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

~~First edition~~

Contents

Foreword

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This document was prepared by Technical Committee ISO/TC 113, *Hydrometric,* Subcommittee SC 6 *Sediment transport*.

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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) a) maintenance of navigation channels,

b) b) optimization of dredging operations,

c) 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.

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~~https://www.iso.org/obp

— ~~—~~IEC Electropedia: available at ~~https://www.electropedia.org/~~https://www.electropedia.org/

3.1
radiation transmission method
gamma, X-ray transmission method to measure the density of water-*sediment* ~~(3.2)~~(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.

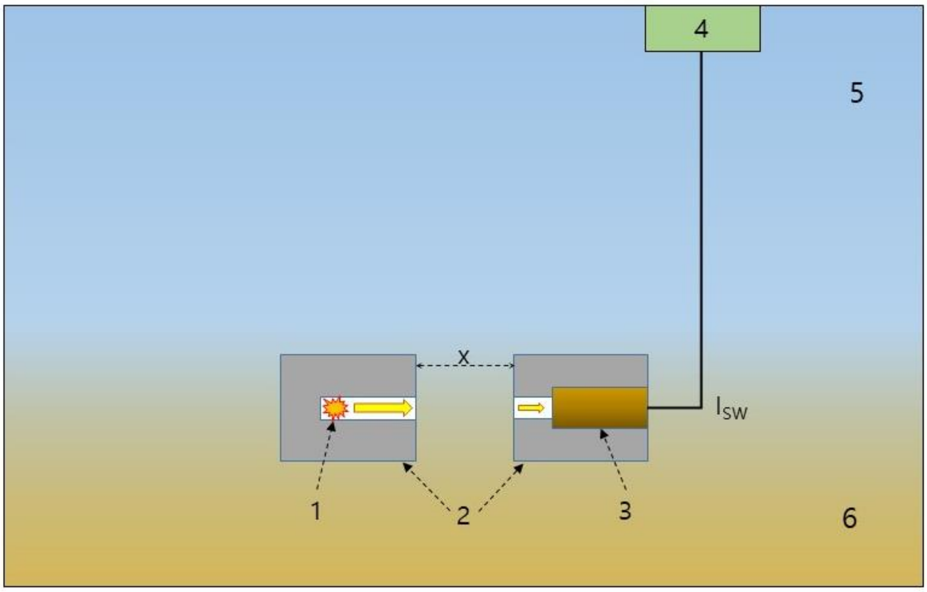
6 Principles of radiation transmission and backscattering methods

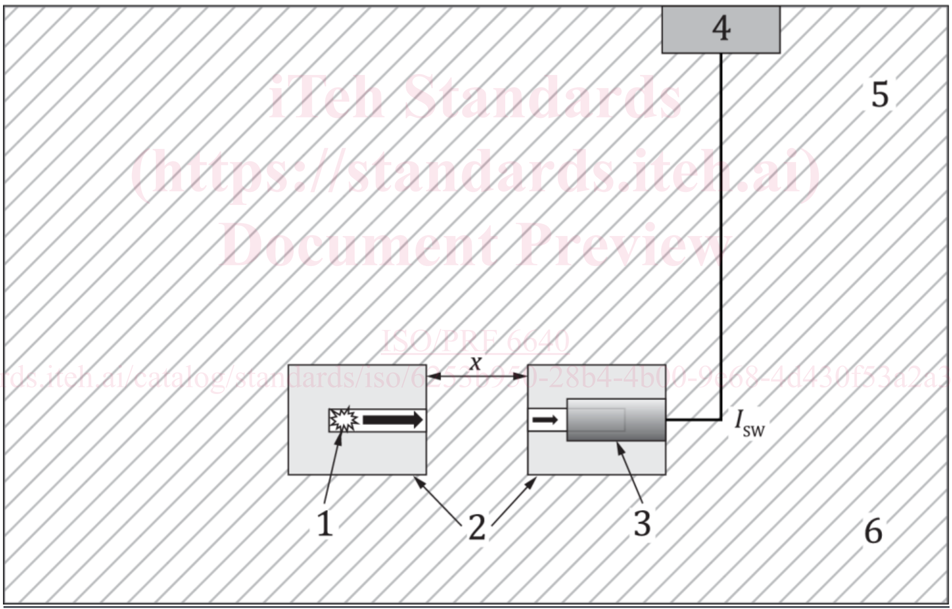
6.1 General

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.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). 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:

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

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:

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

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

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

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

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

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

where, μ_s is the linear attenuation coefficient of sediment; ~~v_w~~ v_w and ~~v_s~~ 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 cm^3 of the mixture) the volume fractions are defined as:

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

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

where, ~~ρ_s~~ ρ_s is the sediment density.

~~Formula (3)~~Formula (3) can be modified by substituting the volume fractions:

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

~~Formula (2)~~ $$\mu_{sw} = v_w \mu_w + v_s \mu_s = (1 - \frac{c}{\rho_s}) \mu_w + \frac{c}{\rho_s} \mu_s = \mu_w + \frac{c}{\rho_s}(\mu_s - \mu_w) \quad (6)$$

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

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

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

By taking natural logarithm of ~~Formula (7):~~Formula (7):

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

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

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

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

$$\rho_m = c + (1 - \frac{c}{\rho_s}) = \frac{\rho_s - 1}{\rho_s} c + 1 \qquad (9)$$

Therefore:

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

~~Formula (8)~~

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

Formula (8) can be modified by substituting the concentration c using ~~Formula (10):~~Formula (10):

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

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

Let the constant terms, ~~$-\frac{\mu_s - \mu_w}{\rho_s - 1} \cdot x$~~ $-\frac{\mu_s - \mu_w}{\rho_s - 1} \cdot x$ and ~~$\frac{\mu_s - \mu_w}{\rho_s - 1} \cdot x$~~ $\frac{\mu_s - \mu_w}{\rho_s - 1} \cdot x$ be denoted by A and B, respectively, then ~~Formula (11)~~Formula (11) is simplified as:

~~$$\ln \frac{I_{sw}}{I_w} = A \cdot \rho_m + B$$~~

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

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:

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

Formula (12)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)Formula (1) is not theoretically valid i.e. there might be no true linear relationship between $\ln I_{sw}$ $\ln(I_{sw})$ and ρ_m.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.Annex B. A case study is discussed in Annex C.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.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.