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Gravity anomalies of two-dimensional bodies

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ABSTRACT
Two simple and interesting rules are derived by extending the line integral method to find the equations for the gravitational attraction components due to a planar surface in the directions perpendicular and parallel to the surface itself. The attraction components, $G_{AB\perp}$ and $G_{AB\|}$, perpendicular and parallel to the surface AB are given by $G_{AB\perp} = 2\,\gamma\,\sigma\,R\,(Ø_B - Ø_A)$ and $G_{AB\|} = 2\,\gamma\,\sigma\,R\,\ln\,(r_A / r_B)$, where R is the perpendicular distance from a point of calculation to the face AB, r_A and r_B are the lengths of the radius vectors of A and B, $Ø_A$ and $Ø_B$ are the angles made by them with X-axis. These rules are found to be useful to derive the vertical and horizontal components of gravitational attractions of two dimensional bodies bounded by planar surfaces and their applicability is demonstrated by deriving the equations for gravity anomalies of finite inclined dike and trapezoidal prism. The correctness of the anomaly equations are verified by calculating and comparing the anomalies of dike and trapezoidal models with corresponding polygon models. The stability of inversion with these models and also with polygon models are studied by carrying out inversion of synthetic and field gravity anomalies.

INTRODUCTION

Interpretation of gravity anomalies is ambiguous unless the shape of the causative body is known (Roy, 1962). It is a common practice to assign a regular shape to the causative body, mainly based on geological constraints, to facilitate a meaningful interpretation. In the inverse modeling of gravity anomalies, the solution is stable if we constrain the geological model by a set of parameters. Fairly large number of parameters can be interpreted by the optimization techniques such as Marquardt's algorithm. The derivation of anomaly equation for a suitable model is an important aspect in the inverse modeling. A straight forward method of deriving the anomaly equation of a two-dimensitional body involves surface integration over the cross-section of the body. It has been observed that the derivation of anomaly equations of even simple models demands considerable effort (Bhimasankaram, Nagendra and Seshagiri Rao, 1977a; Bhimasankaram, Mohan and Seshagiri Rao, 1977b).

Gulatee (1938) published simple rules for vertical magnetic anomaly of two-dimensional bodies with planar surfaces, where as such equivalent rules are not published in the gravity data. During the course of interpretation of the gravity anomalies of different models, two interesting and simple rules have been found to derive the equations for gravity anomalies of various two dimensional models with planar surfaces. Hubbert (1948) has shown that the surface integral can be replaced by a line integral, and developed graticules to calculate the vertical component of gravitational attraction. Talwani et al (1959) have derived equations for the vertical and horizontal components of gravitational force of attraction of two-dimensional n-sided polygon. However, the inversion of the gravity anomalies with these equations is not stable in many cases as the number of parameters involved is more compared to the anomaly equations presented with model parameters. In this paper a method has been developed in which even the line integral can be evaluated by a set of rules, thus facilitating in easy derivation of anomaly equations of two-dimensional models with planar surfaces, and present the anomaly equations in terms of model parameters. This is another way of presenting the gravity anomaly equations apart from Talwani et al (1959). These rules are similar to Gulatee's (1938) in the magnetic case. As an illustration of the method, anomaly equations of an inclined dike and symmetrical trapezium are derived. Forward and inverse modeling have been carried out with these equations and compared with the equations of

Talwani et al (1959).

METHOD

Let AB represent a planar surface of a two-dimensional body dipping at an angle θ with the horizontal with reference to XOZ coordinate system (Fig.1). Let S(X, Z; r, Ø) be any point on the line AB. The line AB is any side of closed vertical cross-section of any two-dimensional body such as inclined dike (Fig. I), trapezium (Fig. II), etc.
Then the line integrals

$$V_{AB} = 2\gamma\sigma \int_{AB} Z \, d\text{Ø} \quad \text{....... (1)}$$

and

$$H_{AB} = 2\gamma\sigma \int_{AB} X \, d\text{Ø} \quad \text{....... (2)}$$

represent the vertical and horizontal components of gravitational attraction due to the face AB at the origin, O (Talwani et al, 1959). Let r_A and r_B be the lengths of the radius vectors of the points A and B respectively and let $Ø_A$ and $Ø_B$ be the respective angles made by them. Let R represents the perpendicular distance from the origin to the face AB. Instead of evaluating the vertical and horizontal components as given by equations (1) and (2), we evaluate the attraction components along perpendicular and parallel directions to AB. To achieve this, the coordinate system has been rotated by an angle θ in the clockwise direction. The new coordinate system is represented by X′OZ′ such that OX′ and OZ′ are parallel and perpendicular to AB respectively. The angles made by the radius vectors r_A and r_B are given by $Ø'_A$ and $Ø'_B$ respectively, and are obtained by subtracting θ from $Ø_A$ and $Ø_B$. Let the coordinates of the point S with reference to X′ OZ′ be (X′, Z′; r, Ø′). Then the line integrals

$$G_{AB\perp} = 2\gamma\sigma \int_{AB} Z' \, dØ' \quad \text{.......(3)}$$

and

$$G_{AB\|} = 2\gamma\sigma \int_{AB} X' \, dØ' \quad \text{.......(4)}$$

represent the components of gravitational attraction along Z′ and X′ axes respectively. In other words, these represent the components of gravitational attractions of AB along perpendicular and parallel directions to the face AB, and could easily be evaluated. Along AB, Z′ remains constant and hence, the perpendicular component is given by

$$G_{AB\perp} = 2\gamma\sigma Z' \int_{AB} dØ' = 2\gamma\sigma Z' (Ø'_B - Ø'_A) = 2\gamma\sigma Z' (Ø_B - Ø_A) \quad \text{....(5)}$$

The parallel component can be evaluated from tan $Ø' = Z'/X'$ and hence, $dØ' = -\,(Z'/r^2)\,dX'$, where $r^2 = X'^2+Z'^2 = X^2 + Z^2$. The parallel component is, therefore, given by

$$G_{AB\|} = 2\gamma\sigma \int_{AB} X' \, dØ' = 2\gamma\sigma Z' \ln (r_A / r_B) \quad \text{...(6)}$$

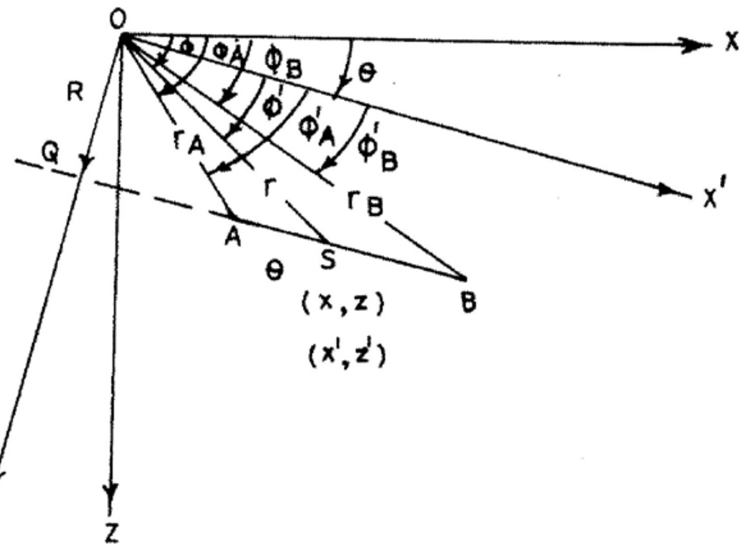

Figure 1. Transformation of coordinate system to evaluate the gravitational attraction components

In equation (5) and (6), Z′ represents the perpendicular distance from the origin to the face AB, and hence these could be given by

$$G_{AB\perp} = 2\,\gamma\,\sigma\,R\,(Ø_B - Ø_A) \quad \text{.........} \quad (7)$$

and

$$G_{AB\|} = 2\,\gamma\,\sigma\,R\,\ln\,(r_A / r_B). \quad \text{..........} \quad (8)$$

The values of R, $Ø_A$, $Ø_B$, r_A and r_B in equations (7) and (8) do not depend on the X′ O Z′ coordinate system. Hence, if the perpendicular distance from the point of calculation is known, then the equations (7) and (8) could be used directly to give the attraction components along perpendicular and parallel directions to the face. It should be noted that the direction of $G_{AB\perp}$ is along the perpendicular to the face from the origin (point of calculation) and the direction of $G_{AB\perp}$ is along parallel to the face such that this mutually perpendicular system conforms to the XOZ coordinate system. The angles $Ø_A$ and $Ø_B$ should be measured from positive X-axis towards positive Z-axis.

In other words R in equations (7) and (8) is considered to be positive if it meets the outer side of AB, and negative if meets the inner side of AB. If θ is the dip of the face AB measured positive in the clockwise direction from the horizontal, the vertical and horizontal components of gravitational attraction due to the face AB are given by

$$V_{AB} = G_{AB\perp}\cos\theta + G_{AB\|}\sin\theta$$
$$= 2\,\gamma\,\sigma\,R\,[\,(Ø_B - Ø_A)\cos\theta + \ln\,(r_A / r_B)\sin\theta] \quad \text{.......} \quad (9)$$

$$H_{AB} = -\,G_{AB\perp}\sin\theta + G_{AB\|}\cos\theta$$
$$= 2\,\gamma\,\sigma\,R\,[-\,(Ø_B - Ø_A)\sin\theta + \ln\,(r_A / r_B)\cos\theta] \quad \text{..........} \quad (10)$$

Equations (9) and (10) are useful to give the contributions of the face AB directly towards the vertical and horizontal components of gravitational attraction in terms of the parameters defining the model.

GRAVITY ANOMALIES

Application of the above method has been demonstrated by deriving the equations for the vertical and horizontal components of gravity anomalies of inclined dike and symmetrical trapezoidal models, and is given in the appendix. The resulting equations are simple, compact and convenient compared to those appearing in the literature. These equations are verified by calculating the anomalies with Z_1=1.0 km, Z_2=5.0 km, T=2.0 km, D=10.0 km, $\theta=60^0$ and σ=0.3gm/cc for both dike and trapezoidal models and are given in Table 1. The anomalies are also calculated with Talwani's equations with the corresponding values for the X-vertices: 12.0, 14.31, 10.31, 8.0 and the Z-vertices: 1.0, 5.0, 5.0 and 1.0 for the dike model and the X-vertices: 12.0, 14.31, 5.69, and 8.0 and the Z-vertices: 1.0, 5.0, 5.0, 1.0 for the trapezoidal model and are given in Table 1. It is found that the anomalies obtained by both the methods are coinciding with each other in the two cases, and thus confirming the correctness of the dike and trapezium anomaly equations.

INVERSION

The gravity anomalies (vertical field) given in Table 1 for dike and trapezoidal models are considered for comparison with the inversion of the anomalies. As the inversion also estimates the regional, a regional field of 10 mgals is added to these anomalies. The inversion is carried out using the Marquardt algorithm (Bhaskara Rao and Ramesh Babu 1991, 1993). The dike anomalies with two decimal accuracy is taken and carried out the inversion using the initial values for Z_1 = 0.5 Km, Z_2 = 4.0 Km, T = 1.5 Km, D = 11.0 Km, $\theta = 60^0$, σ = 0.3 gm/cc and the Datum = 5.0 mgal and all the parameters of the dike are accurately obtained. Similar results are also obtained with the polygon model with corresponding initial values. To stimulate errors, the data is truncated to 1 mgal accuracy and the inversion is carried out using the dike model and the polygon model. Satisfactory results are obtained with dike and polygon models with the density contrast of 0.3 gm/cc. However, satisfactory results could not be obtained with polygon model of five and more vertices even when the density contrast is constrained. The anomalies due to trapezoidal model are also inverted with the equations given in the text and also with polygon model. As in the case of the dike model similar results are obtained here also. These results show that inversion with regular models is more

Table 1. Gravity anomalies of dike and trapezium

x	DIKE				TRAPEZIUM			
	Δg(x)		ΔH(x)		Δg(x)		ΔH(x)	
	Present method	Talwani method	Present method	Talwani method	Present method	Talwani method	Present method	Talwani method
0	1.40	1.40	5.41	5.41	3.15	3.15	9.22	9.22
1	1.67	1.67	5.88	5.88	3.84	3.84	10.00	10.00
2	2.02	2.02	6.43	6.43	4.75	4.75	10.89	10.89
3	2.50	2.50	7.08	7.08	5.99	5.99	11.86	11.86
4	3.16	3.16	7.85	7.85	7.68	7.68	12.85	12.86
5	4.11	4.11	8.77	8.77	10.02	10.02	13.76	13.76
6	5.57	5.57	9.84	9.84	13.22	13.22	14.28	14.28
7	7.93	7.93	10.93	10.93	17.45	17.45	13.82	13.82
8	11.76	11.79	11.20	11.21	22.30	22.33	11.23	11.21
9	16.28	16.28	8.94	8.94	25.80	25.80	6.04	6.04
10	19.24	19.23	4.43	4.44	26.89	26.89	-0.01	0.00
11	19.89	19.89	-1.06	-1.06	25.80	25.80	-6.04	-6.04
12	17.83	17.80	-6.19	-6.21	22.36	22.33	-11.20	-11.21
13	13.96	13.96	-9.04	-9.04	17.45	17.45	-13.82	-13.82
14	10.50	10.50	-9.82	-9.82	13.22	13.22	-14.28	-14.28
15	7.86	7.86	-9.63	-9.63	10.02	10.02	-13.76	-13.76
16	5.94	5.94	-9.05	-9.05	7.68	7.68	-12.85	-12.86
17	4.55	4.55	-8.34	-8.34	5.99	5.99	-11.86	-11.86
18	3.55	3.55	-7.64	-7.64	4.75	4.75	-10.89	-10.89
19	2.83	2.83	-6.98	-6.98	3.84	3.84	-10.00	-10.00
20	2.29	2.29	-6.40	-6.40	3.15	3.15	-9.22	-9.22

stable than with polygon model.

The anomalies of the polygon ABCDE with vertices (10.0,1.0), (14.0,3.0), (12.0,6.0), (8.0,5.0) and (7.0,2.0) are calculated with a constant density contrast of 0.3gm/cc and a constant regional of 10.0 mgal is added to these anomalies and plotted in Fig .2. Inversion of these anomalies is carried out using the polygon model with six vertices and dike and trapezoidal models by the Marquardt algorithm. The density contrast of 0.3gm/cc is constrained in all these three cases. The results of inversion for the polygon model are shown as dotted lines in Fig.2. Satisfactory model is not obtained with six vertices. The model is still worse with seven and more vertices. The inversion results for the dike and trapezium are also plotted in Fig.2. These studies show that the inversion with dike and trapezoidal models is satisfactory and more stable compared with polygon model.

Fig.3 shows the interpretation of a gravity anomaly profile over the lower Godavari valley, Andhra Pradesh, India, located approximately at

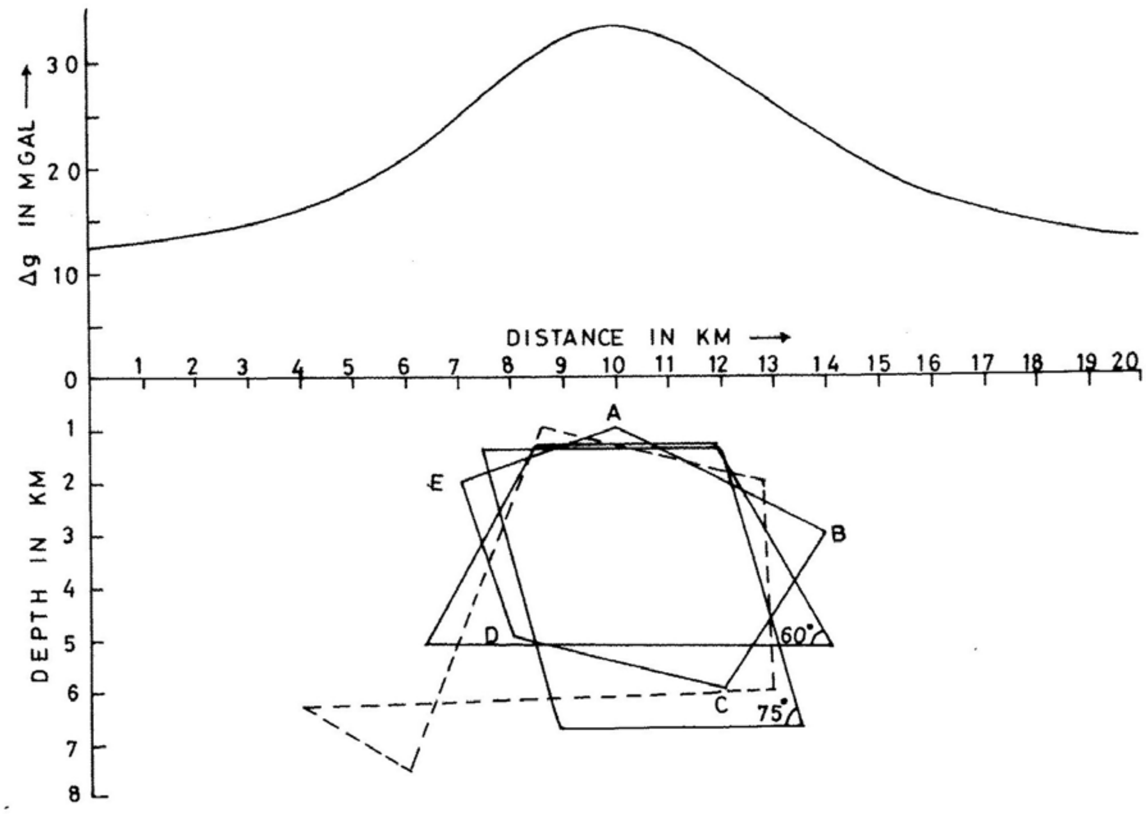

Figure 2. Inversion of gravity anomalies over a polygon model

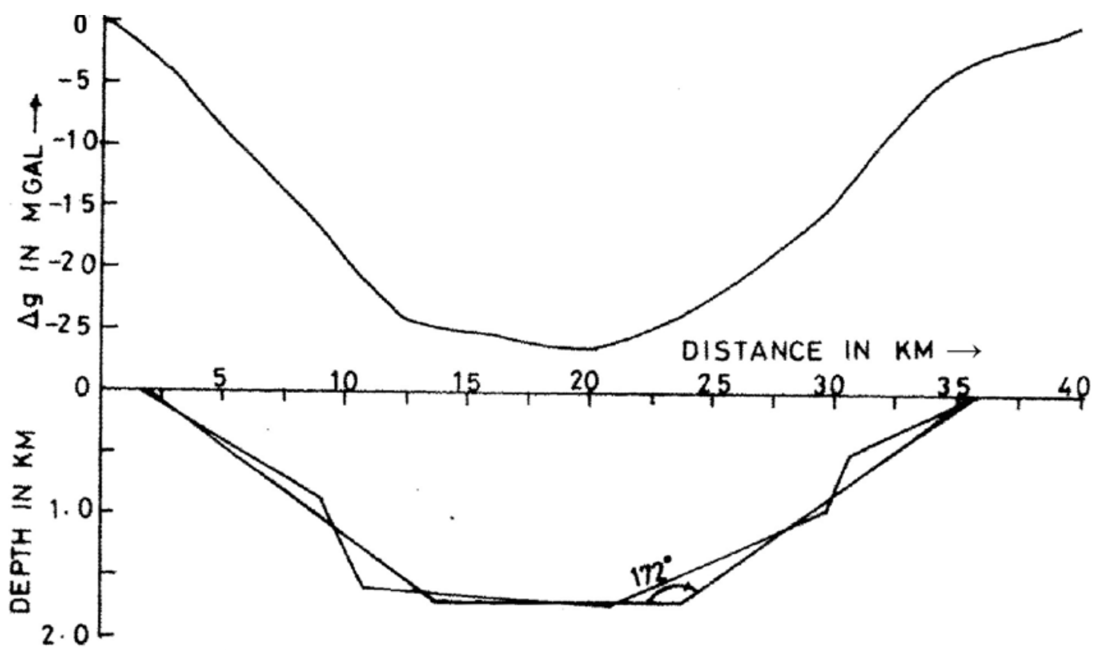

Figure 3. Inversion of gravity anomalies over Godavari valley

17°N and 81°E with a strike direction NW-SE using trapezoidal and polygon models. This profile is taken from Bhaskara Rao and Venkateswarulu (1974), who interpreted it by considering the basin as two outcropping faults with constant density contrast of -0.4gm/cc. The depth to top and density contrast for both the models are constrained at 0.001 km and -0.4gm/cc respectively. The results of inversion for these models are plotted in Fig .3. These results are nearly the same.

DISCUSSION

The line integral method is extended to derive the equations for the gravitational attraction components due to a planar surface of a two-dimensional body, in the directions perpendicular and parallel to the surface itself. These attraction components are related to various geometrical elements of the face in a simple manner as given by equations (7) and (8). Many structures in sedimentary strata could be approximated by models bounded by planar surfaces. This method is used here to derive the equations for the vertical and horizontal components of gravitational attractions of finite inclined dikes and trapezoidal prisms. The resulting equations are simple, compact and convenient to program than the corresponding equations appearing in the literature. The method is particularly simplified if some of the faces of the model are horizontal and / or vertical as the horizontal and vertical components could be directly obtained. As seen in various examples given in the text, the perpendicular distances even to inclined faces can be obtained easily. These equations are similar to Gulatee's (1938) rules in the magnetic case. The method developed in this paper is useful to the students as well as researchers as the gravity anomaly equations could be derived very easily for any two-dimensional model bounded by planar surfaces. This is another way of presenting the anomaly equations in terms of parameters of the model instead of vertices.

Anomalies calculated using the anomaly equations of dike and trapezoidal models are coinciding with the anomalies calculated using polygon models with corresponding values of the vertices, thus confirming the correctness of the equations derived in the text. Inverse modeling is carried out using dike and trapezoidal models and compared with the polygon model. The results show that the inversion with regular models is more stable than with polygon models in some cases. The equations (7) and (8) derived here are useful to consider a suitable model depending on the geology and derive the corresponding equations easily.

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APPENDIX

The anomaly equations for finite inclined dike and trapezoidal models are derived here as follows:

a) FINITE INCLINED DIKE

Let OX represents the X-axis perpendicular to the strike of a finite inclined dike, whose vertical cross-section is given by ABCD (Fig. I). The origin of the coordinate system is chosen at O, which is the epicenter of a point bisecting AB. Z axis is positive downwards. The dike is dipping at an angle θ, whose upper and lower surfaces are at depths of Z_1 and Z_2 respectively. The width of the dike is given by 2T. Let r_1, r_2 ,r_3 and r_4 be the radius vectors from the point P(X ,O) to A,B,C and D respectively. Let $Ø_1$, $Ø_2$, $Ø_3$ and $Ø_4$ be the angles made by the radius vectors r_1, r_2, r_3 and r_4 respectively with X-axis. Lines CB and DA are extrapolated so that they meet X-axis at E and F respectively, and PQ and PR are perpendiculars from P to BC and AD respectively. Let PQ = R_1 and PR = R_2. From Fig. I, EP = X – T + Z_1 cot θ. Hence, R_1= EP sin θ = (X– T) sin θ + Z_1 cos θ. Similarly, R_2 = FP sin θ = (X+T) sin θ + Z_1 cos θ.

Let us evaluate the attraction components of AB, BC, CD and DA in the directions perpendicular and parallel to themselves. From equation (7), the gravitational component perpendicular to AB, $G_{AB\perp}$ is given by

$$G_{AB\perp} = 2\,\gamma\,\sigma\,Z_1\,(\varnothing_2 - \varnothing_1)$$

Similarly, from equation (8) the gravitational component parallel to AB, $G_{AB\|}$, is given by

$$G_{AB\|} = 2\,\gamma\,\sigma\,Z_1 \ln\,(r_1 / r_2).$$

Here the dip of the face is 0^0 and hence, the vertical and horizontal components, from equations (9) and (10) are given by

$$V_{AB} = 2\,\gamma\,\sigma\,Z_1\,(\varnothing_2 - \varnothing_1)$$
$$H_{AB} = 2\,\gamma\,\sigma\,Z_1 \ln\,(r_1/r_2).$$

The gravitational component perpendicular to BC, $G_{AB\perp}$ is given by

$$G_{AB\perp} = 2\,\gamma\,\sigma\,R_1\,(\varnothing_3 - \varnothing_2).$$

The gravitational component parallel to BC, $G_{BC\|}$ is given by

$$G_{BC\|} = 2\,\gamma\,\sigma\,R_1 \ln\,(r_2 / r_3).$$

Here the dip of the face is θ and, hence, from equations (9) and (10),

$$V_{BC} = G_{BC\perp} \cos\theta + G_{BC\|} \sin\theta$$
$$= 2\,\gamma\,\sigma\,R_1\,[\,(\varnothing_3 - \varnothing_2) \cos\theta + \ln\,(r_2 / r_3) \sin\theta\,]$$

and

$$H_{BC} = -\,G_{BC\perp} \sin\theta + G_{BC\|} \cos\theta$$
$$= 2\,\gamma\,\sigma\,R_1\,[-\,(\varnothing_3 - \varnothing_2) \sin\theta + \ln\,(r_2 / r_3) \cos\theta]$$

The gravitational component perpendicular to CD, $G_{CD\perp}$, is given by

$$G_{CD\perp} = -\,2\,\gamma\,\sigma\,Z_2\,(\varnothing_4 - \varnothing_3).$$

The gravitational component parallel to CD, $G_{CD\|}$, is given by

$$G_{CD\|} = -\,2\,\gamma\,\sigma\,Z_2 \ln\,(r_3 / r_4).$$

Here the dip of the face is 180^0 and hence, the vertical and horizontal components are given by

$$V_{CD} = 2\,\gamma\,\sigma\,Z_2\,(\varnothing_4 - \varnothing_3)$$

and $$H_{CD} = 2\,\gamma\,\sigma\,Z_2 \ln\,(r_3 / r_4).$$

The gravitational component perpendicular to DA, $G_{DA\perp}$ is given by

$$G_{DA\perp} = -\,2\,\gamma\,\sigma\,R_2\,(\varnothing_1 - \varnothing_4).$$

The gravitational component parallel to DA, $G_{DA\|}$ is given by

$$G_{DA\|} = -\,2\,\gamma\,\sigma\,R_2 \ln\,(r_4 / r_1).$$

Here the dip of the face = $\pi + \theta$. Hence, the vertical and horizontal components are given by

$$V_{DA} = G_{DA\perp} \cos(\pi+\theta) + G_{DA\|} \sin(\pi+\theta)$$
$$= 2\,\gamma\,\sigma\,R_2\,[\,(\varnothing_1 - \varnothing_4) \cos\theta + \ln\,(r_4 / r_1) \sin\theta\,]$$
$$H_{DA} = -\,G_{DA\perp} \sin(\pi+\theta) + G_{DA\|} \cos(\pi+\theta)$$
$$= 2\,\gamma\,\sigma\,R_2\,[-\,(\varnothing_1 - \varnothing_4) \sin\theta + \ln\,(r_4 / r_1) \cos\theta]\,.$$

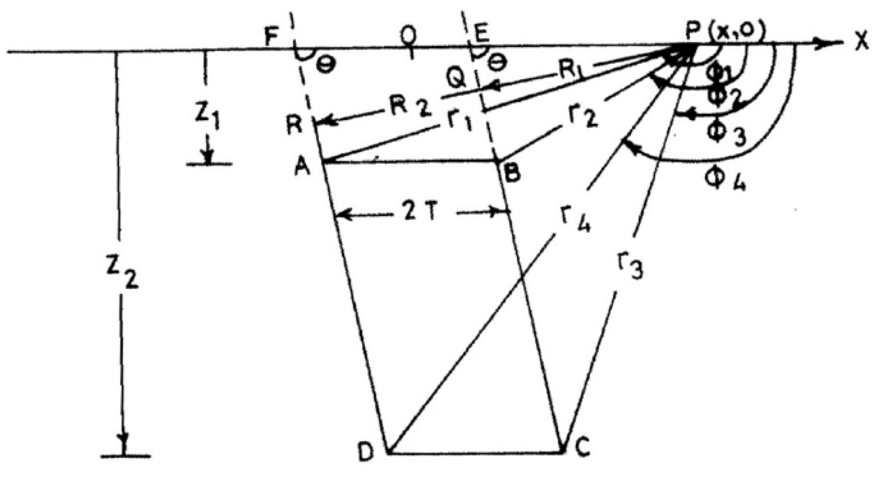

Figure I. Geometrical elements involved for a finite inclined dike.

The vertical and horizontal components of the dike can be obtained by summing the respective components of the individual faces. Thus,

$V(X,O) = V_{AB}+V_{BC}+V_{CD}+V_{DA}$
$= 2\,\gamma\,\sigma\,[Z_1\,(Ø_2 - Ø_1) + Z_2\,(Ø_4 - Ø_3) + R_1\{(Ø_3 - Ø_2)\cos\theta + \ln(r_2/r_3)\sin\theta\} + R_2\{(Ø_1 - Ø_4)\cos\theta + \ln(r_4/r_1)\sin\theta\}]$ ....(11) and

$H(X,O) = H_{AB}+H_{BC}+H_{CD}+H_{DA}$
$= 2\,\gamma\,\sigma\,[Z_1 \ln(r_1/r_2) + Z_2 \ln(r_3/r_4) + R_1\{(Ø_2 - Ø_3)\sin\theta + \ln(r_2/r_3)\cos\theta\} + R_2\{(Ø_4 - Ø_1)\sin\theta + \ln(r_4/r_1)\cos\theta\}]$ ....(12)

where

$r_1^2 = (X+T)^2 + Z_1^2$

$r_2^2 = (X-T)^2 + Z_1^2$

$r_3^2 = (X - T - \overline{Z_2 - Z_1}\cot\theta)^2 + Z_2^2$

$r_4^2 = (X + T - \overline{Z_2 - Z_1}\cot\theta)^2 + Z_2^2$

$Ø_1 = \pi/2 + \arctan(X+T)/Z_1$

$Ø_2 = \pi/2 + \arctan(X-T)/Z_1$

$Ø_3 = \pi/2 + \arctan(X - T - \overline{Z_2 - Z_1}\cot\theta)/Z_2$ and

$Ø_4 = \pi/2 + \arctan(X + T - \overline{Z_2 - Z_1}\cot\theta)/Z_2$ as shown in Fig. I.

b) TRAPEZOIDAL PRISM

Let ABCD represents a vertical cross-section of a two-dimensional trapezoidal prism (Fig. II), whose faces AB and CD are horizontal and the faces BC and AD are inclined to the horizontal with an angle θ. The origin of the coordinate system is chosen at O, which is the epicenter of a point bisecting AB. X-axis is along OP and Z-axis is positive downwards. Let AB = 2T. Let P(X,O) be any point at which we shall derive the equations for the gravity anomaly. The lines CB and DA are extrapolated to meet the X-axis at E and F respectively. From Fig. II,

$EP = X - T + Z_1 \cot\theta$ and hence,
$R_1 = EP\sin\theta = (X - T)\sin\theta + Z_1\cos\theta.$

Similarly, $FP = X + T - Z_1\cot\theta$, hence
$R_2 = FP\sin\theta = (X+T)\sin\theta - Z_1\cos\theta.$

With the usual notation, we could immediately write down the gravitational attraction components of various faces as follows:

$V_{AB} = G_{AB\perp} = 2\,\gamma\,\sigma\,Z_1\,(Ø_2 - Ø_1)$
$H_{AB} = G_{AB\parallel} = 2\,\gamma\,\sigma\,Z_1 \ln(r_1/r_2)$
$V_{BC} = G_{BC\perp}\cos\theta + G_{BC\parallel}\sin\theta$
$= 2\,\gamma\,\sigma\,R_1\,[(Ø_3 - Ø_2)\cos\theta + \ln(r_2/r_3)\sin\theta]$

$H_{BC} = -G_{BC\perp}\sin\theta + G_{BC\parallel}\cos\theta$
$= 2\,\gamma\,\sigma\,R_1\,[-(Ø_3 - Ø_2)\sin\theta + \ln(r_2/r_3)\cos\theta]$
$V_{CD} = -G_{CD\perp} = 2\,\gamma\,\sigma\,Z_2\,(Ø_4 - Ø_3)$
$H_{CD} = -G_{CD\parallel} = 2\,\gamma\,\sigma\,Z_2 \ln(r_3/r_4)$
$V_{DA} = -G_{DA\perp}\cos(2\pi - \theta) + G_{DA\parallel}\sin(2\pi - \theta)$
$= 2\,\gamma\,\sigma\,R_2\,[-(Ø_1 - Ø_4)\cos\theta + \ln(r_4/r_1)\sin\theta]$

and
$H_{DA} = -G_{DA\perp}\sin(2\pi - \theta) - G_{DA\parallel}\cos(2\pi - \theta)$
$= 2\,\gamma\,\sigma\,R_2\,[-(Ø_1 - Ø_4)\sin\theta - \ln(r_4/r_1)\cos\theta]$

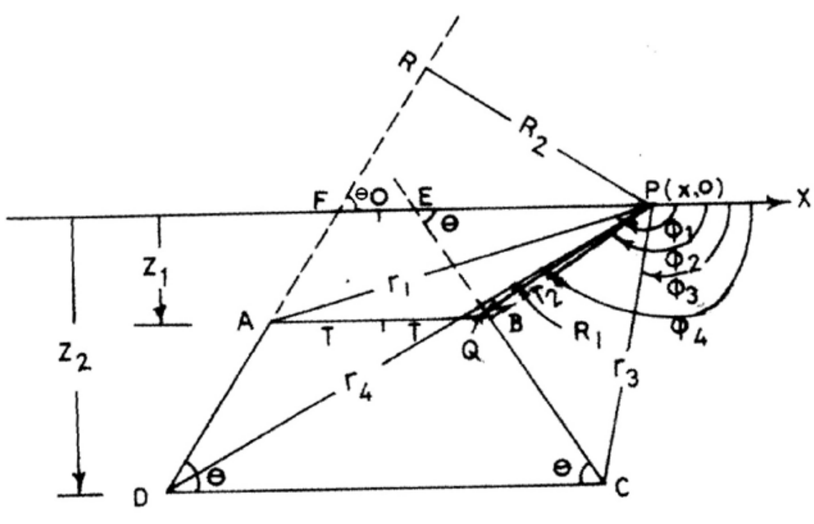

Figure II. Geometrical elements involved for a trapezoidal prism.

Hence,

$$V(X,O) = V_{AB} + V_{BC} + V_{CD} + V_{DA}$$
$$= 2\,\gamma\,\sigma\,[\,Z_1\,(\varnothing_2 - \varnothing_1) + Z_2\,(\varnothing_4 - \varnothing_3) + R_1\,\{(\varnothing_3 - \varnothing_2)\cos\theta + \ln(r_2/r_3)\sin\theta\} + R_2\,\{(\varnothing_4 - \varnothing_1)\cos\theta + \ln(r_4/r_1)\sin\theta\}] \quad ......(13)$$

$$H(X,O) = H_{AB} + H_{BC} + H_{CD} + H_{DA}$$
$$= 2\,\gamma\,\sigma\,[\,Z_1 \ln(r_1/r_2) + Z_2 \ln(r_3/r_4) + R_1\,\{(\varnothing_2 - \varnothing_3)\sin\theta + \ln(r_2/r_3)\cos\theta\} - R_2\,\{(\varnothing_1 - \varnothing_4)\sin\theta + \ln(r_4/r_1)\cos\theta\}] \quad .... (14)$$

where r_1 to r_4 and $\varnothing_1$ to $\varnothing_4$ are the distances and angles as defined in Fig. II. If the distances are measured from the reference point (left end of the profile), then X should be replaced by X-D in the above equations; where D is the distance of the origin from the reference point.

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