



**International
Standard**

ISO 6640

**Measurement of density of water-
sediment mixture using radiation
transmission method**

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Contents

	Page
Foreword	iv
Introduction	v
1 Scope	1
2 Normative references	1
3 Terms and definitions	1
4 Protection against ionizing radiation	2
5 Properties of sediments	2
5.1 General.....	2
5.2 Particle size.....	2
6 Principles of radiation transmission and backscattering methods	2
6.1 General.....	2
6.2 Principle of gamma and X-ray transmission method.....	2
6.3 Principle of gamma ray backscattering method.....	5
7 Calibration procedure	6
Annex A (informative) Prototypes of instruments	7
Annex B (informative) Calibration	9
Annex C (informative) Case study: Measurement of vertical profile of water-sediment mixture density	12
Bibliography	14

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO document should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

Radiation transmission method for measuring the density of water-sediment mixture in water bodies such as rivers, dams and harbours has been employed for many years. It can continuously measure the suspended sediment concentrations providing data for optimal operation and better management of dams, reservoirs and navigation channels. The major applications of the radiation transmission method are:

- a) maintenance of navigation channels,
- b) optimization of dredging operations,
- c) management of dams and reservoirs.

Dams and reservoirs are vital in terms of water supply, irrigation and electricity generation. Large investments are needed for maintenance and efficient operation of dams and reservoirs. Sustainable operation of dams and reservoirs requires an in-depth understanding and monitoring of sedimentation rates.

In harbour navigation channels, radiation transmission method is applied to measure nautical depth. The method supplements the preliminary indications provided by ultrasound devices.

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Measurement of density of water-sediment mixture using radiation transmission method

1 Scope

This document specifies the radiation transmission method for measurement of density of the water-sediment mixture, suspended or deposited, in water bodies such as streams, canals, harbour basins, dams and reservoirs.

The method is based on principles of transmission of X or Gamma rays. This document covers brief description of the operating principle of the method and details of some of the instruments used.

This document applies to the measurement of water-sediment mixture density in water bodies using radiation transmission method, particularly gamma and X-ray transmission method. The working principles, applications, advantages and associated instruments are elaborated in this document.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 772, *Hydrometry — Vocabulary and symbols*

ISO 4363, *Measurement of liquid flow in open channels — Methods for measurement of characteristics of suspended sediment*

ISO 11657, *Hydrometry — Suspended sediment in streams and canals — Determination of concentration by surrogate techniques*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 772, ISO 4363, ISO 11657 and the following apply.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

- ISO Online browsing platform: available at <https://www.iso.org/obp>
- IEC Electropedia: available at <https://www.electropedia.org/>

3.1 radiation transmission method

gamma, X-ray transmission method to measure the density of water-sediment (3.2) mixture in water bodies

3.2 sediment

solid particles derived from rocks, biological materials or chemical precipitants, that are transported by, suspended in or deposited by flowing water

Note 1 to entry: Sediment usually means inorganic material and consists of clay, silt, sand or gravel.

4 Protection against ionizing radiation

Exposure of any part of the human body to ionizing radiation can be injurious to health.

5 Properties of sediments

5.1 General

Water-sediment mixture density is affected by physical properties of the sediments.

5.2 Particle size

Sediments under study can be classified by their grain size, from clay to sand. The Wentworth's classification is one of the most widely used classifications for sediments, as given below:

- sand: particles between 0,063 mm to 2 mm in diameter,
- silt: particles between 0,002 mm to 0,063 mm in diameter,
- clay: particles less than 0,002 mm in diameter.

Sediments can be divided into cohesive and non-cohesive classes. Silt and clay are cohesive while the sand is non-cohesive. According to the Wentworth classification, fine or pelitic sediments, known as mud, are those with dimensions lesser than 0,063 mm.

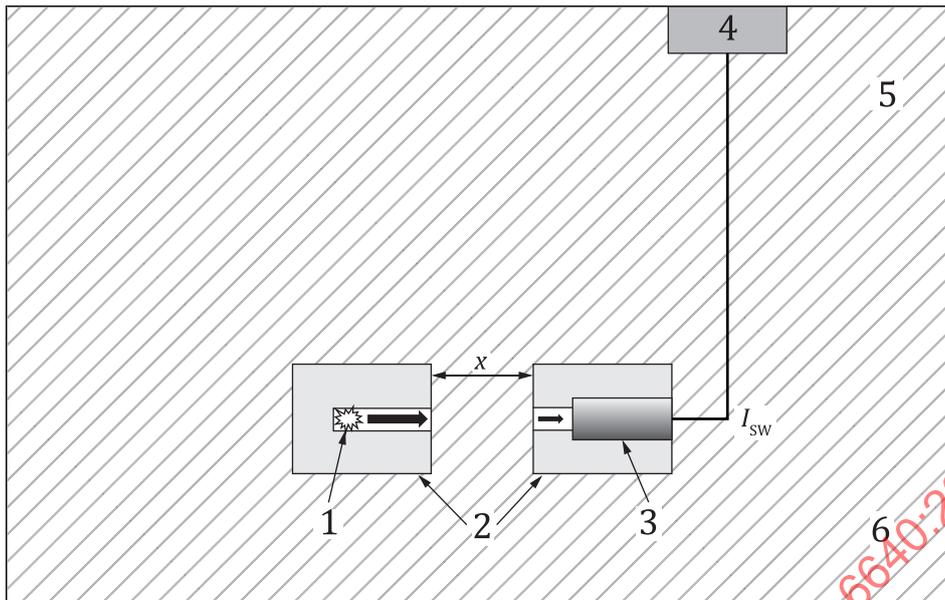
6 Principles of radiation transmission and backscattering methods

6.1 General

Both radiation transmission and backscattering methods can be used for measurement of density of water-sediment mixture in water bodies. The methods enable measurement of a wide range of densities. The typical instruments used in these methods are presented in [Annex A](#).

6.2 Principle of gamma and X-ray transmission method

The measurement is based on the attenuation of a collimated beam of gamma or X-rays traversing through the water-sediment mixture in the direction of a collimated detector mounted on opposite side of the source (see [Figure 1](#)).



Key

- 1 radiation source
- 2 collimators
- 3 radiation detector
- 4 data acquisition system on a boat
- 5 water
- 6 sediment water mixture
- x thickness of water column
- I_{sw} intensity of transmitted radiation

Figure 1 — Principle of the gamma and X-ray transmission method

When a monoenergetic beam of radiation impinges on a water column of thickness x cm, the intensity of the transmitted radiation I_w (counts/unit time) is given as:

$$I_w = I_0 \cdot e^{-\mu_w \cdot x} \quad (1)$$

where

I_0 is the radiation intensity measured in the air;

μ_w is the linear attenuation coefficient of water, in cm^{-1} .

In the water-sediment mixture, the intensity of the transmitted radiation, I_{sw} , is given as:

$$I_{sw} = I_0 \cdot e^{-\mu_{sw} \cdot x} \quad (2)$$

where μ_{sw} is the linear attenuation coefficient of the water-sediment mixture.

The linear attenuation coefficient, μ_{sw} , is defined as:

$$\mu_{sw} = v_w \mu_w + v_s \mu_s \quad (3)$$

where, μ_s is the linear attenuation coefficient of sediment; v_w and v_s are the volume fraction of water and sediment in the mixture, respectively. As the sediment concentration is c , (the weight of sediment in 1 cm³ of the mixture) the volume fractions are defined as:

$$v_s = \frac{c}{\rho_s} \quad (4)$$

$$v_w = 1 - v_s = 1 - \frac{c}{\rho_s} \quad (5)$$

where, ρ_s is the sediment density.

[Formula \(3\)](#) can be modified by substituting the volume fractions:

$$\mu_{sw} = v_w \mu_w + v_s \mu_s = \left(1 - \frac{c}{\rho_s}\right) \mu_w + \frac{c}{\rho_s} \mu_s = \mu_w + \frac{c}{\rho_s} (\mu_s - \mu_w) \quad (6)$$

[Formula \(2\)](#) can be modified by substituting the linear attenuation coefficient, μ_{sw} :

$$I_{sw} = I_0 \cdot e^{-\mu_{sw} \cdot x} = I_0 \cdot e^{-\left(\mu_w + \frac{c}{\rho_s} (\mu_s - \mu_w)\right) \cdot x} = I_0 \cdot e^{-\mu_w \cdot x} \cdot e^{-\frac{c}{\rho_s} (\mu_s - \mu_w) \cdot x} = I_w \cdot e^{-\frac{\mu_s - \mu_w}{\rho_s} \cdot x \cdot c} \quad (7)$$

By taking natural logarithm of [Formula \(7\)](#):

$$\ln \frac{I_{sw}}{I_w} = -\frac{\mu_s - \mu_w}{\rho_s} \cdot x \cdot c \quad (8)$$

The density (ρ_m) of water-sediment mixture with concentration c can be calculated using the following formula:

$$\rho_m = c + \left(1 - \frac{c}{\rho_s}\right) \rho_s = \frac{\rho_s - 1}{\rho_s} c + \rho_s \quad (9)$$

Therefore:

$$c = \frac{\rho_s}{\rho_s - 1} \rho_m - \frac{\rho_s}{\rho_s - 1} \rho_s \quad (10)$$

[Formula \(8\)](#) can be modified by substituting the concentration c using [Formula \(10\)](#):

$$\ln \frac{I_{sw}}{I_w} = -\frac{\mu_s - \mu_w}{\rho_s} \cdot x \cdot \left(\frac{\rho_s}{\rho_s - 1} \rho_m - \frac{\rho_s}{\rho_s - 1} \rho_s\right) = -\frac{\mu_s - \mu_w}{\rho_s - 1} \cdot x \cdot \rho_m + \frac{\mu_s - \mu_w}{\rho_s - 1} \cdot x \cdot \rho_s \quad (11)$$

Let the constant terms, $-\frac{\mu_s - \mu_w}{\rho_s - 1} \cdot x$ and $\frac{\mu_s - \mu_w}{\rho_s - 1} \cdot x \cdot \rho_s$ be denoted by A and B , respectively, then [Formula \(11\)](#)

is simplified as:

$$\ln \frac{I_{sw}}{I_w} = A \cdot \rho_m + B \quad (12)$$

To obtain the values of constant, A and B , the intensities of the transmitted radiation, I_{sw} , are measured with water-sediment mixtures of known densities. A calibration curve is obtained by plotting the measured data. The slope and intercept of the curve provide the values of constant A and B . Once values of A and B

are obtained, the density of water-sediment mixture can be calculated from the measured intensity of the transmitted radiation, I_{sw} , using the following formula:

$$\rho_m = \frac{\ln \frac{I_{sw}}{I_w} - B}{A} \quad (13)$$

[Formula \(12\)](#) is valid for monoenergetic beam of radiation. However, in practice it is not always possible to use monoenergetic beam of radiation; especially nowadays when X-ray tubes are preferred instead of sealed gamma radiation sources.

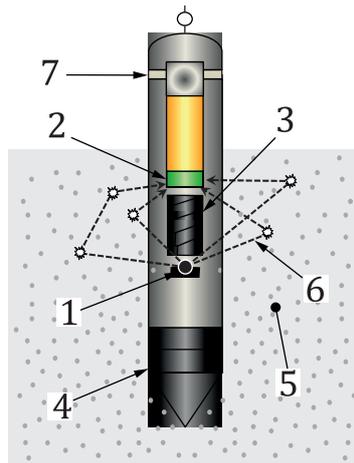
In such situations, the linear relationship in [Formula \(1\)](#) is not theoretically valid i.e. there might be no true linear relationship between $\ln(I_{sw})$ and ρ_m . Therefore, an experimental calibration curve should be prepared and utilized for estimating the density of sediments from the measured intensity of the transmitted radiation, I_{sw} . In most of the cases, the experimental calibration curves look linear as shown in a typical experimental calibration curve given in [Annex B](#). A case study is discussed in [Annex C](#).

6.3 Principle of gamma ray backscattering method

Principle of the gamma ray backscattering method for measurement of density of water-sediment mixture is shown in [Figure 2](#). The backscattered response signal is a function of density of the water-sediment mixture.

Rather high-energy gamma rays are generally employed in backscattering method. In principle, X-rays and lower energy gamma rays can also be used but one need to be careful as these radiations are much more sensitive to elemental composition of sediments. This means that if the X-ray energy is close at the absorption edge of a chemical element, the scattering yield is no longer only a function of the density of the surrounding material. If X-rays or low-energy gamma rays (60 keV gamma from ^{241}Am) are used, the "extra" absorption will have to be accounted for while plotting the calibration curve and also expressed in the formula. The relative effect of this absorption is of course dependent on the energy used and the elemental content, and concentration of the mud. Therefore, the instrument should be calibrated using the same mud composition as in the real field experiment. Thus, it is not feasible to make use of X-ray and low energy gamma sources for backscattering method. The gamma ray source generally used in backscattering method is ^{137}Cs .

The devices using backscattering method are cylindrical or conical in shape to ensure maximal geometrical efficiency and possibility to penetrate the sediment deposits. The density of the water-sediment mixture is determined from the relationship between the concentration of the sediments in the mixture in the monitored environment and the signal generated by the detector.

**Key**

- 1 gamma source
- 2 radiation detector
- 3 radiation shield
- 4 ballastic weight
- 5 sediments
- 6 scattered radiations
- 7 pressure gauge

Figure 2 — Principle of gamma ray backscattering method

The backscattered count rate, R_{sw} , measured by the detector in the mixture is a function of sediment concentration and is related to the count rate, R_w , of the gamma rays measured in pure water by the formula:

$$\frac{R_{sw}}{R_w} = (a \cdot \rho)^n \cdot \exp(-a \cdot \rho) \quad (14)$$

where, ρ (g/cm^3) is the density of water-sediment mixture, while 'a' and 'n' are constants characterizing the measuring setup and are obtained experimentally by calibration in laboratory under simulated field conditions. [Formula \(14\)](#) is an empirical relation obtained based on extensive laboratory calibrations.

7 Calibration procedure

Calibration is an important aspect of measuring the density of water-sediment mixture using transmission and backscattering methods. The purpose of the calibration is to establish a curve that correlates the measured radiation intensity (count rate) with the density of the water-sediment mixture. It has to be determined in laboratory condition prior to field measurements, using the native sediment of the field site. The good homogenization of the water-sediment mixture is a precondition of the measurements.

The steps of the calibration procedure (see [Annex B](#)) are:

- addition of native sediments,
- homogenization of the mixture,
- measurements in the homogenized mixture, and
- sampling from the homogenized mixture.

The calibration is required for each experimental site.

Annex A (informative)

Prototypes of instruments

A.1 Instruments based on transmission method

A.1.1 Gamma ray transmission instrument

[Figure A.1](#) shows a gamma ray transmission instrument used for water-sediment mixture density measurement.

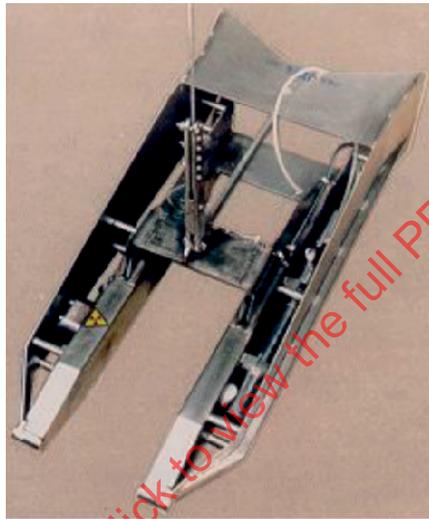


Figure A.1 — Gamma ray transmission instrument

This transmission instrument can be used for density measurement in static or dynamic mode.

The main characteristics are:

- maximum water depth: 100 m
- measuring range of relative densities: 1,02 to 1,35
- gamma radiation source / activity: ^{137}Cs / 222 MBq, ^{241}Am / 20 GBq.

A.1.2 X-ray transmission instrument

[Figure A.2](#) shows an X-ray transmission instrument used for measuring water-sediment mixture density. It is mostly used for obtaining static or dynamic vertical density profiling of water sediment mixture.



Figure A.2 — X-ray transmission instrument

The main characteristics are:

- maximum water depth: 100 m
- measuring range of relative densities: 1,02 to 1,35
- radiation Source: X-ray micro-tube of 30 keV.

A.2 Instrument based on backscattering method

[Figure A.3](#) shows a typical gamma backscattering instrument used for water-sediment mixture density measurement. It is mostly employed to control sediments deposited in harbour basins, navigation channels, dams and reservoirs. This instrument is suitable for vertical density profiles.



Figure A.3 — Gamma backscattering instrument

The main characteristics of the instrument are:

- maximum water depth: 100 m
- measuring range of densities: 30 g/l to 1 000 g/l
- Gamma radiation source / activity: ^{137}Cs / 18,5 MBq

Annex B
(informative)

Calibration

B.1 Calibration procedure

Calibration is necessary for measuring the density of water-sediment mixture using transmission and backscattering methods. It has to be determined in laboratory prior to the field measurements. This document deals with radiation transmission method only.

[Figure B.1](#) shows the calibration procedure of the instrument based on radiation transmission method.



a) Adding native sediments



b) Homogenization of the water-sediment mixture



c) Placing the instrument into the calibration tank

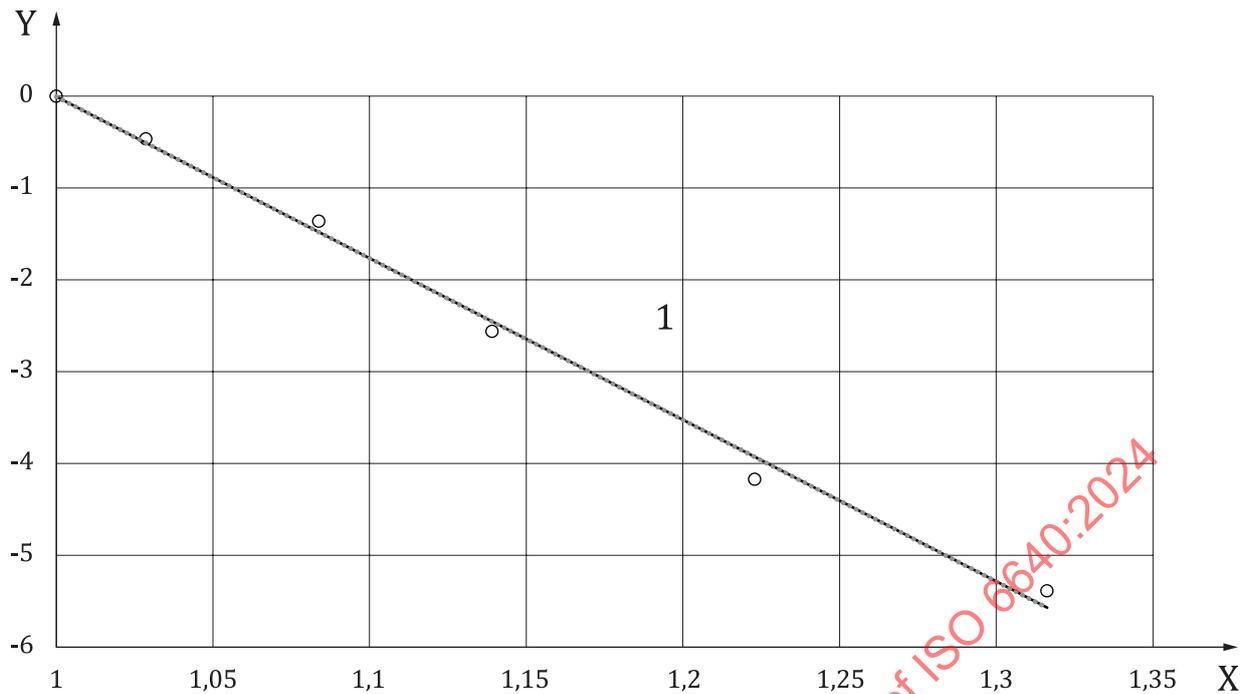


d) Measurement and sampling

Figure B.1 — Example of calibration procedure

The homogenization is ensured by monitoring the signal recorded during the process. When the signal remains constant, samples are withdrawn from the detection volume to construct the calibration curve.

A typical calibration curve obtained for transmission method is shown in [Figure B.2](#).



Key

- X density of water-sediment mixture ρ_m , in g/cm³
- Y $\ln(I_{sw} / I_w)$
- 1 $\ln(I_{sw} / I_w) = -17,594 \rho_m + 17,587$ with $R^2 = 0,994\ 6$
- I_w intensity of the radiation transmitted through water column
- I_{sw} intensity of the radiation transmitted through water-sediment mixture column
- R^2 determination coefficient

Figure B.2 — Calibration curve obtained for transmission method

From the regression analysis of the calibration curve (Figure B.2), the values of the constant A and B were obtained to be -17,594 and 17,587, respectively. Therefore, Formula (14) is modified as:

$$\rho_m = \frac{\ln \frac{I_{sw}}{I_w} - B}{A} \cong -0,056\ 8 \ln \frac{I_{sw}}{I_w} + 1 = 1 + 0,056\ 8 \ln \frac{I_w}{I_{sw}}$$

B.2 Uncertainty of water-sediment mixture measured using radiation transmission method

The calibration curve presented in Figure B.2 was obtained for six densities of water-sediment mixture taken from an experimental site. From the regression analysis of the calibration curve, the values of the constant, slope A and intercept B were obtained to be A = -17,6 and B = 17,6, respectively; while the linear regression coefficient R was found very high, $R^2 = 0,994\ 6$, which indicates a good fitting.

The factors that influence the uncertainty during the calibration process are mostly the uncertainty of density (ρ_m) and the uncertainties of radiation counts, $\ln(I_{sw} / I_w)$. The uncertainties of A and B are

determined from the relation: $\ln \frac{I_{sw}}{I_w} = A\rho_m + B$.

Calculation of the uncertainties of slope A and intercept B using experimental data ($\rho_m, \ln \frac{I_{sw}}{I_w}$) of [Figure B.2](#) gave the following results:

- uncertainty of the slope A = $\pm 0,6$
- uncertainty of the intercept B = $\pm 0,7$

As the calculation shows, the relative uncertainty of the slope is 3,7 % while the relative uncertainty of the intercept is 4,2 %.

Some thousands radiation counts to be registered provide a relative uncertainty of radiation of 2 % to 3 %.

The uncertainty of the density of the water-sediment mixture in field measurement is a combination of several uncertainties, such as slope, intercept, and radiation measurement. This can be done with the known formula of uncertainty propagation.

Taking account of these factors of uncertainties, an estimation of the final relative uncertainty of the density of the water-sediment mixture in water bodies lies within the interval of 5 % to 10 %.

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