1. Introduction

Merapi is a classical, andesitic stratovolcano, located in Central Java (7.54^o S, 110.44^o E, elevation 2968 m (condition in 2001)); it is one of the most active volcanoes in Indonesia (fig. 1.1). Since 1006 A.C. 82 hazardous eruptions are documented. Merapi is located at the subduction zone between the Eurasian and the Indo-Australian plate. This subduction zone extends for about 2000 km from Sumatra to the Lesser Sunda Islands. In the Java-Bali sector, subduction occurs between the 10-km thick oceanic (Indo-Australian) plate and the intermediate 20-km thick (Eurasian) plate (see http://www.vsi.esdm.go.id/).

Evolution of Merapi volcano can be divided into four periods:

- before 400,000 B.C.: Pre-Merapi
- 60,000 - 8,000 BC: Old-Merapi
- 6,000 - 2,000 BC: Mature-Merapi
- since 2,000 BC : New-Merapi

New-Merapi stage is characterized by three types of eruptive products:

- basaltic and andesitic lava flows,
- pyroclastic flows,
- magmatic and phreatomagmatic eruptions.

Since 600 years activity has been dominated by grow of lava domes and their destruction either by gravitational collapse or by explosive activities.

The activity of Merapi is unique due to many internal as well as external factors, such as summit or crater morphology, physic-chemistry condition of magma, lava outflow rate, existing dome condition, rain interference, and even local tectonic effects.

Today two different eruptive mechanisms can be distinguished at Merapi:

- highly explosive eruptions and
- long periods of dome growth accompanied by gravitational collapses and resulting block and ash flows.

In recent years, the volcanic activity has been confined to periods of lava dome growth in the summit area and dome collapse events that generate small-volume pyroclastic flows (in Indonesian language: *Awan Panas*) at regular interval of few years (fig. 1.2). Some pyroclastic flows have traveled as far as 13 km from the crater rim with a speed up to 110 km/hour. The temperatures of the pyroclastic flows are in the range between 300^o – 400^o C. In contrast to the time before, when the preferred direction of pyroclastic flows was towards the South, the recent pyroclastic flows were directed towards the South-West and West.

Merapi was elected by IAVCEI within the International Decade of Natural Disaster Reduction (IDNDR) declared by UNO as one of 15 so called high risk volcanoes in the world. Due to its exposed situation in the neighborhood of the city of Yogyakarta and the number of 2 million people permanently living in its endangered zone Merapi is an object of many international research activities.

In this thesis the importance of gravity changes in space and time for the analysis of volcanic processes of Merapi is analyzed and further developed. For the interpretation of gravity anomalies several programs have been written using the MATLAB software package.

Two models of the volcano are developed. The first model tries to explain the gravity changes at the crater rim stations, and the second deals with the gravity changes at stations far away from the crater rim.

Fig. 1.1. Location of Merapi volcano.

Fig. 1.2. Pyroclastic flows of Merapi.

2. International Research Activities at Merapi

Routinely the Volcanological Survey of Indonesia (VSI) is monitoring the volcanic activities of Merapi. Additionally different international programs are running, whereby as many as possible different observation methods are applied ranging from geology over geophysics to geodesy.
In the following sections a short overview is given about the different used methods, whereby gravity observations are dealt with in more details.

2.1. Applied Methods

2.1.1. Geology

Van Bemmelen (1949) published a first subsurface model of Merapi which is located at the intersection of two faults. The volcano itself can be divided in the "old Merapi" and "new Merapi" west of the old crater. The new part has subsided with respect to the old volcano along a number of more or less hyperbolic slip faults. More detailed models are described by Berthommier (1990) and Gertisser (2001).
Dome collapse events or deposit of short-lived and modest eruption columns produced a large number of small volume block and ash flows during the past 12,000 years. Moderately to larger explosive eruptions with short-lived plinian eruption columns have been the reasons for pumiceous pyroclastic-fall deposits that rarely exceed a few ten centimetres in thickness. Prominent pumiceous fallout deposits in the Middle to Late Holocene stratigraphic record of Merapi serve as time stratigraphic marker beds (Gertisser and Keller, 1998). The density of small lava samples is changing between 1600 kg/m^3 and 2900 kg/m^3 (Spieler and Dingwell, 1998).

2.1.2. Geochemistry

The compositions of volcanic gases in Merapi's fumaroles have been already analyzed by Volcanological Survey of Indonesia (VSI). Further investigations on chemistry and mineralogy of gas fumaroles and sublimates were performed by Gerlach (1982), Le Guern and Bernard (1982), Le Guern et al. (1993), Symonds et al. (1987), Symonds (1993), Kavalieris (1994), Purbawinata et al. (1997) and Vitter et al. (1997); isotopic investigations were carried out by Allard (1982, 1983) and Priatna (1996). Direct investigation of gas fumaroles at the summit using a field gas chromatograph was done by Le Guern et al. (1982a, b).
The endogen lava dome composed of andesitic magma continues to grow on the west side of the Merapi volcano. Degassing of the dome is relatively weak; the main degassing takes place outside the freshly extruded lava, in Woro and Gendol fumaroles fields.
Since 1997 on-line analysis of volcanic gases at Woro and Gendol fumaroles are performed. The compositions of gas emitted from Merapi at the time interval May 14 to 24, 1997 are H_2O (89 – 99 %), CO_2 (0.1 – 6.7 %), and SO_2 (0.5 – 4.2 %). First results of the on-line gas measurements show a clear positive correlation between CO_2 and SO_2 whereas both are negatively correlated with H_2O. Higher sulphur and carbon dioxide concentrations could be observed prior to distinct seismic events (Zimmer and Erzinger, 1998). The gas mixture from Merapi at the time interval August 24 to 26, 1998 consists mainly of H_2O (90 – 99 %) followed by CO_2 (0.5 – 7.5 %), and a minor

amount of SO_2, H_2, and N_2 (0 – 1.5 %). Concentration of SO_2, H_2 and CO_2 as well as temperature increases, if the amount of H_2O and N_2 decreases (Zimmer et al. 1999).
The degassing of magma at Merapi volcano is an open-system process where volatile components escape easily during the ascent of magma. The eruptive cycles observed at Merapi are strongly dependent on the magma dynamics in the shallow degassing reservoir and can be explained by sudden departure from steady-state behaviour followed by continuous pressure increase beneath the lava dome (Gauthier et al., 2001). The available geochronological and geochemical data provide a remarkable picture of cyclic volcanic, magmatic activity and temporal variation in magma composition, which may help to improve the understanding of characteristic and long-term estimates of eruptive scenarios at Merapi. Three cycles have been identified within the prehistoric eruptive products of the last 2000 years, each characterized by high eruption rates and by decreasing SiO_2 content of the eruptive products with time (Gertisser and Keller, 2001).

2.1.3. Geophysical Investigations

2.1.3.1. Seismic Investigations

2.1.3.1.1. Passive Seismic Investigations

Seismic activity of Merapi is monitored by a dense network of seismic stations. Since 1995 also SSE-broadband seismometers have been installed.

2.1.3.1.1.1. Seismic activities within the volcano edifice

The distribution of hypocenters of earthquakes gives hints for the existence of a second shallow magma chamber (Ratdomopurbo and Poupinet, 1995), which however is not confirmed by other researchers (Beauducel and Cornet, 1999).
The automatic classification and localization of seismic signals of interest have been calibrated and tested for a data segment from the first day of July, 1998 during a period of high seismic activity accompanying an eruption cycle of Merapi volcano. The evaluation test showed good performance for both the classification and the localization algorithm (Ohrnberger et al., 1999).
During the activity in 2001, there is still a lack of MP (multiphase) events, even though the lava outflow occurs almost continuously, producing rock falls and glowing lava avalanches. In contrast to previous eruptions of Merapi, this year the volume of the lava dome is about constant. It suggests the magma reaches the summit, directly pushes the dome side, and produces glowing rock falls. In this case, the seismograms are only dominated by rock fall signals. That means that a small debit of magma could not produce MP events (Ratdomopurbo, 2001).

2.1.3.1.1.2. Teleseismic activities

Teleseismic methods can be used to investigate the deeper extent of the Earth's structure beneath the Earth's surface. Receiver functions (P-to-S converted waves) from teleseismic earthquakes registered at Merapi have been investigated to resolve the Earth's deeper structure beneath the volcano downward to the subduction zone.

The apparent epicentres are always located near the centre of Merapi. That seems to be a topographic effect (Goßler, 1999).

2.1.3.1.2. Active seismic experiments

The investigation of Merapi volcano by active seismic methods is feasible although the rough topography, complex geology, climate and many other factors clearly are a special logistic and methodical challenge. The active seismic exploration of Merapi has according (Lühr et al., 1998) the following objectives:

- to determine the seismic velocity structure of the volcano in order to identify anomalies and improve the localization of natural seismic sources,
- to investigate properties affecting seismic signal propagation such as reflectivity, scattering, and absorption in order to support the analysis of the mechanisms of natural seismic source,
- and to provide a basis for active seismic repeat measurements to monitor temporal changes in the velocity structure of the volcano caused by magma or fluid movement or deformation.

An active seismic experiment (ASE) was realized in the years 1997 and 1998 as part of the Indonesian-German joint project MERAPI (Mechanism Evaluation, Risk Assessment and Prediction Improvement). The seismic velocities range from some hundreds m/s close to the surface to more than 3000 m/s at a maximum depth of approximately 300 m (Märcklin et al., 1999).

2.1.3.2. DC Resistivity Observations

Surveys along the flanks and in the solfatara region of Merapi with DC resistivity methods showed that the resistivity varies over 4 orders of magnitude and may yield valuable information about the internal structure of the volcano. For the west flank of Merapi a 2-D resistivity model was proposed from which the existence and extent of a hydrothermally influenced zone may be inferred (Friedel et al., 1998).

Models for the north, west, and south flanks to depth of investigation between 600 and 1000 m were developed. For the high conductivity zones appearing in the West and South a hypothesis was brought forward that the anomalies are caused by meteoric water penetrating highly permeable layers of volcanic deposits to great depth where it influences the extent of hydrothermal zones (Friedel et al., 1999). In August 2000 a permanent monitoring station was established at the fumaroles field Woro. SP (self potential) was measured at three dipoles (25 m – 75 m) with a sampling rate of 20 Hz (Friedel and Byrdina, 2001).

2.1.3.3. Magnetotelluric and Electromagnetic Observations

In order to study relationship between resistivity structure and volcanic activity of an active volcano, Magnetotelluric (MT), Controlled Source Audio Magnetotelluric (CSAMT) and Time Domain Electromagnetic (TDEM) methods have been applied at Sakurajima volcano in Japan and at Merapi volcano in Indonesia.

The resistivity structure of Merapi volcano is characterized by clusters of high resistivity values, more than 1000 Ωm, around the summit area. This high resistivity value corresponds with the accumulation of lava dome, lava fragments and lava flow under dry conditions.

The volcanic body of Merapi, which is composed of tuff, sand, lava flow and pyroclastic deposits, has resistivity values ranging from 100 to 250 Ωm. The conductive layer has a wide distribution not only beneath the volcanic body of Merapi but also in the adjacent area of Merapi with resistivity values from 25 – 50 Ωm. The conductive layer beneath Merapi is generated by heating by the magma reservoir while in the far range the groundwater distribution and changes are responsible (Arsadi et al., 1995a).
Magnetotelluric observations demonstrate the existence of a good conductor between 1000 and 2000 m below surface (Ritter, et al., 1998).
The study of audio-magnetotellurics has demonstrated the ability of CSAMT (Controlled Source Audio Magnetotelluric) to provide good data quality in a difficult terrain that can contribute to the understanding of the structure of Merapi. In the summit area, a conductive body concentrated on west side and south side at depths of 450 to 580 m from the surface was identified. The CSAMT sounding data also show the existence of an anomalous shallow conductive body on the southern flank of Merapi, about 8 to 10 km from the summit at the depth of about 400 m beneath the surface (Supriadi et al., 1999).

2.1.3.4. LOTEM

LOTEM (long-offset transient electromagnetic) have been applied first time in August 1998 at Merapi. Data have been recorded successfully at 41 locations on three profiles parallel to the magnetotelluric and seismic surveys (see 2.1.3.3). The study has demonstrated the ability of LOTEM to provide good data quality in difficult terrain, which can contribute to the understanding of the structure of Merapi (Müller et al., 1998). Müller has reported the result of the 1D and 3D modelling for the south-north cross section of LOTEM survey at Merapi. The resistivity of this layer ranges from 11 – 24 Ωm. Below the summit area the conductor rises up to 1200 m above sea level. There, the decrease of resistivity is probably produced by partial melting or by the hydrothermal system of magma reservoir. At 8 km south of the summit, a west-east striking anomaly of unknown origin exists (Müller et al., 1999).

2.1.4. Deformations

Deformations at Merapi volcano are observed in space and time using various techniques. Some experiments set up continuous recording instruments. Some repeat observations in a fixed time interval.

2.1.4.1. Tilt and Deformation Observations

Several groups from Indonesia, Japan, France, the United States, and Germany have installed tiltmeters at Merapi volcano (Purbawinata et al., 1997). Most of them monitor tilts at the summit of the volcano near the active dome. The Indonesian-German deformation experiment focuses on the hillsides, whereby arrays of tiltmeters have been installed in 4 m deep boreholes.
Tilt anomalies, apparently larger than the rain induced tilts, and an increase in seismic activity were detected about one month before the volcanic event October 31, 1996. If internal fracture processes prior to the eruption are the cause for the anomalous high

seismic activity, the coincident deformations might partially explain the recorded tilt signal (Westerhaus et al., 1998).

Only small tilt anomalies at the slopes of Merapi were observed during two volcanic crises:

- one anomaly of 1 μrad concurrent with the eruptions in January 1997,
- another anomaly associated with loading effects due to pyroclastic flows in July 1998 (Rebscher et al., 1999).

The analysis of tilt and deformation changes carried out by the French group, proposes the existence of only one magma chamber 8600 m below the summit and 2 km east of it. The volume of the chamber is estimated about 10.8 x 10^6 m^3 (Beauducel and Cornet, 1999).

2.1.4.2. Kinematic GPS

Kinematic GPS offers a modern tool to solve the problem of temporal and spatial sampling of the displacement field, but the precision is usually insufficient to monitor small displacements. A deformation net consisting of 50 stations in the summit region was installed in 1999. Indonesian teams are performing the repetition campaigns every month since December 1999 in the summit region of Merapi. Large displacements (about 10 cm) are towards the northwest between June and July 2000. This can be associated with the recent seismic unrest at Merapi, and is probably due to a new magma feeding below the 1998 lava dome (Beauducel and Cornet, 1999).

2.1.4.3. Electro-optical Distance Measurement (EDM)

The Electro optical Distance Measurements (EDM) at the summit area of Merapi volcano had been carried out periodically in 1988, 1990, and 1992. Extensions in pre-eruption period or before the 1992, February 2 eruption and contraction in post-eruption period have been clearly observed by EDM measurement in the summit area. Result of strain analysis shows that

- extension with a little shear-strain corresponds to low seismicity during the period 1998-1990 and
- extension with a significant shear-strain is correlated to high seismicity during the period 1990-1991.

The location of pressure sources between 1998 - 1990 might be located a few hundreds meter southwest of summit crater. It was inferred that the ground deformation was caused by pressure change in shallow magma chamber or by dike intrusion (Suganda et al., 1995)

2.2. Gravity Observations

Gravity observations are dealt with in a separate chapter, since all following chapters will focus on this method. Gravity observations at Merapi volcano have been carried out with different aims:

- Mapping of the gravity field in space to determine subsurface structures of the volcano.
- Observation of gravity changes in time to deduce mass migration before and after volcanic activities.

2.2.1. Mapping of gravity in space

2.2.1.1. Digital Elevation Models

Accurate Digital Elevation Models (DEMs) are necessary for the computation of the topographic reduction of gravity values.

In the beginning DEMs have been deduced by digitizing the topographic maps 1:25000 around Merapi, produced in 1944. The maps are not up to date especially concerning the summit area of Merapi.

A more accurate model was developed by (Jousset, 1996) using SPOT-images. However the most important part of the images – the crater rim of Merapi – is covered by smoke and clouds. These gaps are interpolated again by using topographic maps.

The existing DEMs lack in precision and therefore two new approaches are carried out to generate a more accurate model:

- The first approach tried to produce a model from Synthetic Aperture Radar (SAR) data taken from the remote sensing satellites ERS 1 and ERS 2.
- The second approach was done by a photogrammetric analysis of aerial images of Merapi and Merbabu (Gerstenecker et al., 1999).

However it is not possible to develop the DEM from a particular data source alone as from photogrammetric optical images or SAR images. A complete accurate DEM has been developed by combination of both techniques (Gerstenecker et al., 2001a). This DEM is also the base of a new orthophoto map of Merapi and Merbabu.

2.2.1.2. Gravity measurements

The first gravity measurements around Merapi have been carried out by Yokoyama in 1970 (Yokoyama et al, 1970), Untung and Sato (1978). Further observations have been made by Dvorak et al., 1984.

In the 80ties, students of Gadjah Mada University have mapped the gravity field within S1 thesis projects as

- Semi regional gravity measurement and estimation of free air anomalies (Kadir, 1985);
- Estimation of complete Bouguer anomalies (Wahyudi, 1986);
- Estimation of free air anomalies and complete Bouguer anomalies (Sidik, 1987).

Eight traverses of gravity survey were carried out on the body of Merapi volcano by Research Development Center for Geotechnology (RDCG-LIPI) team in 1988, 1989 and 1990.

The Bouguer anomaly pattern shows that Merapi is characterized by a low anomaly centred on the summit area. A two-dimensional gravity model indicates that the material on the summit of Merapi area has a density contrast of –900 kg/m^3. Based on the model, there are three density values of Merapi: 2600 kg/m^3 around the foot, 1800 kg/m^3 in the mid-body, and 1600 kg/m^3 in the summit area. This model is calculated by assuming a mean regional density value of 2500 kg/m^3. The rocks in the summit areas are probably composed of sand, tuff, lava fragments and lava dome (Arsadi, et al., 1995b).

Estimation of Bouguer anomalies considering arch topography effects is reported by Firdaus (1996).

In winter 1996/1997, the mapping of gravity field of Merapi and Merbabu was repeated, with the aim to fill data gaps. Positioning was done with geodetic GPS-receivers. Significant quality improvements in the measurements of the gravity field, position and elevation on Merapi have been achieved; complete Bouguer anomaly has been calculated and an improved model of the subsurface structure of Merapi has been created (Sarkowi, 1998). The analysis of the data shows an asymmetric subsurface structure. However, the position of the magma chamber cannot be detected (Gerstenecker and Suyanto, 2000).

2.2.2. Gravity Changes in time

Repeated high precision gravity measurement at Merapi can give information about mass changes within the volcano.

Several gravity and microgravity surveys including accurate levelling on Merapi volcano have been carried out by French-Indonesian teams since 1993. Significant variations in both gravity and elevation were observed for the period 1993-1994. The gravity increased by 100 to 400 μgal, depending on the location. Most of the gravity variations are explained by the change of neighbouring topography due to the growth of the dome during the considered period (Jousset, 1996).

In 1993-1995, gravity variation in time in Babadan and surrounding the summit was observed by Jousset (1996).

In 1997 a gravity repetition network was established consisting of 23 stations. Gravity observations with four gravimeters are carried out in parallel with static GPS-measurements.

Observation methods and results are part of this work and will be described in more detail in chapter 5 and 6.