Chapter 2
Methods Based on the Absorption of Gamma-Ray Beams by Matter

Abstract Physical effects of a gamma-ray beam passing through matter as a basis for soil density determination is discussed. These effects for moderate-energy gamma rays are the photoelectric and Compton effects and production of electron-positron pairs in the electric field of the nuclei. In order to justify this general statement the narrow and broad gamma-ray beams were experimentally analysed. It is shown that for light elements and intermediate-energy of gamma rays the mass absorption coefficient μ is independent from the atomic number and consequently on the chemical composition of the material. This effect creates the physical basis for use of gamma-ray absorption for measuring the density of multi-component media like rock and soil material. The mass absorption coefficient for gamma-rays is an important parameter for absorbing media, governing the sensitivity of the gamma-ray absorption method, the degree to which such measurements represent the medium as a whole and the reliability of density measurements. Studies of moisture dynamics in soils and other ground materials, evaporation processes and also determination of the amount of water stored in the snow cover by the gamma-ray absorption method are discussed in this chapter.

2.1 Main Principles

Methods based on gamma-ray absorption are used most widely for measuring the in situ bulk density of soil and rock materials in geoengineering and hydrogeological studies. It is also used for the study of moisture dynamics in an unsaturated zone and for direct measurement of snow water content at the assessment of a water balance. The basic principle of these methods is that the absorption of a given gamma-ray beam in a particular material depends on the total mass between the source and detector and under certain conditions the transmitted gamma-ray intensity depends only on the bulk density of the absorbing medium (Babinets and Zvolsky 1961; Danilin 1957; Artsybashev 1965; Ferronsky et al. 1968, 1977; International Atomic Energy Agency 1968, 1983, 1999; Clayton 1983).

Since the absorption method can be used to determine the mass of the material along the path traversed by the gamma rays, it follows that in this sense the method is equivalent to weighing as a means of determining mass. Moreover, the ground or

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rock material can be "weighed" with the aid of the gamma rays under natural conditions, i.e., in situ. Ground layers 40–50 cm thick can be explored in this way and the mean density for the entire layer can thus be determined. Hence, in contrast to the direct sampling method, the gamma-ray absorption method provides bulk density data that are more representative for the soil material. The advantages of the method are as follows:

a. The measurements can be carried out directly in the field with low expenditure of labour and time;
b. The density of any ground can be measured independently of its granulometric, mineralogical and chemical composition and also independently from its aggregate state, structural properties and texture;
c. The method can be used to determine the density of ground and rock material of any consistency (quicksand, water-saturated sand, clay, etc.).

It is well known that moderate-energy gamma rays undergo the following basic interactions with matter: (a) total absorption (photoelectric effect), (b) Compton scattering by electrons and (c) production of electron-positron pairs in the electric field of the nucleus:

$$\sigma = \sigma_{ph} + \sigma_c + \sigma_{pp}, \tag{2.1}$$

where σ_{ph}, σ_c and σ_{pp} are the partial cross-sections describing the above three basic interactions. The probability of interaction of a gamma ray with matter per unit path length is called the linear absorption coefficient, which is defined by:

$$\mu_0 = \sigma n_a, \tag{2.2}$$

where n_a is the number of atoms per unit volume of the material. The reciprocal of the linear absorption coefficient is defined as the mean free path:

$$\lambda = \frac{1}{\mu_0}. \tag{2.3}$$

The ratio of the linear absorption coefficient to the density of the medium is the mass absorption coefficient:

$$\mu = \frac{\mu_0}{\rho}. \tag{2.4}$$

The possible energy change when gamma rays interact with matter can be divided into three ranges. In each range one of the above three basic interactions is the most probable (Table 2.1). At low energies, gamma rays interact mainly through the photoelectric effect. Compton-effect predominates at intermediate energies and, finally, pair production is the leading process at high energies.

In the energy range in which Compton scattering predominates, the mass absorption coefficient μ is a very slowly varying function of the atomic number Z. In fact,

Table 2.1 Gamma-ray energy ranges in which one of the three basic interactions predominates. (Leypunsky et al. 1960)

Medium	Photoelectron effect (keV)	Compton effect	Pair production (MeV)
Air	E≤20	20 keV<E<23 MeV	E>23
Aluminium	E≤50	50 keV<E<15 MeV	E>15
Iron	E≤120	120 keV<E<9.5 MeV	E>9.5
Lead	E≤500	500 keV<E<4.7 MeV	E>4.7

$$\mu = \frac{\sigma_c n_a Z}{\rho} = \sigma_c Z \frac{A_0}{A}, \tag{2.5}$$

where Z is the charge of the nucleus; A is the atomic weight; A_0 is Avogadro's number; and ρ is the density of the material. In light nuclei, in which the number of protons and neutrons is the same, the Z/A ratio is constant and equal to 1/2. Therefore:

$$\mu \approx \frac{1}{2}\sigma_c A_0 Z = \text{const.} \tag{2.6}$$

The exception is hydrogen, for which Z/A=1.

It follows from Fig. 2.1 that for light elements and intermediate-energy gamma rays the mass absorption coefficient μ is independent from the atomic number and

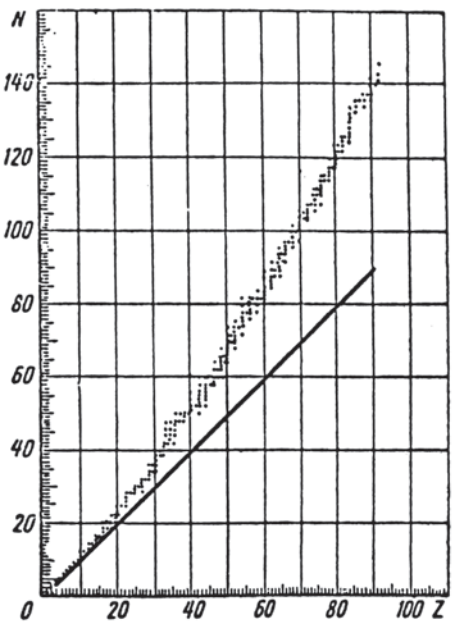

Fig. 2.1 Dependence on number of neutrons (*N*) per atom of atomic number Z for stable isotopes: ------—Z/A=1/2; ····—Z/A<1/2

consequently of the chemical composition of the material. This is the physical basis for use of gamma-ray absorption at intermediate energy in measurements of density of multi-component media such as rock and soil material.

2.2 Transmission of Narrow and Broad Gamma-Ray Beams Through Matter

The absorption of a narrow beam of gamma rays in a given material is described by exponential law:

$$I = I_0 e^{-\mu\rho x}, \tag{2.7}$$

where I_0 is the beam intensity at the point of observation in the absence of the absorbing material; I is the intensity in the presence of the absorbing material; ρ is the density of the medium in g/cm^3; and x is the thickness of the medium traversed by the beam in cm.

For a narrow gamma-ray beam originating in an isotropic and mono-energetic point source, the above absorption formula can be rewritten in the form:

$$I = \frac{Q_S}{4\pi R^2} \cdot e^{-\mu\rho x}, \tag{2.8}$$

where Q_S is the activity of the source in counting rate per second; R is the distance between the source and the point of observation.

In the absence of the absorbing medium the gamma-ray intensity at a point at a distance x from the source is given by:

$$I_0 = \frac{Q_S}{4\pi x^2}, \tag{2.9}$$

If the gamma-ray intensity is measured at a distance x by a suitable detector of efficiency ε, then the gamma-ray counting rate is given by:

$$n_\gamma = I_\varepsilon, \tag{2.10}$$

and the quantity:

$$n_0 = \frac{Q\varepsilon}{4\pi x^2} = I_0\varepsilon \tag{2.11}$$

is the counting rate in the absence of the absorbing medium. From Eq. (2.7) we find that the counting rate recorded by the detector can be written in the form:

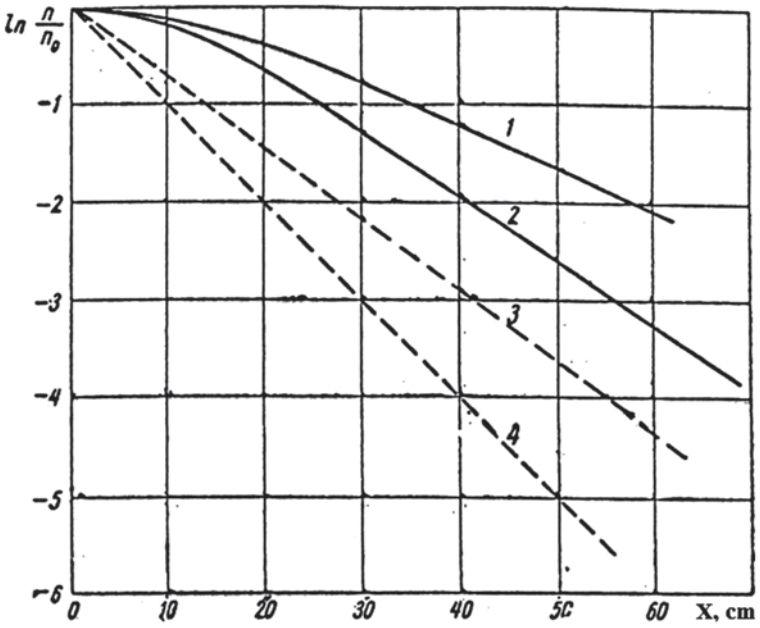

Fig. 2.2 Curves of gamma-ray beam attenuation from the point source of ^{60}Co (*1*, *3*) and ^{137}Cs (*2*, *4*) in a sand medium of 1.3 g/cm^3: *1* and *2* are for a broad beam of gamma rays; *3* and *4* are for a narrow beam of gamma rays. (Ferronsky et al. 1968)

$$n = n_0 e^{-\mu\rho x}, \tag{2.12}$$

and hence

$$\rho = \frac{\ln(n_0/n)}{\mu x}. \tag{2.13}$$

Therefore, by measuring the ratio n_0/n, which gives the degree of attenuation of the gamma-ray beam in the medium under investigation, we can determine the density of the medium if we know the mass absorption coefficient μ. It also follows from Eq. (2.12) that, if the absorption curve is plotted on a semi-logarithmic scale, the result is a straight line (Fig. 2.2).

Equations (2.7) and (2.12) are valid only in the case of narrow-beam geometry. This condition is difficult to achieve in practice because it requires the use of a large collimating system (Fig. 2.3a). A more common procedure in practice is to use a broad (Fig. 2.3b) or partially collimated gamma-ray beam that has passed through the medium but also multiply scattered secondary gamma rays. The semi-logarithmic graph of the gamma-ray intensity as a function of distance from the source will then lie above the straight line corresponding to the narrow-beam geometry and the slope of this curve will be increasing over the initial section of the curve (see Fig. 2.2).

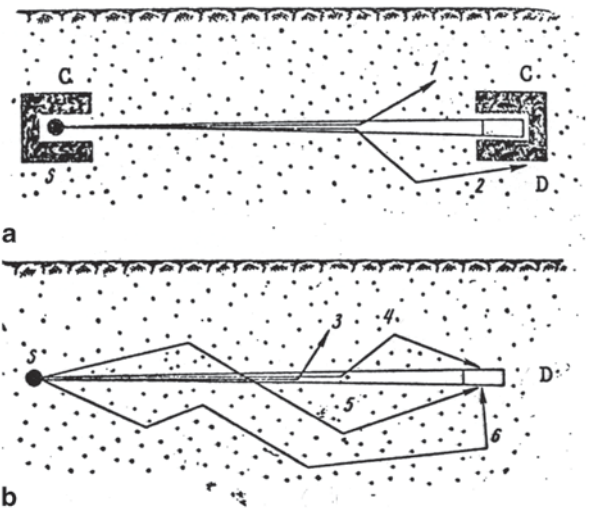

Fig. 2.3 Narrow (**a**) and broad (**b**) beam geometry: *S* is the gamma-ray source, *D* is the detector, *C* is the collimators, *1* and *3* are singly scattered gamma rays, *2*, *4*, *5*, *6* are the multiply scattered gamma rays. (Ferronsky et al. 1968)

Compton scattering is the main effect responsible for the appearance of secondary gamma rays. For example, in the case of 1 MeV gamma rays in water, the mean number of Compton scatterings is greater by a factor of about 14 than the mean number of photoelectric events.

In each interaction the gamma rays lose energy and these losses are on average much smaller for low-energy gamma rays. Secondary gamma rays must therefore accumulate in the low-energy part of the spectrum. This build up is restricted by the fact that as the energy of the scattered gamma rays decreases, there is a rapid increase in the photoelectric contribution to the overall absorption.

Since the secondary gamma rays have a broad energy distribution and can propagate in different directions, in effect "forgetting" their previous history, the broad-beam geometry problem cannot be regarded as solved if only the intensity at a given point in the medium is known. To obtain a complete description of the gamma-ray field we must know the spectral and angular distributions at a given point in the medium. It is frequently sufficient to have the integral characteristics of the gamma-ray field. As a rule, these are more readily determined experimentally. The attenuation of a broad gamma-ray beam is thus described by the expression:

$$I = BI_0 e^{-\mu\rho x}, \tag{2.14}$$

where B is the so-called build-up factor, which is usually determined experimentally. It depends on the energy of the primary gamma rays, the type of detector and geometry of the experiment.

A very fruitful practical device has been the use of the effective mass absorption coefficient beam μ_{eff} for a broad beam, in which case the absorption law is described by an expression similar to (2.12) except that μ is replaced by μ_{eff}. The effective mass absorption coefficient depends on the same parameters as the built-up factor B and is also determined experimentally (see below).

Measurements on a broad monochromatic gamma-ray beam of moderate energy and originating from a point source in an infinite homogeneous medium without heavy impurities show that:

1. As the distance from the source increases, there is an increase in the contribution of multiply scattered gamma rays to the total intensity.
2. Equilibrium in the energy and angular distributions is established at a certain distance from the source.
3. The maximum of the energy distribution of multiply scattered gamma rays occurs at about 0.05–0.08 MeV.

In the region where the scattering radiation reaches equilibrium energy distribution the absorption of a broad gamma-ray beam again follows the exponential law. This is indicated by the fact that absorption curves plotted on the semi-logarithmic scale again become a straight line (Fig. 2.2).

Finally, in the region of the equilibrium, i.e., where there is no substantial redistribution of the spectral components of the transmitted gamma rays, the value of μ_{eff} is practically constant and the spectral sensitivity of the detectors has little effect upon it. Thus, for a ^{60}Co point source the effective mass absorption coefficient is $\mu_{eff} \approx 0.037–0.040$ cm^2/g for different types of gas-filled and scintillation counters.

In the case of broad–beam geometry, even a small amount of absorbing material ensures that most of the recorded intensity consists of a softer secondary component for which photoelectric absorption is important. It follows that, in the case of rocks containing heavy-atom impurities (Fe, Cu, Zn, Pb, Sn etc.), the effective mass absorption coefficient μ_{eff} will depend on the concentrations of these elements and unambiguous density determinations become very difficult. These impurities absorb strongly the soft-scattered component as a result of the photoelectric effect, so that the spectral distribution of the radiation is distorted and the density measurements are subject to errors.

2.3 Mass Absorption Coefficients of Rocks

The mass absorption coefficient for gamma rays is an important parameter of absorbing media, governing the sensitivity of the gamma-ray absorption method, the degree to which such measurements represent the medium as a whole and the reliability of density measurements of soil and rock material by the method. The magnitude of this coefficient depends largely on the gamma-ray energy. Under certain conditions μ_{eff} is practically independent from the chemical composition of the rock and soil material. This is exceedingly important, because it ensures that the method is very general.

For gamma-ray energies of approximately 0–20 MeV and the most important elements in soil and rock materials, the mass absorption coefficients decrease with increasing gamma-ray energy (Table 2.2). A particularly rapid reduction in the value of this coefficient is observed between 0 and 0.5 MeV. This is due to the rapid reduction in the probability of photoelectric absorption with increasing gamma-ray energy.

Table 2.2 Mean mass absorption coefficient μ (cm^2/g) for ^{60}Co and ^{137}Cs sources in various rocks

Rock	^{60}Co	^{137}Cs
Soils	0.0565	0.0767
Igneous rocks	0.0559	0.0760
Sedimentary rocks	0.0563	0.0767
Sandstone	0.0560	0.0761
Clayey rocks	0.0563	0.0767
Limestone rocks	0.0563	0.0769
Pure sand	0.0563	–
Water	0.0627	–
Mean value of μ for the above rocks	0.0562	0.0765

Table 2.3 Values of μ of ^{60}Co and ^{137}Cs gamma rays for the most important rock-forming elements

Element	Si	Al	O	Na	Mg	K	Ca	Fe	C	H
^{60}Co	0.0560	0.0546	0.0566	0.0539	0.0559	0.0547	0.0558	0.0534	0.0566	0.112
^{137}Cs	0.0774	0.0764	0.0771	0.0734	0.0760	0.0752	0.0768	0.0727	0.0771	0.0144

Photoelectric absorption, which is very dependent on the atomic number, increases rapidly at low energies (0–100 keV) so that it is difficult to establish unambiguous values for the density of multi-component media.

We have used data given by Rukhin (1961) on the chemical composition of some rocks to calculate the value of μ for these materials. The values of μ were calculated on the basis of data published by Leypunsky et al. (1960). The absorption coefficient μ was found to be practically the same for these very different rocks (Artsybashev 1965).

In fact, the deviation of μ for ^{60}Co and ^{137}Cs gamma rays is only slightly dependent on the composition including water. Density measurements on soil and rock materials by the gamma-ray absorption method are therefore usually carried out with the natural moisture content.

While the Z/M ratio for elements making up the soil and rock material is 0.5, in the case of hydrogen this ratio is equal to unity. Hence the value of μ for hydrogen is higher by a factor of 2 than for the other elements in the soil material (see Table 2.3). It follows that the mass absorption coefficient of water is higher by 11 % as compared with the rock skeleton.

Tables 2.3 and 2.4 give the values of μ for the main chemical element and compound (sand-clay and carbonate) rocks. These values were calculated using the experimental data published by Leypunsky et al. (1960) interpolated to the energy of ^{60}Co and ^{137}Cs and applying a second- order polynomial and the Lagrange method.

The moisture content is the most important factor affecting the mass absorption coefficient and hence the accuracy of bulk density determination.

Table 2.4 Values of μ of ^{60}Co gamma rays and the most important compounds in sedimentary rocks

Compound	SiO_2	Al_2O_3	Fe_2O_3	FeO	CaO	MgO	K_2O	Na_{2O}	CO_2	H_2O
μ	0.0563	0.0555	0.0544	0.0542	0.0561	0.0561	0.0554	0.0553	0.0586	0.0627

We can estimate the error that is introduced if one neglects the difference between the mass absorption coefficients of water and the soil skeleton when the bulk density ρ_w of moist soil material of thickness h_s is determined. In this case the expression (2.13) acquires the form:

$$\rho_w = \frac{\ln(n_0/n)}{\mu_s h_s}. \tag{2.15}$$

On the other hand, taking into account the difference between μ_w and μ_s, one has:

$$\rho_w = \frac{\ln(n_0/n)}{\mu_s h_s} - \frac{\rho_w h_w}{\mu_s h_s}. \tag{2.16}$$

Expressing the value of $h_w \rho_s h_s/100$, we obtain:

$$\rho_w = \frac{\ln(n_0/n)}{\mu_s h_s} - \frac{\mu_w - \mu_s}{\mu_s}\frac{w\rho_s}{100}, \tag{2.17}$$

where w is the natural moisture content (%).

The second term in this equation is a measure of the absolute error in the density measurement by the gamma-ray absorption method if we use the μ_s for moist soil. Consequently,

$$\Delta\rho = \frac{\mu_w - \mu_s}{\mu_s}\cdot\frac{w\rho_s}{100} = -0.11\frac{w\rho_s}{100}. \tag{2.18}$$

The relative systematic error is therefore given by:

$$\delta = \frac{\Delta\rho}{\rho} = -0.11w. \tag{2.19}$$

As the moisture content increases, this error will also increase. Thus, for a moisture content of w = 10, 20 and 30 % the systematic errors in the bulk density measurements will be 1.1, 2.2 and 3.3 %, respectively.

A narrow gamma-ray beam depends on the size and shape of the collimating apertures and also on the collimator materials. Any collimating system can readily be developed and used under stationary laboratory equipment for the determination of the density of rocks and other materials (Artsybashev 1965; Filippov 1962).

The use of collimation under field conditions, on the other hand, is practically impossible or involves major technological difficulties. In most cases, therefore, field measurements of the density of rocks by the gamma-ray absorption method are carried out with broad-beam geometry and either slight collimation or no collimation at all (Fig. 2.3).

This can be done in two ways. In the first method, use is made of (2.13) with μ_{eff} determined in a preliminary experiment for the given type of the density-measuring equipment. The second method involves the use of a calibration graph giving the intensity of the recorded radiation (or some function of it) versus the density.

The theoretical (calculated) values of μ_{eff} are the basic control data that one should try to obtain in the development of the measuring apparatus and method. The closer the value of μ_{eff} is to the theoretical, the more accurate will be the final density (other things being equal). It is therefore important to select the conditions of the measurement so that they ensure the maximum possible value for μ_{eff}.

Dubinchuk (1966) carried out an experimental study of the dependence of μ_{eff} on the mass ρx of material. Such experiments must be carried out on media that are homogeneous in density for a broad range of thickness, which is difficult to achieve in natural soil material. Homogeneous concrete plates were therefore made for these experiments. Their size was $50 \times 50 \times 5$ cm and their density lay between 0.56 and 2.1 g/cm^3. The values of μ were calculated from the known chemical composition for ^{60}Co (0.056 cm^2/g) and ^{137}Cs (0.076 cm^2/g). Stacks of plates of the required thickness and density were placed between the radiation source and the detector and the transmitted gamma-ray intensity was recorded.

The gamma-ray counting rate was first determined without the absorbers (in air) and then with the absorber in position. The gamma-ray detector was a scintillation-counter spectrometer [NaI(Tl) phosphor of 30×40 mm, working in conjunction with an FEU-29 photomultiplier] incorporating a single-channel analyser, so that it was possible to record the pulse-height spectra transmitted by the absorbers (Fig. 2.4a, b).

The pulse height corresponding to the gamma rays is plotted along the horizontal axis and is normalised to the height of the photo-peak (total absorption peak) corresponding to direct radiation, i.e., it is given in units of $V/V_{0.66}$ for the ^{137}Cs and $V/V_{1.25}$ for ^{60}Co. For the sake of convenience, the gamma-ray spectra are normalised in the area. The primary gamma-ray photo-peaks are clearly seen on the right of the spectra recorded by the scintillation counter. These are due to the photoelectric effect in the scintillator. In the soft part of the spectrum there are peaks scattered component predominates in the recorded gamma radiation. For an absorber thickness of 3–4 mean free paths there is no substantial redistribution of the spectrum components, i.e., equilibrium is set up in the spectral composition.

Figure 2.5a and b show on a semi-logarithmic scale and relative units the gamma-ray absorption curves for ^{60}Co and ^{137}Cs obtained for different levels of amplitude discrimination. The absorber layer thickness in units of the mean free path, $Z = x/\lambda = \mu\rho x$, is plotted along the horizontal axis. It follows from Fig. 2.5 that the absorption curve obtained for a narrow beam of ^{60}Co gamma rays was the same to within the experimental error as the theoretical curve calculated from Eq. (2.12)

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