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EDITORIAL

A Novel Approach to Compute Isostatic Anomaly

A. Vasanthi
CSIR-National Geophysical Research Institute, Hyderabad - 500 007, India
E-mail: *vasanthi@ngri.res.in*

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INTRODUCTION

It is well known that the Earth is a dynamic system which responds to various surface and subsurface loads in different ways over longer geological periods. The isostasy describes the response of Earth to these loads and form an important limiting case in which the crust and mantle are in a state of equilibrium. The continents comprising of the belts of large mountains float on a denser mantle that behaves like a viscous fluid. Since the volume of the mantle rocks displaced by the roots of these mountains weigh far more than the roots themselves, it provides necessary buoyancy to keep the mountains in equilibrium.

In the 18th century, Pierre Bouguer, a French Geodesist and Mathematician, provided one of the first observations related to the deflections in the vertical plumb line caused by the presence of Mt. Chimborazo, which is the highest mountain in Ecuador. Mountain ranges act as the topographic expression of excess mass above a certain datum and thus there is a gravitational attraction towards the mountains. Its effect is manifested as a deflection of a survey plumb line, which needs to be measured relative to an established line of reference. Bouguer observed a deflection that was less than the gravitational attraction he anticipated, however, he did not provide any explanation for these deflections. In 1755, Ruggero Giuseppe Boscovich, an Italian astronomer, suggested that such deflection was caused by mass deficiency beneath the mountains. However, these observations went unnoticed till the triangulation surveys carried out in India during 1806-1843 by George Everest. He observed a discrepancy between geodetically and astronomically measured distances between two sites, Kalianpur near Kanpur and Kaliana in the foothills of Himalaya. The anomalously low plumb-line deflections were subsequently explained by the presence of mass deficiency at depth below the mountains, that led to two major hypotheses, one by Airy in 1855 and the other by Pratt in 1859. According to Airy, the Earth's crust is a rigid shell floating on a denser substratum, which behaves like a viscous fluid. Under the mountains, the crust bends and penetrates deeper into the substratum. Pratt was also of the same opinion as of Airy regarding mass deficiency, but provided a different scheme to explain the way compensation takes place. According to him, the crust remains uniform below the sea level. The major shift in this approach is the varying density of each block, floating on a homogeneous denser fluid. However, in both Airy and Pratt models, the compensation was assumed to be local. Subsequently, based on marine gravity measurements, Vening Meinesz felt that the lighter upper layer does float on a denser and weaker fluid substratum. According to him, the upper layer is an elastic plate. Therefore, any topographic load bends the elastic plate downward. The displaced fluid provides the buoyancy force to attain equilibrium. He envisaged that it is not just the central depression below the surface load, but isostatic compensation also comes from the regions far away from it.

Isostatic anomaly is a measure of the degree of compensation. Depending on the theory, different model-based approaches like, Airy-Heiskanen, Pratt-Hayford or Vening Meinsz, are now adopted to compute the isostatic anomaly. In the case of Airy-Heiskanen model, the required parameters in the computation include, crustal thickness, crustal density, and the density contrast between the lower crust and underlying mantle, which are determined by other methods, such as seismic refraction and measurement of rock densities. Therefore, to achieve high degree of accuracy, the onus lies on how accurately these three parameters can be estimated, as they vary from place to place, country to country and continent to continent. Therefore, assuming one density and one thickness value for the crust, appears to be an oversimplification. In case of Pratt-Hayford method, the density excess or deficit, is determined to the base of the crust for each column of land. Similarly, in case of Vening Meinsz technique, as the compensation has a local and a regional component, it would lead to more uncertainties to build such an Earth model.

A Novel Method for Computing Isostatic Anomaly

Considering the above factors, it was felt necessary to develop a technique, where all these assumptions can be eliminated, or at least minimized. With this backdrop, we at CSIR-NGRI, developed a novel technique, based on Finite Element Method (FEM), to compute the regional gravity component (Mallick and Sharma, 1999; Mallick et al., 2012, 2020; ; Vasanthi and Santosh, 2021). In this technique, only the observed gravity values at the nodes of the element are used in the regional computation, and no other data from the survey space will enter into the computation, thereby avoiding the anomalous zones present in the study area. This method is not site-specific, and thus does not require any *a priori* assumptions. In this approach, the regional gravity field is computed as a Dirichlet boundary value problem and employs the observed gravity values at the boundary of the finite element, which is square or rectangular. The element may be linear, if the boundary values are considered only at the four corners of the element (Fig. 1a), quadratic, if the field is considered at four corner nodes and at the mid-points of the sides (Fig. 1b), and cubic, if besides the corner points, two equidistant points on the sides (Fig. 1c) are also considered. However, in some cases, the anomalous zones may overlap some of the nodes of the element superimposing the gravity map, leading to erroneous results. In that case, there are two possible approaches. We can increase the element size if additional gravity data are available, otherwise, the observed gravity value at that node,

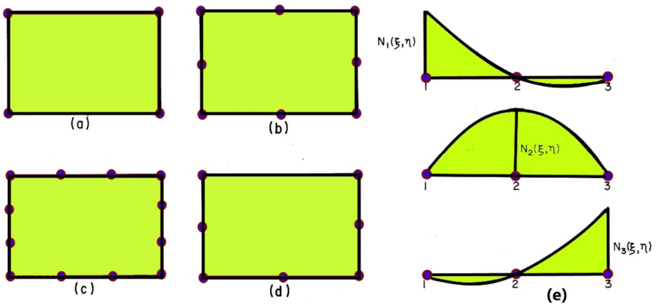

Fig. 1. Different types of elements - linear-4 node **(a)**, quadratic-8 node **(b)**, cubic-12 node **(c)**, irregular-7 node **(d)**, and weighting functions at different nodes of the 8-node element **(e)**.

which lies on the anomalous zone, can be skipped in the computation of regional component. This is termed as irregular element (Fig. 1d). However, the weighting coefficients (shape functions) need to be redefined keeping in mind the conditions that $\Sigma N_i(\xi, \eta) = 1$ at the i^{th} node and zero elsewhere, and $\Sigma N_i(\xi, \eta) = 1$ are fulfilled.

The governing equation for computing the regional gravity field at the midpoint of the element is

$$g_{reg}(\xi, \eta) = \Sigma_{i=1}^{8} N_i(\xi, \eta)\, g_i,$$

where g_i are the eight nodal gravity values. $\Sigma N_i(\xi, \eta)$, are the shape or weighting functions of the element given by:

$$N_i(\xi, \eta) = [(1 + \xi\xi_i)(1 + \eta\eta_i)(\xi\xi_i + \eta\eta_i - 1)] / 4 \quad \text{(For corner nodes i = 1, 3, 5, 7)}$$

$$N_i(\xi, \eta) = [(1 - \xi^2)(1 + \eta\eta_i)] / 2 \quad \text{(For mid-side nodes i = 2, 6)}$$

$$N_i(\xi, \eta) = [(1 - \eta^2)(1 + \xi\xi_i)] / 2 \quad \text{(For mid-side nodes i = 4, 8)}$$

Where ξ_i and η_i are the nodal co-ordinates. $N_i(\xi,\eta) = 1$ at i^{th} node and zero elsewhere and $\Sigma N_i(\xi, \eta) = 1$.

This regional component is then subtracted from the observed Bouguer gravity to obtain the residual anomaly.

Recent Studies on FEM Applications

Inherent advantage of Finite Element Method in separation of the regional and residual gravity components, led many investigators to use this technique to process the theoretical and field gravity data (Kaftan et al., 2005, 2010; Agarwal and Srivastava, 2010; Ekinci, 2010; Ekinci and Yigitbas, 2012, 2015; Hamai et al., 2015; Xu and Huo, 2020). Kaftan et al. (2010) have reported interesting results based on FEM application. They applied FEM and conventional methods to synthetic gravity (Fig. 2), as well as field data over Chintalpudi subbasin (India). Figure 2a shows the gravity response of three blocks of different volume, depth and density contrast. In this figure, first two blocks 1 and 2 (located at depths 5 and 15 km respectively) produce the residual gravity component, while the gravity response of block 3 (located at depth 50 km), was assumed to represent the regional effect. The regional anomalies for this model are derived by filtering technique (Fig. 2b), third-order polynomial (Fig. 2c), and FEM (Fig. 2d). It is seen from the figure that the gravity response of the deeper block (block 3) is interestingly enhanced in case of FEM (Fig. 2d), whereas the maximum gravity amplitudes could not be located over block 3 by

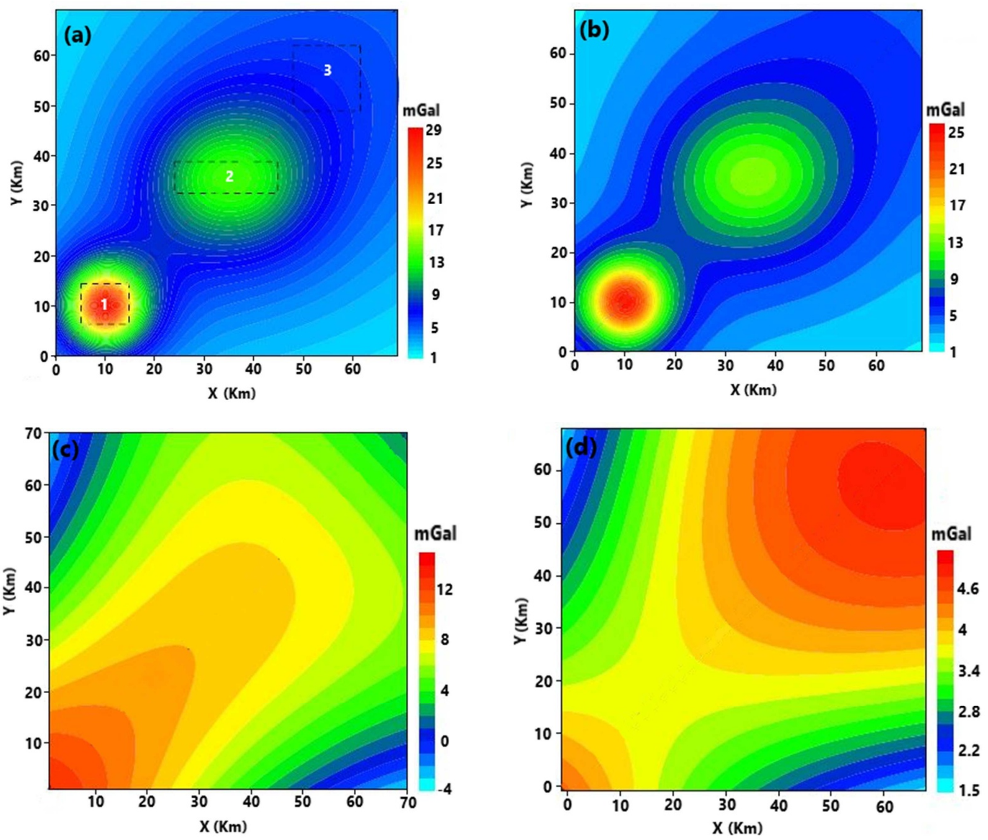

Fig. 2. Synthetic gravity anomaly over three blocks (1-3) having different volume and density contrast located at different depths **(a)**, regional gravity computed using low-pass filtering (cut-off frequency: 0.1 cycle/grid spacing) **(b)**, third-order polynomial **(c)**, and FEM technique **(d)**. (Modified after Kaftan et al., 2010). The first two blocks 1 and 2 produce the residual gravity component, while block 3 represent the regional effect.

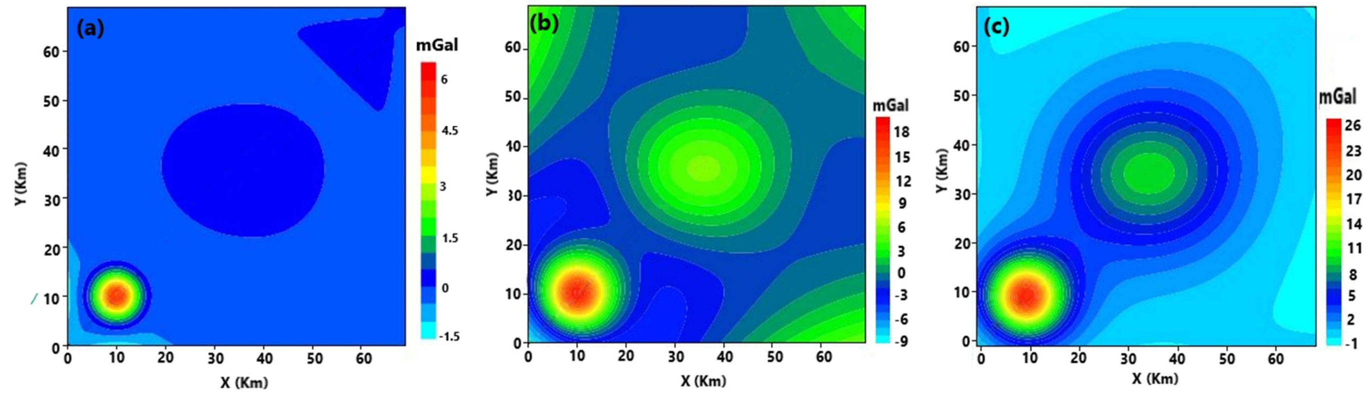

Fig. 3. Residual gravity component obtained using high-pass filtering (cut-off frequency: 0.1cycle/grid spacing) **(a)**, third-order filtering **(b)**, and FEM technique **(c)**. (Modified after Kaftan et al., 2010). The FEM residual appears far superior in terms of anomaly pattern and amplitude.

low-pass filtering and polynomial fitting procedure (Fig. 2b, c). Also, there are no pseudo anomalies present in the FEM regional, whereas they slightly contribute towards low-pass filtered regional (Fig. 2b). Figure 3 shows the corresponding residual gravity anomalies. The high-pass and third-order polynomial residuals (Fig. 3a, b) contain number of pseudo anomalies, making it unsuitable for further interpretation. In contrast, the FEM residual in Fig. 3c, appears far superior in terms of anomaly pattern and amplitude. FEM is thus having advantage over the filtering and polynomial fitting methods in computing the regional gravity component. Similarly, for the field gravity data, we observe the advantage of FEM over the other conventional methods in defining the anomaly pattern (Kaftan et al., 2010).

Besides, the Finite Element Method has an added advantage in removing the isostatic effect from the gravity field in areas having significant elevation discrepancies. We made a detailed study of the gravity field over North China Craton (NCC), which is one of the most geologically and geodynamically complex Archean craton in the world. In a recent study, Li and Yang (2020) computed the isostatic gravity anomalies over this craton based on the Vening-Meinesz model, where the thin elastic lithosphere flexes were imaged in response to internal and external loads. In addition to the topographic data, this model requires prior information of the geological parameters, such as (i) density contrast between upper mantle and crust, (ii) average density of the topographic load, water, apart from the density of the top layer, and (iii) normal crustal thickness and effective elastic thickness (T_e). They tested for a large range of T_e between 5 and 80 km values, and compared the resulting models with the approximate boundaries of the tectonic units and major faults from the tectonic map of that region. In addition, they tried for ranges of other parameters, such as normal crustal thickness of 30 and 35 km, density contrast between crust and mantle varying from 0.35 to 0.5 g/cm^3, which were inferred from the available seismic information on the region. Their final model parameters included normal crustal thickness of 30 km, density contrast 0.5 g/cm^3, and effective elastic thickness as 30 km, which resulted in isostatic residual anomaly map, as shown in Fig. 4a. However, the authors felt that the model parameters that have been chosen to arrive at final isostatic residual gravity anomaly were oversimplified to constant values in a general sense, and thus their model can be further improved by incorporating the lateral variations in T_e and density contrast. With this backdrop, we applied the FEM for this region to compute the isostatic residual gravity anomaly (Vasanthi and Santosh, 2021), which is shown in Fig. 4b. It shows similarity in magnitudes and anomaly patterns with the isostatic residual

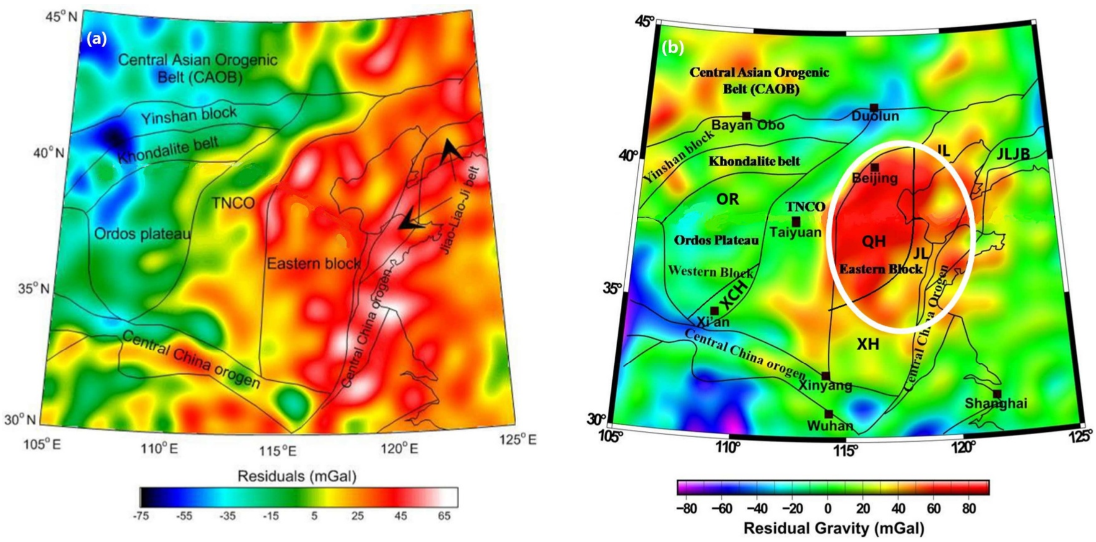

Fig. 4. Isostatic residual gravity anomaly obtained assuming Vening Meisnz model (modified after Li and Yang, 2020) **(a)**, FEM deduced isostatic gravity anomaly (modified after Vasanthi and Santosh, 2021), which brings out additional gravity anomalies with clearer boundaries over the different geotectonic terrains **(b)**. White enclosure represents the location of Jizhong depression in Bohai Basin (North China Craton), where Moho is uplifted by almost 20 km.

anomaly map derived by Li and Yang (2020). However, it is obvious that the FEM-derived residual gravity map, brings out additional gravity anomalies with clearer boundaries over the different geo-tectonic terrains, for example, the Bohai Bay Basin in the Eastern Block and Central Asian Orogen and Khondalite belts in the Western Block of NCC.

Need for the Revised Isostatic Anomaly Map of India

There is a general practice world-wide to periodically revise the gravity data base (Hinze et al., 2005). In India, CSIR-NGRI in collaboration with GSI, ONGC and OIL had launched a National Project namely, 'Revision of Gravity Map Series of India (RGMI)' during 1999-2000, to revise and improve the First Gravity Map Series of 1978, to maintain compatibility with international standards. Subsequently, a new and revised Gravity Map Series took its shape in the year 2006, which is based on more detailed gravity data and improved data reduction techniques. However, in this Series, the isostatic anomaly map has not yet been revised. In the First Map Series of 1978, the isostatic anomaly map of India was prepared by using Airy-Heiskanen hypothesis, wherein the crustal thickness is taken as 30 km, and the crustal and sub-crustal densities as 2.67 g/cm^3 and 3.27 g/cm^3 respectively. As mentioned above, assumption of one crustal thickness value and one density value for the entire continent may lead to inherent ambiguities. Therefore, there is a need to prepare a revised isostatic anomaly map of India following improved methodologies like FEM, which has distinct advantages over the other conventional methods.

It may be a mere coincidence that isostasy was basically discovered in India and a suitable method to compute it now also originates from here. Globally, where gravity values vary rapidly in areas such as younger orogens, syntaxes and subduction zones, isostatic anomalies computed using Finite Element Method will be of great help.

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