative heights with respect to a stable point, the radial processing mode was used instead of a network adjustment mode. In this case, the relative ellipsoidal heights of all stations are determined relative to SMG1 station. For data processing, a precise ephemeris was used instead of the broadcast ephemeris. The effects of tropospheric and ionospheric biases are mainly reduced by the differencing process and the use of dual-frequency observations. The residual tropospheric bias parameters for individual stations are estimated to further reduce the tropospheric effects. The algorithms for the tropospheric parameter estimation can be found in *Beutler et al.* (2007). In processing baselines, most of the cycle ambiguities of the phase observations were successfully resolved.

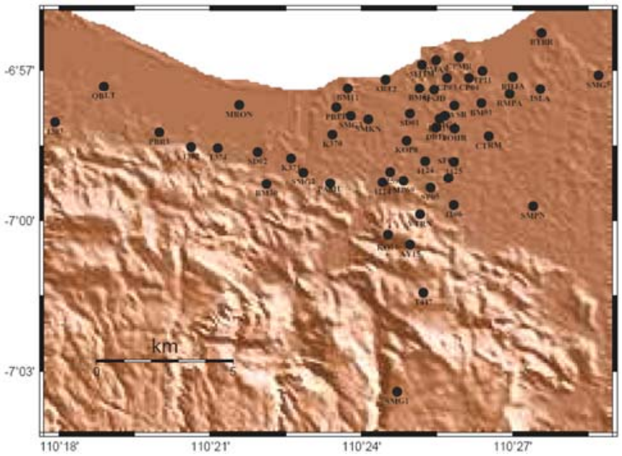

Figure 8. GPS network for studying land subsidence in Semarang.

Station: PMAS Station: DRIP

Station: MTIM Station: BM11

Station: SMG5 Station: SMG1

Figure 9. Example of GPS stations for monitoring land subsidence in Semarang.

The standard deviations of GPS-derived relative ellipsoidal heights from all surveys were in general better than 1-2 mm (see Figure 10). A few points have slightly larger standard deviations, due to the lack of observed data caused by the signal obstruction.

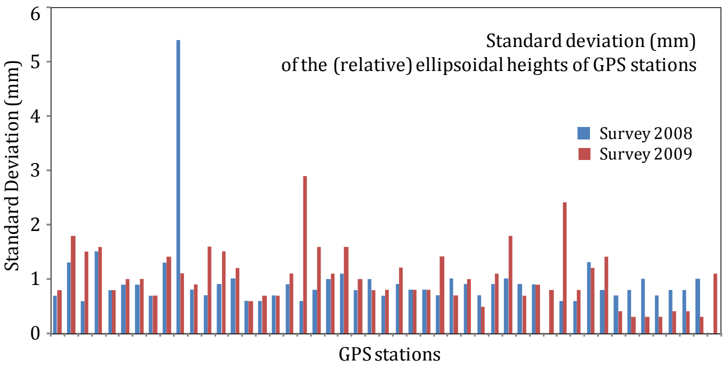

Figure 10. Standard deviations of GPS-derived relative heights in mm.

In using GPS surveys method, the height change Δdh_{ij} and its rate $v\Delta dh_{ij}$ at each station are derived using the following relation:

$$\Delta dh_{ij} = dh(t_j) - dh(t_i) \quad (1)$$

$$v\Delta dh_{ij} = \Delta dh_{ij} / (t_j - t_i) \quad (2)$$

where $dh(t_i)$ and $dh(t_j)$ are the relative ellipsoidal heights with respect to SMG1, obtained from the ith and jth GPS surveys. Subsidence is represented by a negative value of Δdh_{ij}.

In order to statistically check the significance of the estimated subsidence values, we apply the general linear hypothesis test [*Leick,* 2004] to the estimated height parameter. The null hypothesis of the test is that the estimated relative ellipsoid heights at epoch j equal the estimated value of the previous epoch i., i.e. there is no subsidence has occurred. Therefore,

null hypothesis $\quad H_o.: \Delta dh_{ij} = 0 \quad (3)$

alternative hypothesis $\quad H_a.: \Delta dh_{ij} \neq 0 \quad (4)$

The test statistics for this test is

$$t = \frac{\Delta dh_{ij}}{\hat{\sigma}(\Delta dh_{ij})} \quad (5)$$

which has the customary Student's t-distribution if H_o is true. The null hypothesis is rejected if

$$|t| > t_{df,\alpha/2} \quad (6)$$

where *df* is the degrees of freedom and α is the significance level. In our case the degree of freedom is very large since the GPS baselines were derived using 8 to 10 hours of observations at 30 seconds interval. A t-distribution with infinite degree of freedom is identical to a normal distribution. At a confidence level of 99% (i.e. α=1%), the critical value is $t_{\infty,0.005} = 2.576$.

Based on the results given in Figure 11, it could be statistically concluded that with 99% confidence level there were significant ellipsoidal changes observed by GPS surveys at all the stations during the period between July 2008 and June 2009, except for a few stations, namely KOP8, PAMU, PBR1, SMKN and T374.

The GPS-derived ellipsoidal height changes and their rates that have passed the statistical testing are shown in Table 1.

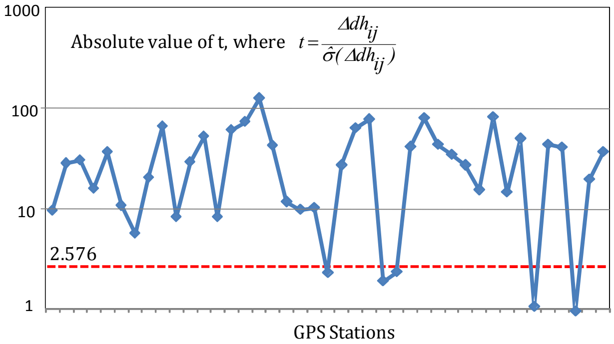

Figure 11. Summary of congruency test of GPS derived land subsidence results.

Table 1. GPS-derived subsidence results in Semarang, based on GPS surveys of July 2008 and June 2009.

GPS Station	Subsidence (cm)		Subsidence rate (cm/yr)	
	Δdh_{12}	$\sigma(\Delta dh_{12})$	$\nu\Delta dh_{12}$	$\sigma(\nu\Delta dh_{12})$
0259	-1.0	0.1	-1.1	0.1
1106	-6.2	0.2	-6.8	0.2
1114	-4.8	0.2	-5.3	0.2
1124	-3.4	0.2	-3.7	0.2
1125	-4.1	0.1	-4.5	0.1
1303	-0.8	0.1	-0.8	0.1
AY15	-2.0	0.1	-2.2	0.1
BM01	-12.4	0.2	-13.5	0.2
BM05	-4.5	0.6	-4.9	0.6
BM11	-3.5	0.1	-3.8	0.1
BM16	-9.4	0.2	-10.3	0.2
BM30	-1.5	0.2	-1.6	0.2
BTBR	-8.0	0.1	-8.8	0.1
CTRM	-6.1	0.1	-6.7	0.1
ISLA	-11.3	0.1	-12.3	0.1
JOHR	-4.4	0.1	-4.9	0.1
K371	-3.0	0.3	-3.3	0.3
KO16	-1.8	0.2	-2.0	0.2
MP69	-4.7	0.2	-5.1	0.2
MSJD	-7.9	0.1	-8.7	0.1
MTIM	-8.6	0.1	-9.4	0.1
PMAS	-4.9	0.1	-5.3	0.1
PRPP	-8.3	0.1	-9.1	0.1
SD01	-7.3	0.2	-8.0	0.2
SD02	-3.9	0.1	-4.2	0.1
SFCP	-3.6	0.1	-3.9	0.1

Table 1. (continuation)

SMG2	-1.2	0.1	-1.3	0.1
SMG3	-10.1	0.1	-11.0	0.1
SMG5	-5.2	0.1	-5.7	0.1
SMPN	-4.8	0.1	-5.3	0.1
SP05	-10.4	0.3	-11.3	0.3
T447	-2.8	0.1	-3.0	0.2
VTRN	-6.2	0.2	-6.8	0.2

Results from GPS show that land subsidence in Semarang has spatial variations, ranging from 0.8 to 13.5 cm/year with the mean of 5.9 cm/year (see Table 1 and Figures 12). Northern region of Semarang city exhibits higher rates of subsidence compare to its southern region, as shown in Figures 13 and 14.

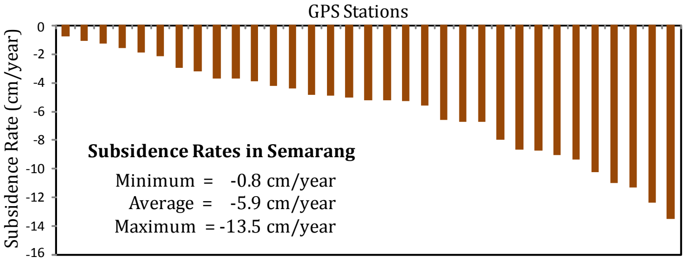

Figure 12. GPS-derived subsidence rates in Semarang

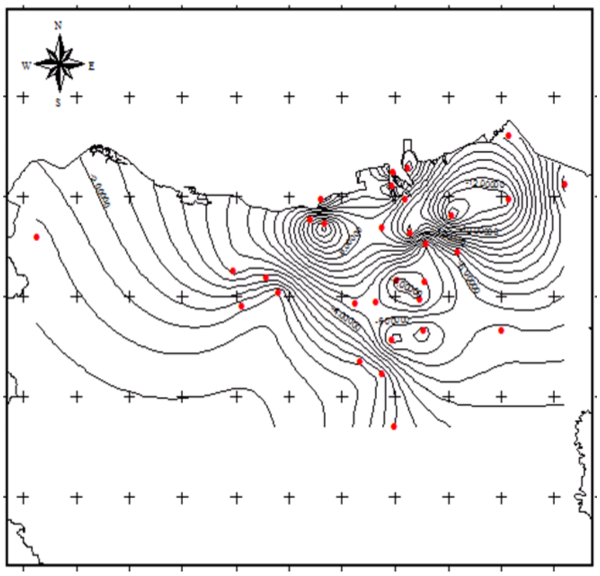

Figure 13. GPS derived contours of subsidence rates in Semarang

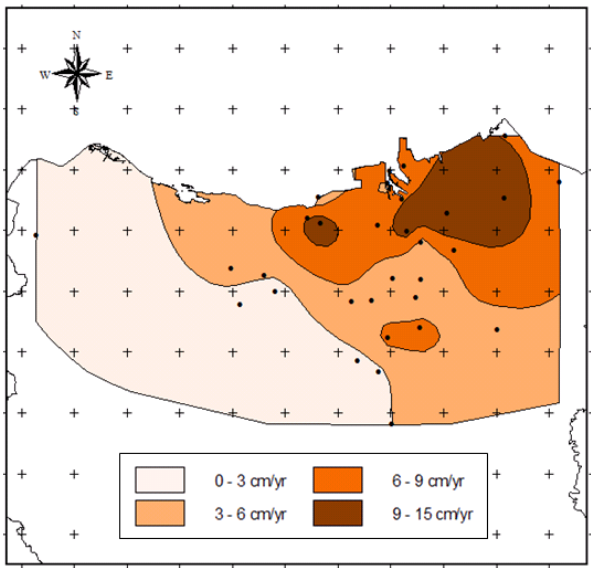

Figure 14. GPS derived zones of subsidence rates in Semarang.

The GPS derived subsidence results show more or less the same rates and pattern of subsidence as derived by Levelling, PS InSAR and Microgravity methods. GPS results also indicate that subsidence process is still going on until recently (i.e. June 2009) in Semarang.

4. LAND SUBSIDENCE MEASURED BY InSAR

Geodesy Research Division of ITB has also used InSAR method to study land subsidence in Semarang using data from the ALOS/PALSAR satellite, which was launched in January 2006 as a successor of JERS-1/SAR. There are three ALOS PALSAR images were processed in this case (see Table 2). They were acquired in Fine Beam Single Polarization mode (HH polarization) with off-nadir angle of 41.5 degrees. InSAR processing has been performed using Level 1.1 products (SLC: Single Look Complex).

There are two pairs of images were processed (see Table 3). The first pair is between 24 October 2007 (071024) and 11 December 2008 (081211), and the other is between 9 December 2007 (071209) and 11 December 2008 (081211). The baselines of image pairs are about 684 m and 849 m, respectively. In this case, the subsidence is derived using two pass differential method, and SRTM data was used for generating the DEM for the area. The final results of subsidence are shown in Figure 15.

Table 2. ALOS/PALSAR images used for studying land subsidence in Semarang city

Date	Looking direction
24 October 2007	Ascending
09 December 2007	Ascending
11 December 2008	Ascending

Table 3. Image pair of data

Image Pair	Baseline (Perpendicular)
071024_081211	683.877 meter
071209_081211	848.753 meter

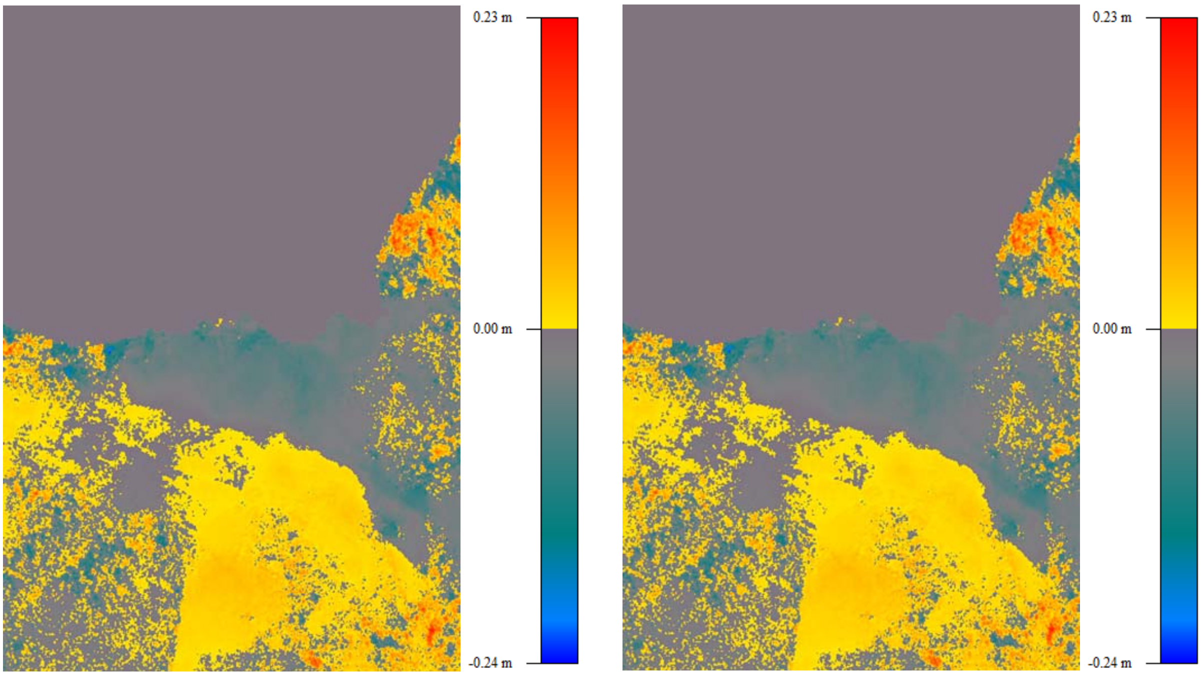

Figure 15. ALOS/PALSAR InSAR derived subsidence in Semarang city, from (071024_081211) pair (left), and (071209_081211) pair (right)

Results shown in Figures 15 show that subsidence in Semarang city is generally occuring in the northern part of the city, with the maximum rates of about 15 cm/year. These results are more or less similar with the aforementioned results derived by other methods.

It should be noted in this case that, the uplift presence in Figure 15 is mostly caused by the very low correlation of images, and the uplift presence in this Figure should not be considered as a 'real' uplift [*Sidiq,* 2009].

5. CLOSING REMARKS

Land subsidence in northern part of Semarang is believed to be caused by the combination of natural consolidation of young alluvium soil, groundwater extraction and load of buildings and constructions. Due to this coastal land subsidence, part of the north coast area of Semarang city has been showing a growth of sea water inundation since almost the last three decade.

Groundwater abstraction in Semarang city is increasing sharply since early 1990s, especially in industrial area (see Figure 16). According to [*Marsudi*, 2001], the number of registered wells in 1900 is 16; becomes 94 wells in 1974, 178 wells 1981, 350 wells in 1989, 600 wells in 1990, 950 wells in 1996, and 1050 wells in 2000. The registered groundwater abstraction is increasing from about 0.4 million m^3/year in 1900, to 0.9 million m^3/year in 1974, 1.8 million m^3/year in 1981, 8.8 million m^3/year in 1989, 16.9 million m^3/year in 1990, 32.8 million m^3/year in 1996 and 38 million m^3/year in 2000.

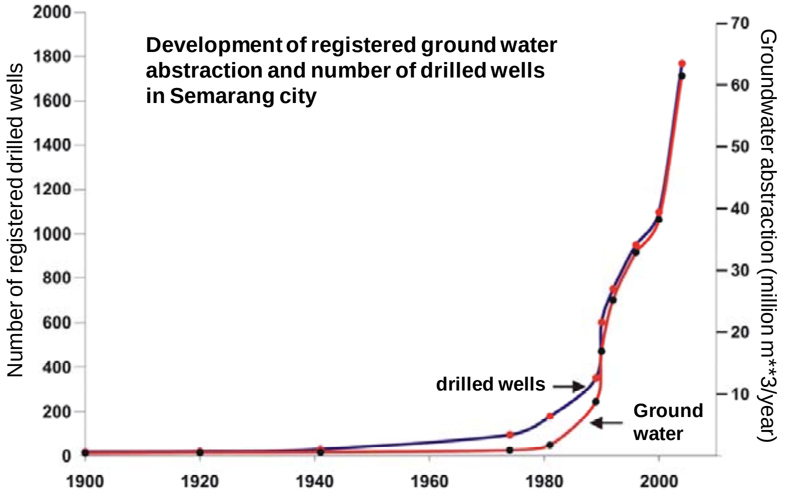

Figure 16. Development of ground water abstraction and registered drilled wells in Semarang, after [*Murdohardono et al,* 2007].

Due to excessive groundwater abstraction, the groundwater level in Semarang during the period of 1980 and 1996 is lowering with the rates of about 1.2 to 2.2 m/year [*Marsudi,* 2001]. This will then introduce land subsidence above it.

More data and further investigations are required to understand the intricacies of the relationship between land subsidence and natural consolidation and groundwater extraction in

Semarang area. Additional causes of subsidence, e.g. load of buildings and construction, and tectonic movements, should also investigated and taken into account.

Finally it should be noted that in the coastal areas of Semarang, the combined effects of land subsidence and sea level rise will make worse the tidal flooding phenomena which already experienced by Semarang during the high tide periods. The adaptation measures to reduce the impacts of this hazard therefore should be developed as soon as possible.

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