Two-Dimensional Boundary Element Method Application for Surface Deformation Modeling around Lembang and Cimandiri Fault, West Java

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Abstract. Lembang and Cimandiri fault are active faults in West Java that thread people near the faults with earthquake and surface deformation risk. To determine the deformation, GPS measurements around Lembang and Cimandiri fault was conducted then the data was processed to get the horizontal velocity at each GPS stations by Graduate Research of Earthquake and Active Tectonics (GREAT) Department of Geodesy and Geomatics Engineering Study Program, ITB. The purpose of this study is to model the displacement distribution as deformation parameter in the area along Lembang and Cimandiri fault using 2-dimensional boundary element method (BEM) using the horizontal velocity that has been corrected by the effect of Sunda plate horizontal movement as the input. The assumptions that used at the modeling stage are the deformation occurs in homogeneous and isotropic medium, and the stresses that acted on faults are in elastostatic condition. The results of modeling show that Lembang fault had left-lateral slip component and divided into two segments. A lineament oriented in southwest-northeast direction is observed near Tangkuban Perahu Mountain separating the eastern and the western segments of Lembang fault. The displacement pattern of Cimandiri fault shows that Cimandiri fault is divided into the eastern segment with right-lateral slip component and the western segment with left-lateral slip component separated by a northwest-southeast oriented lineament at the western part of Gede Pangrango Mountain. The displacement value between Lembang and Cimandiri fault is nearly zero indicating that Lembang and Cimandiri fault are not connected each other and this area is relatively safe for infrastructure development.

1. Introduction
Lembang and Cimandiri faults are active faults in West Java that yield surface deformation as the effect of fault creeping process. Surface deformation must be analyzed to examine the disaster mitigation and infrastructure development planning. To determine the surface deformation pattern, GPS measurement was conducted in the area along Lembang and Cimandiri fault then the horizontal velocity values of each GPS station were corrected by the effect of Sunda plate horizontal movement. The horizontal velocity value then used as the input data of BEM calculation besides the data of shear modulus value, Poisson’s ratio, and fault orientation to determine the displacement value at each point of observation along Lembang and Cimandiri fault that bounded by coordinate -7.4° S, 106.34°E and -6.6° S, 107.9° E.
BEM is a method to solve the partial differential equation besides Finite Element Method (FEM), and Finite Difference Method (FDM). The use of BEM instead of FEM and FDM in this research suits the distribution of GPS stations that only obtained at the particular point along the fault, as the observation boundary, agree with BEM characteristic. Moreover, BEM can reduce the problem complexity [1]. BEM in this research is computed numerically and generate the displacement value at each point of observation along Lembang and Cimandiri fault.

Lembang and Cimandiri fault are located on Sunda block that resulted from the subduction of Indo-Australia plate beneath Eurasia plate with velocity 67 mm/year [2]. The subduction with northwest direction at Oligocene dan Miocene generated the southwest-northeast oriented structure like Cimandiri fault, and the current subduction generate the east-west oriented structure like Lembang fault [3]. Lembang fault is an active fault and segmented into the older eastern segment and the younger western segment [4]. Cimandiri fault that formed at Miocene era has three major lineament orientations: east-west, northwest-southeast, and southwest-northeast [5].

Figure 1. GPS stations distribution along Lembang and Cimandiri fault (Google Earth. 2015)

2. Method
To investigate the surface displacement distribution around strike-slip faults in Lembang and Cimandiri fault region, two-dimensional boundary element method (BEM) is applied. The BEM employs the differential equations of Laplace equation, similar to the finite-element method, but only requires the discretization of observation area boundaries. Model boundaries are defined as $S$ and observation area is defined as $D$. Laplace equation is defined by equation (1) [6].

$$\nabla^2 \phi(p) = \frac{\partial^2 \phi(p)}{\partial x^2} + \frac{\partial^2 \phi(p)}{\partial y^2} = 0 \quad (p \in D)$$

Where : $\phi(p)$ = the displacement value at observation point $p$

Figure 2. Observation area and observation boundary [6]
Green’s function that defined at equation (2) is the fundamental solution of 2-D Laplace equation \([6]\). Green’s function is a function that correlates the value of \(p\) point to \(q\) point where the displacement is known and has the distance \(r(p,q)\) from \(p\).

\[
G(p,q) = \frac{1}{2\pi} \ln(|r(p,q)|) \tag{2}
\]

\[
\frac{\partial G(p,q)}{\partial n} = \frac{\partial G(p,q)}{\partial f} \frac{\partial f}{\partial n} = \frac{1}{2\pi f} \tag{3}
\]

Because \(p\) is surrounded by the area with radius \(f\), so the boundary became \(s+sf\) and the observation area became \(b-df\). By applying Green’s second identity in equation (4), the value of \(\varphi(p)\) at any observation point can be determined \([6]\).

\[
\int_{D-df} [\varphi \nabla^2 G(p,q) - G(p,q) \nabla^2 \varphi] dD = \int_{s+sf} \left[ \frac{\partial G(p,q)}{\partial n} - G(p,q) \frac{\partial \varphi}{\partial n} \right] dS \tag{4}
\]

The value of \(\nabla^2 \varphi = 0\) and the value of \(\nabla^2 G(p,q) = 0\) in each point of observation, so the left segment of equation (4) is equal to zero \([6]\).

\[
-\int_{s} \left[ \varphi \frac{\partial G(p,q)}{\partial n} - G(p,q) \frac{\partial \varphi}{\partial n} \right] dS = \int_{sf} \left[ \varphi \frac{\partial G(p,q)}{\partial n} - G(p,q) \frac{\partial \varphi}{\partial n} \right] dS \tag{5}
\]

\[
-\int_{sf} \left[ \varphi \frac{\partial G(p,q)}{\partial n} - G(p,q) \frac{\partial \varphi}{\partial n} \right] dS = \frac{1}{2\pi} \int_{0}^{2\pi} \left[ \varphi(p) \frac{1}{f} - \ln \frac{1}{f} \right] d\alpha = c(p) \varphi(p) \tag{6}
\]

Where \(c(p) = \begin{cases} 1, & \text{if } p \text{ is on observation area} \\ \frac{1}{2}, & \text{if } p \text{ is on observation boundary} \\ 0, & \text{if } p \text{ is outside observation area} \end{cases}\)

By substituting equation (6) to equation (5), and applied to any \(i-p\) and \(j-q\), and for any point \(i=j\), equation (7) is obtained, and the value of \(\frac{\partial \varphi(q)}{\partial n}\) can be determined. By substituting the value of \(\frac{\partial \varphi(q)}{\partial n}\) to equation (5), the value of \(\varphi(p_i)\) in each point of observation can be determined.

\[
\left[ c(p_i) + \int_{s_j} \frac{\partial G(p_i,q_j)}{\partial n} dS(q_j) \right] \varphi(q_j) = \int_{s_j} G(p_i,q_j) dS_j \sum_{j=1}^{N} \frac{\partial \varphi(q_j)}{\partial n} \tag{7}
\]

In this research the model boundaries are Lembang and Cimandiri fault lines and the observation points are distributed along the faults. BEM models are therefore useful for determining the geometry of prescribed fault. The application of the boundary element method in this research requires a mesh of the displacement value at the boundary of the observation area. The displacement value that used in this research are the horizontal slip rate values of GPS stations around Lembang and Cimandiri fault that have been corrected by the effect of Sunda block movement to separate the displacement that resulted by fault creeping process from the displacement that resulted by Indo-Australia plate subduction beneath Eurasia plate. GPS data is obtained from 2006 until 2011 for Lembang fault and from 2008 until 2013 for Cimandiri fault. The assumptions that used at the modeling stage are the deformation occurs in homogeneous and isotropic medium, and the stresses that acted on faults are on elastostatic condition. As the observed medium is homogeneous and isotropic, the value of shear
modulus and Poisson’s ratio is defined as the elastic value of volcanic rock as observed at observation area even the lithological units are varied along the observation area. BEM in this research is calculated numerically in MATLAB R2012a and requires the discretization of observation boundary and observation area. Observation area in this research is discretized using 0.05° grid because it yields the same result with 0.01° grid but requires less computational memory. The Lembang fault line as observation boundary was discretized into 26 elements and the Cimandiri fault line was discretized into 34 elements. The computational solution then results the approximate solution in displacement parameter at 544 selected points in the observation area as present at figure 3.

Figure 3. Lembang and Cimandiri fault as observation area boundary and distribution of observation points
3. Result

Research results are presented with displacement distribution map that overlayed with topography map. Displacement distribution is divided in the x-direction (UX) and the y-direction (UY). Positive value in the x-direction (UX) displacement distribution map indicates the displacement is toward the north, and the positive value in the y-direction (UY) displacement distribution map indicates the displacement direction is toward the east. The approximated Lembang fault line is shown with a black dashed line, the approximated Cimandiri fault line is shown with a red dashed line and the interpreted fault’s segment boundary are shown with a white dashed line.

Figure 4. Displacement distribution map in x-direction (UX)

Figure 5. Displacement distribution map in y-direction (UY)

The displacement in the x-direction at the eastern part of Lembang fault has positive value while the western part is dominated with the negative value. Lembang fault has left-lateral slip component as the displacement value at the northern block is less than the displacement value at the southern block, so the northern and the southern blocks are moving to the left direction relatively to each other. Displacement distribution map the in y-direction also shows the displacement direction difference between the eastern and the western part of Lembang fault. The eastern part tends to displace with the negative value and the western part tends to displace with the positive value. The direction difference boundary is located near Tangkuban Perahu Mountain, the same place with the direction difference boundary shown at the displacement distribution map in the x-direction. From the similarities of the lineament shown in displacement distribution map in the x-direction and the y-direction, Lembang fault is interpreted to be divided into two segments, the eastern and the western segment, that separated by a lineament with northeast-southwest orientation with right-lateral slip component as shown in the displacement distribution map in the y-direction.
According to the displacement distribution map in the x-direction, Cimandiri fault is segmented into the eastern segment and the western segment. The eastern segment has left-lateral slip component that shown with the greater negative displacement value at the northern block compared with the southern block of Cimandiri fault. The western segment has right-lateral slip component that shown with the greater positive displacement value at the northern block compared with the southern block of Cimandiri fault. The boundary between the eastern and the northern segment of Cimandiri fault forms a lineament oriented at northwest-southeast direction at the western part of Gede Pangrango Mountain.

The displacement distribution map in the y-direction indicates that the western part of Cimandiri fault is divided into the eastern part of the western segment that tends to displace in the negative value and the western part of the western segment that tends to displace in the positive value. The eastern segment of Cimandiri fault has positive displacement value. The boundary between the eastern segment and the eastern part of the western segment of Cimandiri fault shows a lineament in the same place and orientation with the lineament that shown at the displacement distribution map in the x-direction of Cimandiri fault. This lineament has left-lateral slip component pursuant to the displacement distribution map in the y-direction. The boundary between the eastern part of the western segment and the western part of the western segment also shows a lineament that oriented at northwest-southeast direction with right-lateral slip component pursuant to the displacement distribution map in the y-direction. The displacement value between Lembang and Cimandiri fault is nearly zero as shown at the displacement distribution map in the x-direction and the displacement distribution map in the y-direction and indicates that the Lembang and Cimandiri fault are not connected each other.

4. Conclusion
The models that results from BEM calculation can show the fault segmentation with the input of displacement value near the fault. Lembang fault has left-lateral slip component and is interpreted to be divided into two segments, the eastern and the western segment, that separated by a lineament with northeast-southwest orientation with right-lateral slip component. Cimandiri fault is segmented into the eastern segment and the western segment. The eastern segment has left-lateral slip component and the western segment has right-lateral slip component. The western part of Cimandiri fault is divided into the eastern part of the western segment that tends to displace to south direction and the western part of the western segment that tends to displace to north direction. The displacement value between Lembang and Cimandiri fault is nearly zero indicates that the Lembang and Cimandiri fault are not connected each other, so the area between Lembang and Cimandiri fault is relatively safe for infrastructure development.

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