

PALEOSTRESS ANALYSIS TO INTERPRET THE LANDSLIDE MECHANISM: A CASE STUDY IN PARANGTRITIS, YOGYAKARTA

Salahuddin Husein*¹, Ignatius Sudarno¹, Subagyo Pramumijoyo¹, and Dwikorita Karnawati¹

¹Department of Geological Engineering, Faculty of Engineering, Universitas Gadjah Mada, Indonesia

Abstract

Paleostress analysis on the landslide boundary faults is able to explain the sliding mechanism. This method is particularly useful to study a paleolandslide. About 30 striated fault planes from the Parangtritis paleo-landslide, located in the Yogyakarta coastline, were analyzed to define their principle stress axes. The eastern boundary fault, named as the Girijati Fault, was the main fault responsible for the mass movement and leaving a considerable steep cliff. It moved normal in a left lateral sense with ENE – WSW extension and dragged the rockmass southward, creating a NNW – SSW extension along the Parangtritis Fault and turn it into the western boundary fault. The rockmass slid along the stratigraphic contact between the underlying Nglanggran Formation and the overlying Wonosari Formation, created a semi-circular crown cliff as the northern boundary and produced some isolated topographic highs of the thrust block near the toe.

Keywords: *Paleostress, landslide boundary, fault, paleolandslide.*

1 Introduction

An occurrence of a landslide commonly controlled by geological structures, i.e. bedding and fault planes (Lutton *et al.*, 1979). Thus, iden-

tification the controlling geological structures and their kinematics on a rockslide is principal in studying the occurrence of a landslide. When the controlling faults appear as striated minor planes in the outcrop, they might be used to estimate the orientations of principal stress axes (Angelier, 1990). This method is known as paleostress analysis and the result can be applied for interpretation of the sliding mechanism.

This paper attempt to present an example of paleostress analysis to interpret the landslide mechanism. A case study in Parangtritis Beach, Yogyakarta, was chosen to demonstrate their beneficial approaches to study a paleolandslide.

2 The Parangtritis Paleo-landslide

The Parangtritis Beach in Yogyakarta has been well known as a tourist area (Figure 1). It is featured by interesting landscapes. Instead of its rare-to-find tropical sand dunes that are well-developed along the coastal belt, an imposing steep cliff of the Southern Mountains can be seen to the north and to the east.

The southern part of the cliff suggests a paleo-landslide morphological characteristic (Figure 2). It has a moderate slope gradient with some small hills scattered to the south and is bounded by circular cliff to the north. A steep cliff of northsouth trend is found at the eastern boundary, separating typical karst topography to the east. Srijono and Untung (1981) conducted a geomorphological mapping based on aerial photograph analysis and identified the

*Corresponding author: SALAHUDDIN HUSEN, Department of Geological Engineering, Faculty of Engineering, Universitas Gadjah Mada, Jl. Grafika 2, Yogyakarta 55281. E-mail: shddin@gmail.com

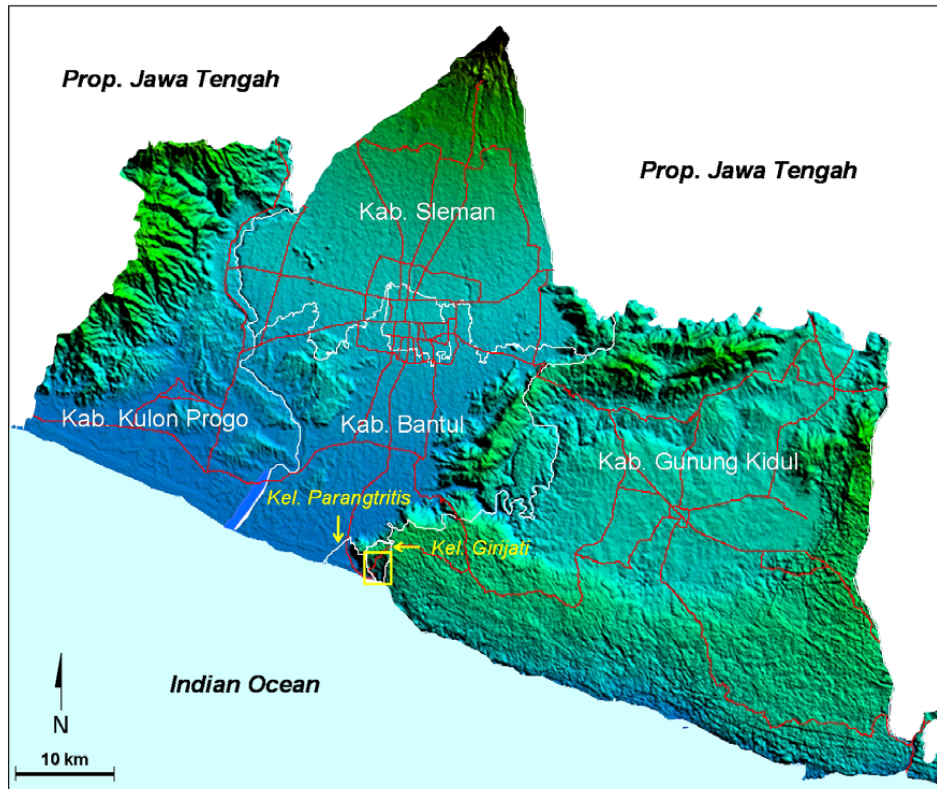


Figure 1: Location for the study area, yellow box.

moderate slope as pseudokarst morphological unit associated with a landslide. They also inferred some faults which acted as boundaries for the landslide: two north-south faults for the eastern and western boundaries, as well as one east-west fault for the northern boundary. The eastern boundary fault was named as Girijati Fault, while the western boundary fault was named as Parangtritis Fault (Sudarno, 1997).

Geophysical investigation on the area with magnetotelluric methods suggests that the basal plane for the paleo-landslide occurred in a depth of 400 m, along the stratigraphic boundary between the underlying Nglanggran Formation andesitic breccia and the overlying Wonosari Formation limestone (Husein *et al.*, 2007). Both formation have angular unconformity contact, with the Nglanggran Formation dips about 25° southeastward and is Late Oligocene to Early Miocene in age (Salahuddin, 1995), while the Wonosari Formation dips gently 10° southeastward and is Late Miocene to Late Pliocene in age (Salahuddin, 1995). It was estimated that the landslide dimension in-

involved a length of 2700 m and a width of 1500 m, approximately the sliding mass volume was a number of 810 million m^3 (Husein *et al.*, 2007).

3 Paleostress Analysis on Field Data

Kinematic data on the boundary faults were required to interpret the landslide mechanism. Thorough observation on numerous minor faults along the boundary faults, particularly the Girijati and Parangtritis faults, were collected and analyzed (Sudarno, 1997) (Figure 3). Paleostress analysis on those data then re-analyzed according to inversion method (Angelier, 1990) and a new perspective was applied to the result in order to explain the sliding mechanisms (Figure 4).

This paleostress method calculates the stress tensor by solving equations whose parameters are computed using the orientation of fault planes and slip vectors (Figure 5a). This method is based on the assumption that, although fault orientation may be arbitrary if inherited faults are present, the direction and

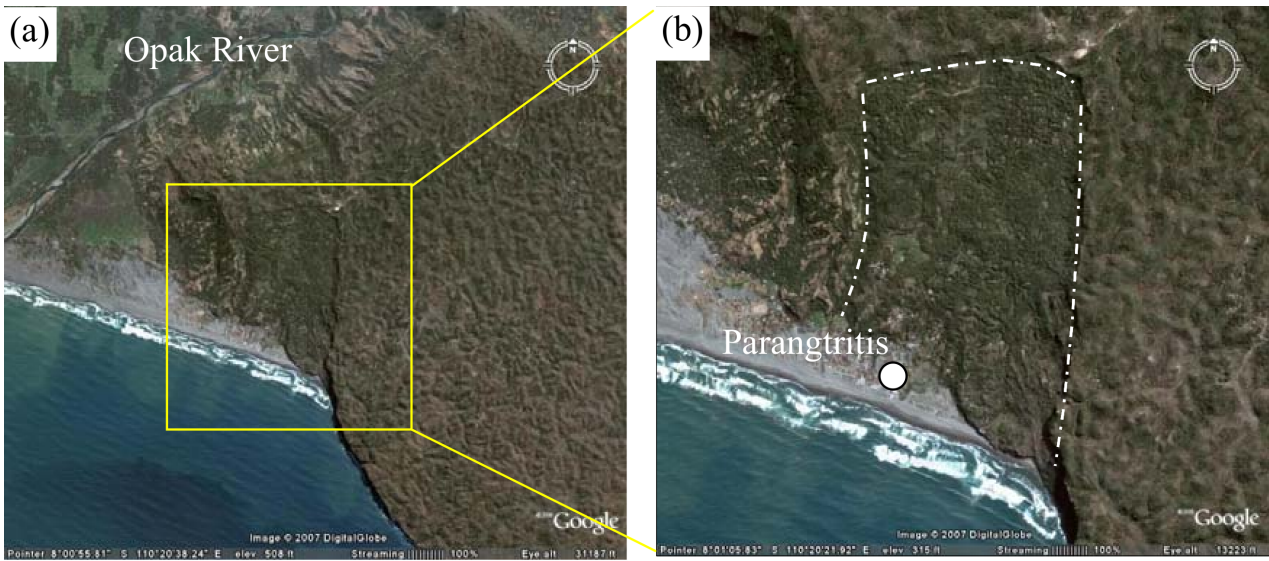


Figure 2: Satellite images on the study area, highlighting the Parangtritis paleo-landslide with boundary faults (white dashed lines in b).

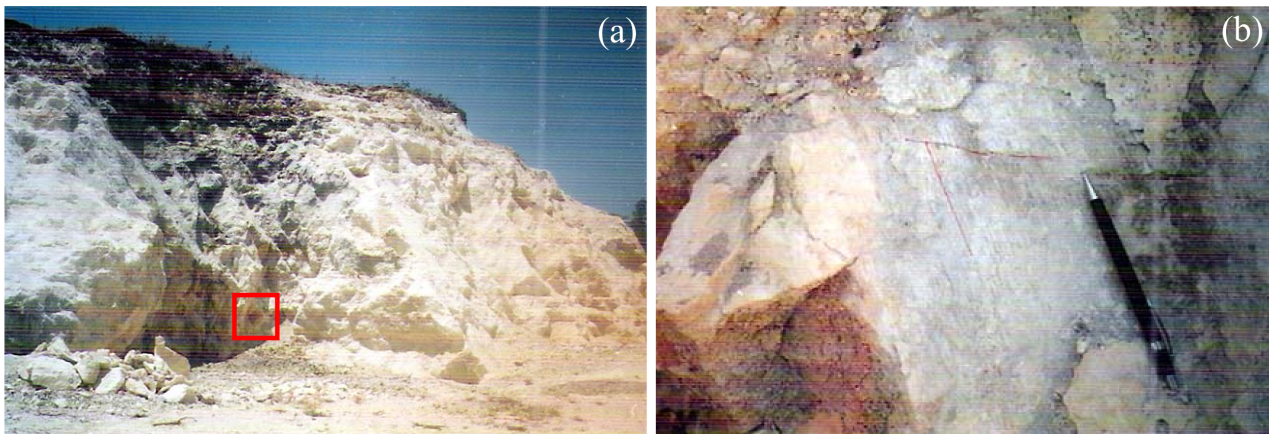


Figure 3: (a) Girijati fault zone, camera facing eastward. (b) Striated fault plane of the Girijati fault zone, their location in the figure 5a is indicated by the red box.

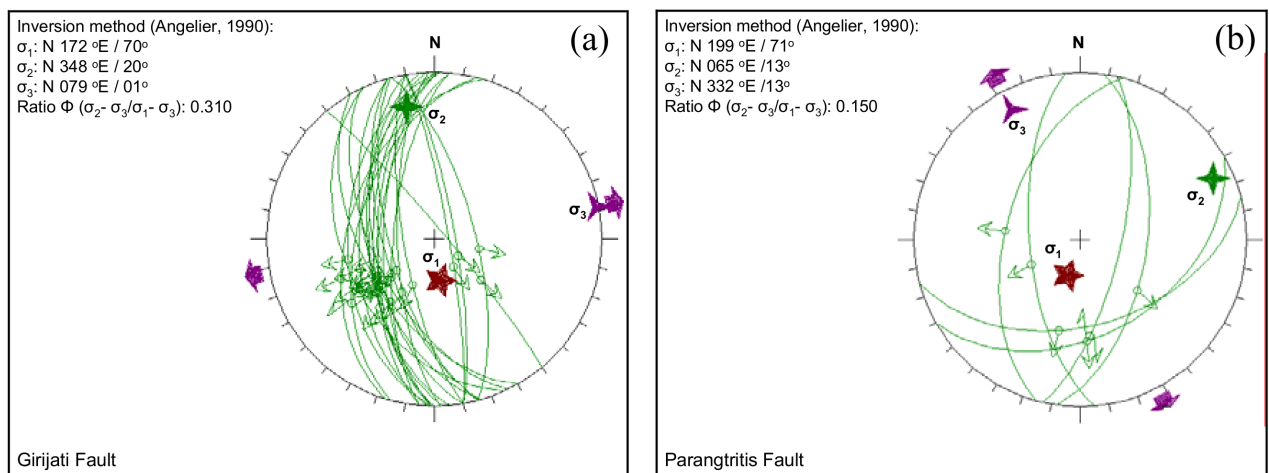


Figure 4: Paleostress analysis on Girijati (a) and Parangtritis (b) faults.

sense of each slip vector should correspond to a single common stress tensor (Angelier, 1990). Let ϑ (theta) be the angle between two vectors in the fault plane: the observed striae and the theoretical direction of displacement based on the orientations of the calculated principal stress axes. The orientations of the principal stress axes are those that minimize the sum of the n values of ϑ (where n is the number of faults included in the analysis). This method also provides stress ellipsoid analysis (Φ ratio) which indicates their movement origin (Figure 5b).

About 24 striations from numerous minor faults along the Girijati Fault zone indicate ENE – WSW extension and their stress ellipsoids suggest normal with slight strike-slip origin (Φ ratio ~ 0.31). On the other side, about 6 striations from the Parangtritis Fault zone indicate NNW – SSE extension and their stress ellipsoids suggest normal origin (Φ ratio ~ 0.15).

4 Interpretation on Landslide Mechanism

In Parangtritis, morphological evidences that indicate the presence of a considerably 250 m height, steep cliff, of the Girijati Fault suggest that faulting seems to be the primary cause of the landslide. The normal with sinistral movement with ENE – WSW extension of the Girijati Fault once was active and dragged the rockmass southward, creating a NNW – SSW extension along the western boundary fault and activated the Parangtritis Fault as a normal fault. The resulted mass movement thus broke the limestone bedding in the northern part and created a semi-circular crown cliff as the northern boundary.

As the rockmass moved southward along the stratigraphic contact as triggered by the Girijati faulting event, the basal plane concavely curved head-ward and toe-ward and cut the limestone bedding planes. Head-ward, the concavity accommodated the southward normal faulting as the rockmass moved downward. Toe-ward, the concavity accommodated the northward thrust faulting as the rockmass pushed downward, thus produced some iso-

lated topographic highs of the thrust block. Furthermore, the landslide event created more fractures and tilted the limestone blocks steeper than the surrounding area. This condition prohibited karst topography to develop in the landslide area.

Interpretation on timing of the sliding event was mainly based on the stratigraphic and morphologic information. As the landslide involved the Wonosari limestone as the youngest rock unit, the event had to be occurred after its deposition, i.e. post Late Pliocene. The event also had to take place during the uplifting of the area as the main mechanism was normal faulting with strike-slip sense. It is assumed that the landslide might occurred on the latest Southern Mountain uplifting event during Late Pleistocene as supposed by Husein and Srijono (2007). That regional-scale event were counted for creating the Wonosari depression as well as for commencement of the karst topography development in the southern part of the Southern Mountain, which today is known as Gunung Sewu. A long period of geological time since the landslide event has given the high energy waves and coastal processes to erode the landslide toe, straightened the coastline and covered the toe with the Holocene sand dunes.

5 Conclusions

Paleostress analysis based on striated fault data is able to explain the landslide mechanism, particularly for ancient events. The interpreted mechanisms of the Parangtritis paleolandslide were sequential events which triggered by the activation of the normal-sinistral Girijati Fault and simultaneously coupled by activation of the normal Parangtritis Fault. The rockmass moved along the basal plane of the stratigraphic contact between the Wonosari and Nglanggran formations, created a series of semi-circular normal faults in the headward and a series of topographic highs in the toe-ward as a result of thrust upward movement. Morphological and stratigraphical data suggest that the landslide event occurred during the latest uplifting episode of the Southern Mountain, possibly during Late Pleistocene.

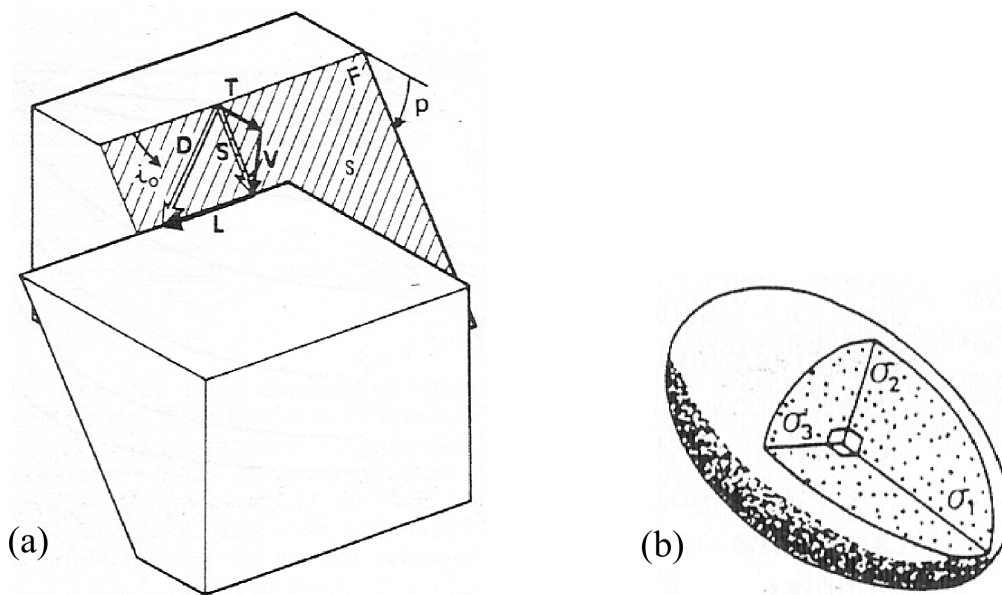


Figure 5: (a) Components of fault slip (Angelier, 1994). D: total displacement (net separation); S: displacement along slope; T: transverse horizontal component of displacement; V: vertical offset; L: lateral horizontal component of displacement; F: fault plane; s: slickenside lineation; p: fault dip; io: pitch of slickenside lineations, from 0 to 90°. Sense of arrows (D, S, T, V and L) refer to relative movement of downthrown block. (b) Stress ellipsoid indicates principal axes of the stress, with $\sigma_1 > \sigma_2 > \sigma_3$ (Angelier, 1994). Their shape was indicated by Φ ratio $((\sigma_2 - \sigma_3) / (\sigma_1 - \sigma_3))$ which is ranging from 0 to 1 and reflects the magnitude of the intermediate principal stress (σ_2) relative to the extreme principal stresses (σ_1 and σ_3).

References

- Angelier, J. (1990). Inversion of Field Data in Fault Tectonics to Obtain the Regional Stress. III. A New Rapid Direct Inversion Method by Analytical Means. *Geophysical Journal International*, 103, pp. 363-376.
- Angelier, J. (1994). Fault Slip Analysis and Paleostress Reconstruction. in: P.L. Hancock (ed.), *Continental Deformation*, Pergamon Press, Oxford, pp. 53- 100.
- Husein, S. and Srijono (2007). Tinjauan Geomorfologi Pegunungan Selatan DIY/Jawa Tengah: telaah peran faktor endogenik dan eksogenik dalam proses pembentukan pegunungan. Seminar Potensi Geologi Pegunungan Selatan dalam Pengembangan Wilayah, Pusat Survei Geologi, Yogyakarta, 27-28 November 2007, 10 pp.
- Husein, S., Ign. Sudarno, and A. Nugraha (2007). Megascale Paleo-landslide at Parangtritis, as deduced from Geological and Geophysical Data. *Proceeding of Joint Convention Bali 2007, the 32nd HAGI, the 36th IAGI and the 29th IATMI Annual Convention*, JCB2007-083, Bali, 8 pp.
- Lutton, R.J., D.C. Banks, and W.E. Strohm, Jr. (1979) Slides in Gaillard Cut, Panama Canal Zone, in: B. Voight (ed.) *Rockslides and Avalanches*, volume 2, *Developments in Geotechnical Engineering 14B*, Elsevier Scientific Publishing Company, Amsterdam, pp. 152-224.
- Rahardjo, W., Sukandarrumidi, and H.M.D. Rosidi (1995) *Geological Map of the Yogyakarta Sheet, Jawa*, 2nd edition, Geological Research and Development Centre, Bandung.
- Salahuddin (1995) *Geologi Daerah Terong – Muntuk, Kecamatan Dlingo, Kabupaten Bantul, Daerah Istimewa Yogyakarta*. Laporan Pemetaan Kuliah Lapangan, Jurusan Teknik Geologi Fakultas Teknik Universitas Gadjah Mada, Yogyakarta, 41 pp. (unpublished).
- Srijono and S. Untung (1981) *Perpetaan Geomorfologi Metode ITC – dengan conto studi daerah Parangtritis*, *Proceedings PIT X IAGI*, Bandung, pp. 64-73.
- Sudarno, I. (1997) *Kendali Tektonik terhadap Pembentukan Struktur pada Batuan Paleogen dan Neogen di Pegunungan Selatan, Daerah Istimewa Yogyakarta dan Sekitarnya*, M.Sc. Thesis at Program Studi Geologi Institut Teknologi Bandung, Bandung, 167 pp. (unpublished)