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Hydrometry — Methods for assessment of reservoir sedimentation

Hydrométrie — Méthodes d'évaluation de la sédimentation dans les réservoirs

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Foreword

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The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

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ISO 6421 was prepared by Technical Committee ISO/TC 113, *Hydrometry*, Subcommittee SC 6, *Sediment transport*.

Introduction

Most natural river reaches are approximately balanced with respect to sediment inflow and outflow. Dam construction dramatically alters this balance, creating a reservoir which often results in substantially reduced velocities and relatively efficient sediment trapping. The reservoir accumulates sediment and loses storage capacity until a balance is again achieved; this normally occurs after the reservoir fills with sediment. The rate and extent of sediment deposition depends on factors which influence sediment yield and sediment transport, as well as the reservoir's trapping efficiency.

The distribution of sediment deposition in different reservoir regions is equally important. Depending upon the shape of the reservoir, mode of reservoir operation, sediment-inflow rates and grain-size distributions, the incoming sediment may settle in different areas of the reservoir. Declining storage reduces and eventually eliminates the capacity for flow regulation and concomitant benefits such as water supply, flood control, hydropower, navigation, recreation, and environmental aspects that depend on releases from storage. Water resource professionals are concerned with the prediction of sediment deposition rates and the probable time when the reservoir would be affected in serving its intended functions.

The estimation of sediment deposition is also important in the design and planning of storage reservoirs. However, it is difficult to estimate the volume and rate of sediment deposition accurately from the known criteria and available sediment transport equations. Reservoir capacity surveys indicate patterns and rates of sedimentation, which help in improving estimation of capacity-loss rates.

This International Standard describes the following reservoir-sedimentation assessment methods:

- conventional topographic surveys (Clause 6)
  - contour method (Clause 7)
  - cross-sectional (range line) method (Clause 8)
  - sub-bottom measurements (Clause 9)
- remote-sensing techniques (Clause 10)
  - light detection and ranging (Clause 11)
    - aerial applications
    - ground-based applications
  - aerial imagery (Clause 12)
    - photogrammetry methods
    - satellite imagery methods

Hydrometry — Methods for assessment of reservoir sedimentation

1 Scope

This International Standard describes methods for the measurement of temporal and spatial changes in reservoir capacities due to sediment deposition.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any revisions) applies.

ISO 772, *Hydrometry — Vocabulary and symbols*

3 Terms and definitions

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

4 General

4.1 Origin of the sediment deposited in the reservoir

Reservoirs are subjected to several types of sedimentation as a function of the geomorphology (geology, slope, topography and land use, drainage density, climate, etc.) of the watershed and the biological cycles in the reservoir or the drainage basin, in the following order of importance.

a) **Erosion** of the drainage basin produces dissolved substances and mineral particles with an assortment of sizes, shapes and types that are related to the rock type and slope of the drainage basin. In addition, landslides produce debris flows. Sediment is delivered to the reservoir both as suspended sediment load and as bed load.

b) **Sedimentation** occurs due to plant debris from the drainage basin and from vascular plants and phytoplankton in the reservoir. The debris decomposes very slowly and often forms alternating layers with mineral deposits. The mud resulting from this type of sedimentation is very fine and extremely fluid, often with a gelatinous texture. Accumulation of mud at a rate of several centimetres per year often causes problems when a reservoir is drawn down or drained. It has a very high organic content resulting in heavy consumption of dissolved oxygen.

The proportion of sedimentation caused by each type may be assessed by on-site visual observations and by analyses of the sediment deposit.

4.2 Overview of reservoir-sedimentation assessment methods

Two basic methods for assessment of reservoir sedimentation are described.

1) Sediment transport balance:

The sediment load (bed load and suspended load) is measured over all the watercourses flowing into the reservoir and then compared with the sediment load measured at the reservoir outlet. The difference between these two quantities is assumed to represent the sediment that has been deposited in the reservoir.

The point of measurement should be sufficiently close to the reservoir periphery and particular care shall be taken to complete outflow sampling before it meets the erodible channel downstream.

For further information, see Clause 5.

2) Capacity survey of the reservoir:

Hydrographic surveys of the reservoir are carried out at regular intervals. They reveal the geographic distribution of sediment deposits in the reservoir and also help in determining lost storage capacity. A capacity survey of the reservoirs is carried out using topographic survey methods or remote-sensing techniques.

— Topographic bed surveying (i.e. bathymetry) involves measuring the depth at various locations in the reservoir, following pre-determined profiles, cross sections or using a grid for contour determination. (See Clauses 6, 7, 8 and 9.)

— The remote-sensing technique uses images taken when the water level varies between near-empty and near-full, to define the shoreline contours at various water levels. (See Clauses 10, 11 and 12.)

5 Sediment transport balance

In this method, the total sediment load (bed load and suspended load) is measured at suitable locations near the mouths of all the water courses flowing into the reservoir and at all the reservoir outlets. The difference in the incoming and outgoing total sediment load is assumed to have been deposited in the reservoir. Data on water discharge and sediment discharge at each inflow and outflow location are required to be collected in order to arrive at the total sediment load.

Generally, water discharge is calculated from stream gauge records (for which gauging stations should be set up as specified in ISO 1100-1), then calibrated in compliance with the standards describing the various stream gauging methods, e.g. ISO 748 for the velocity area method, ISO 9555 for dilution methods, etc.

A number of traditional methods are available for computing sediment transport, including an interpolation method for estimating suspended-sediment loads when measured loads are not available. When data are insufficient for the utilization of the interpolation method, sediment-transport curves may also be used to compute suspended-sediment loads. However, estimates of suspended-sediment transport from transport curves – which are also used to compute bed load, and/or total loads – may be subject to significant errors. The equations are predicated on the presence of specific relations among hydraulic variables, sedimentological parameters, and the rate at which bed load or bed-material load is transported. The theory supporting the derivation of the equations tends to be incomplete, oversimplified, or non-existent.

Additionally, even the most theoretically complete equations rely on experimental data to quantify coefficients of the equations. The availability of reliable environmental data to verify estimates from equations is often lacking, and the equations tend to ignore or underestimate the washload component, which can comprise a substantial fraction of the sediment depositing in a reservoir. Rainfall-runoff models based on watershed, meteorological, and hydrological characteristics may be useful, but tend to be time-intensive and, likewise, require reliable environmental data.

Equipment and methods for sediment load measurements are detailed in various ISO standards, such as ISO/TS 3716, ISO 4363, ISO 4364, ISO 4365 and ISO/TR 9212.

Presently, this method is not commonly used for assessment of reservoir sedimentation, because of the availability of improved techniques and because of a number of practical difficulties and limitations. These include:

1) substantial costs and human resources involved for continuous, long-term measurements at several locations;

2) inadequacy of spatial and temporal representativeness of limited observations due to typically large variations of sediment load with time and discharge, and also in the cross section;

3) change in masses, and in proportions of fine and coarse fractions of the transported sediment with time;

4) limited accuracy of sediment measurements due to issues associated with

   i) sampler efficiencies and sampling techniques, and

   ii) potential disturbances induced due to measuring equipment and procedures;

5) large variations in estimates of the bed-load transport rates (in the absence of actual measurements), made using different sediment transport relations or calculated as a fraction of a measured suspended load.

NOTE New surrogate technologies for monitoring sediment transport are being developed that may provide cost-effective and quantifiably accurate sediment-discharge data at gauging stations. ISO 11657 (under development) describes a number of sediment-surrogate monitoring technologies, including the use of continuous turbidity and stream flow measurements to estimate suspended-sediment transport. Bulk-optic, laser-optic, digital-optic, pressure-difference, and acoustic techniques for metering suspended-sediment transport are being investigated. All of these techniques require in-stream calibrations to accepted standard monitoring instruments and techniques.

6 Topographic survey methods

6.1 General

In topographic surveying, in order to assess the volume of sediment deposit along with its location in the reservoirs, direct measurements of the depths or elevations of the reservoir bed and the coordinates of the measurement points are periodically carried out. The main survey methods are the cross-sectional (or range line) method and the contour method. The selection of a method depends on the quantity and distribution of sediment indicated by field inspections, shape of the reservoir, purpose of the survey, and desired accuracy. While the contour survey method is generally applicable for all types of reservoir shapes, the use of the range method should be limited to relatively straight reaches. A suitable combination can also be used.

For smaller reservoirs, a reconnaissance sedimentation survey may be carried out. This survey has been designed to determine the approximate rate of loss of storage capacity; the thickness of the deposited sediment is measured in 15 to 20 or more well distributed locations in a reservoir by means of a simple measuring device known as a spud (see 6.4.5).

6.2 Reservoir sedimentation surveys

6.2.1 Advantages

a) A reservoir survey can be less costly than taking continuous sediment measurements at several locations in the catchment.

b) The accuracy of these surveys is usually high, particularly if advanced equipment is used.

c) The survey can be carried out at any convenient time to get the total sedimentation after the last survey.

d) The time required for a survey can be considerably shortened with the use of advanced equipment.

6.2.2 Limitations

a) Topographic surveys do not provide any information about the variation of sediment yield with time, and give only the total sediments accumulated since the last survey. The above information can only be obtained by gauging.

b) The unit weight of sediment deposits is required for estimating sediment yield. The temporal and spatial variation in the unit weight may introduce errors in the results.

c) This method does not provide sub-catchment-wise sediment yield; this can only be obtained by sediment sampling of different streams.

d) This approach is not very effective where sedimentation is small, as the error of measurement may mask the true sedimentation rates.

e) Sediment outflow data are also required to estimate the total sediment inflow.

6.3 Frequency

The frequency at which reservoir surveys are taken depends on individual site characteristics. Generally, reservoirs are surveyed every 3 to 10 years. The survey frequency depends on the sediment accumulation rate; reservoirs that have high accumulation rates are surveyed more often than those with lower rates. For reservoirs which are losing capacity very slowly, a survey interval in the order of 20 years of even longer may be adequate. For reservoirs which are losing capacity rapidly, or where the impact of sediment management is being evaluated, a survey interval as short as 2 to 3 years may be used.

The cost of running a survey also plays a critical part in deciding the survey frequency. Special circumstances may necessitate a change in the established schedule. For example, a reservoir might be surveyed after a major flood that has carried a heavy sediment load into the reservoir.

A survey may also be run following the closure of a major dam upstream in the same catchment, since the reduction in the free drainage area leads to a reduction in the sediment accumulation rate of the downstream reservoir. The volume of the sediment that has accumulated in a reservoir is computed by subtracting the revised capacity from the original capacity at a reference reservoir elevation (usually the full reservoir level). Since this is the difference of two large numbers, an error, even by a few percentages in either of the two numbers will significantly influence the results.

The minimum survey interval depends on the precision of the survey technique and the rate and pattern of storage loss. For instance, if a survey technique incorporates an error in the order of 2 % of the total reservoir volume, and if the reservoir is losing capacity at 0,25 % per year, a 4-year survey interval may be too short to produce reliable information unless most sediment inflow is focused into a small portion of the impoundment.

6.4 Survey equipment

6.4.1 General

The basic survey items are

a) horizontal or distance measurement, and

b) vertical or depth measurement.

The principal equipment and instruments required for the hydrographic and topographic coverage in relation to the measurements are detailed in the subsequent subclauses.

6.4.2 Positioning equipment

6.4.2.1 General

The global positioning system (GPS) is a space-based global navigation satellite system that provides reliable location and time information, in all weather conditions and at all times, anywhere on or near the Earth when and where there is an unobstructed line of sight to four or more GPS satellites. It is maintained by the United States government and is freely accessible by anyone with a GPS receiver.

There are two general operating methods by which GPS-derived positions can be obtained:

1) absolute point positioning;

2) relative (differential) positioning (DGPS).

6.4.2.2 Absolute point positioning

A GPS satellite continuously transmits microwave radio signals composed of two carriers, two codes and a navigation message. The GPS receiver picks up the GPS signal through receiver antenna and processes it using built-in software. GPS receivers on the ground calculate their positions by making distance measurements to four or more satellites. The satellites function as known reference points that broadcast (free) satellite identity, position and time information via codes on two carrier frequencies. Measurements of the distance to each individual satellite are made by analysing the time it takes for a signal to travel from a satellite to a GPS receiver. Trilateration is then used to establish a GPS receiver's position. The absolute point positioning is highly dependent on the accuracy of the known coordinates of each satellite, accuracy of modelled atmospheric delay and the accuracy of the resolution of the actual time measurement process performed in a GPS receiver (clock synchronization, signal processing, signal noise, etc.). For many applications, absolute point positioning does not provide sufficient accuracy.

6.4.2.3 Differential GPS (DGPS)

6.4.2.3.1 General

Differential positioning is the technique or method used to position one point relative to another. DGPS requires two or more GPS receivers to be recording measurements simultaneously. Differential positioning is more concerned with the relative difference in position between two users, who are simultaneously observing the same satellite, than with the absolute position of the individual user. Since errors in the satellite position and atmospheric delay estimates are effectively the same at both receiving stations, they cancel each other to a large extent. Differential positioning can be performed by using code- or carrier-phase measurements and can provide results in real-time or be post-processed. A DGPS utilizing code-phase measurements can provide a relative accuracy of a few metres. A DGPS utilizing carrier-phase measurements can provide a relative accuracy of a few centimetres.

6.4.2.3.2 DGPS (code-phase)

A code-phase DGPS consist of two GPS receivers, one set up over a known point and one moving from point to point or placed on a moving platform, measuring pseudo ranges to at least four common satellites. Since the satellite positions are known and one of the receivers is over a known point, a "known range" can be computed for each satellite observed. This "known range" can then be subtracted from the "measured range" to obtain a range correction or pseudo-range correction (PRC). This PRC is computed for each satellite being tracked at the known point. The PRC can then be applied to the moving or remote receiver to correct its measured range. Code-phase DGPS has primary applications to real-time positioning systems where the accuracies at the meter level are tolerable.

A real-time dynamic DGPS includes reference station, communications link and user equipment. If the results are not required in real time, the communication link could be eliminated and positional information post-processed.

a) *Reference station:* The reference station measures timing and ranging information broadcast by the satellites and computes and formats range corrections for "broadcast to user" equipment. The reference receiver consists of a GPS receiver, antenna and processor. Using the technology of differential pseudo-ranging, the position of the survey vessel can be found relative to that of the reference station. The pseudo-ranges are collected by a GPS receiver and transferred to a processor where pseudo-range corrections are computed and formatted for data transmission. The reference station is placed on a known survey measurement in the area having an unobstructed view of the sky. The antenna should not be located near objects that will cause multipath or interference.

b) *Communication links:* The communication link is used as a transfer media for the differential corrections.

c) *User equipment:* The remote receiver should be a multichannel single frequency GPS receiver. The receiver shall be able to accept the differential corrections from the communications link and then apply those corrections to measured pseudo range.

d) *Separation distances:* The maximum station separation between the reference and the remote station in order to meet hydrographic surveying standard of 2 m, can be maintained up to a distance of 300 km.

6.4.2.3.3 DGPS (carrier-phase)

Carrier-phase tracking provides for a more accurate range resolution due to the short wavelength and ability of a receiver to resolve the carrier phase down to about 2 mm. This method may be employed with either static or kinematic receivers. Methods for resolving the carrier-phase ambiguity in the dynamic, real-time mode have been developed and implemented by several GPS receiver manufacturers for real-time positioning. These methods are referred to as “Real Time Kinematic” or RTK and provide 3D positions accurate to a few centimetres.

The carrier-phase positioning system is very similar to the code-phase tracking technology. A GPS reference station shall be located over a known survey monument. The reference station shall be capable of collecting both pseudorange and carrier-phase data from the satellites. The reference station consists of a carrier-phase dual-frequency full-wavelength GPS receiver, a processor and a communication link. The processor used in the reference station will compute the pseudorange and carrier-phase corrections and format the data for the communications link. The user equipment on the survey vessel consists of a carrier-phase dual-frequency full-wavelength GPS receiver with a built-in processor. The built-in processor must be capable of resolving the integer ambiguity while the platform survey vessel is moving. This system is not designed to be used in surveys over 20 km away from the reference station.

6.4.3 Distance measuring equipment

Survey equipment (e.g. a chain, tape, plane table, transit sextant, range finder, electronic distance meter) and special hydrographic instruments (e.g. an echo sounder, distance wheels, and other electronic equipment) are generally used.

6.4.4 Depth measuring equipment

Conventional equipment (e.g. a dumpy level and sounding poles) and special hydrographic equipment (e.g. an echo-sounder; refer to ISO 4366 for details) are used to measure depth.

The selection of an echo sounder should take into account the factors affecting survey accuracy and the scope and size of the reservoir under study. The accuracy of bathymetric surveys using echo sounders depends upon several factors including water depth and turbulence, water temperature and salinity (which affect the speed of sound), and reflectivity of bottom materials. Depending upon these factors, users may select echo sounders that employ different transmitting and recording components and arrangements, acoustic frequencies, digitization techniques, and display schemes.

The beam width and depth of water determine the footprint or aerial resolution of the acoustic wave when it strikes the lakebed. For the same depth of water, a narrow-beam transducer produces a smaller acoustic footprint, provides finer resolution, and is generally more accurate than a wide-beam transducer. A narrow-beam transducer is required to measure small deformations of structures, but requires an increased number of survey ranges, or cross-sectional passes, at generally slower boat speeds than required for a wide-beam transducer. Thus, using a narrow-beam transducer could require more time and greater expense. Some echo sounders employ special digitization techniques to reduce the effective footprint.

The digitization techniques employed by the echo sounder can profoundly affect data accuracy. Many graphical or numerical-display echo sounders determine the depth when the reflected acoustic energy exceeds a predetermined threshold. The digitization technique is called “threshold detection”. When measuring depressions or holes, the reflected acoustic energy that exceeds the threshold is likely to come from the edges of the acoustic footprint. If the footprint is large and the width of the hole is small, or if the bed has a significant slope, the depth measured by the echo sounder may not be accurate.

An alternative digitization scheme is to use peak detection rather than threshold detection. The peak-detection technique analyses the return echo and computes the distance associated with the peak amplitude of the return signal rather than a predetermined threshold value; therefore, the peak detection method measures the depth at the approximate centre of the footprint and the beam width is effectively reduced. The peak-detection method is less sensitive to acoustic reflectors in the water column (sediment, debris, etc.) than the threshold-detection method. Although adequate data can be achieved with an echo sounder using threshold detection, peak detection may be more accurate and reliable in turbid and turbulent waters.

Recent developments of multi-beam and sector-scanning sonar systems permit accurate bathymetric data to be collected rapidly over a large area.

Sector-scanning sonar has been used to locate wellheads for drilling operations and as an aid to obstacle avoidance. The technology is similar to a fixed-transducer echo sounder, except that the transducer is mounted on a mechanism that rotates and tilts the transducer. The measurement location and depth of the streambed are determined from the slope distance measured by the acoustic system and the tilt and rotation of the transducer. Complete data coverage of a circular area can be obtained from a single location. If the system is mounted on a moving survey vessel, the system can effectively collect a swathe of data as the vessel is manoeuvred in the stream.

A multi-beam system is similar in capability to the sector-scanning sonar. Multi-beam systems do not actually use multiple beams, but emit a fan of sound and receive segments of the reflected sound by electronically phasing an array of transducers. The transducers are arranged in an arc – typically in configurations of 60 transducers in a 90-degree arc. Thus, a swathe of streambed is measured almost instantaneously.

The accuracy of the sector-scanning and multi-beam systems is highly dependent upon accurate measurements of the position of the transducer, or transducer array, at the time data are collected. When the transducer is at acute angles with the stream bed, small errors in the measured angle of the transducer can cause substantial errors in the depth measurement. Therefore, very stable deployment platforms, or external instruments to accurately measure and compensate for vessel attitude, are required to collect accurate data with these systems. The effective range depends upon the frequency of the acoustics and the characteristics of the water. Sector-scanning sonar has been used to measure depths at ranges of 10 m.

6.4.5 Spud

A spud is sometimes used in reconnaissance type work for a quick estimation of sediment depth. This device is also used in roughly tracing out the original profiles of the reservoir bottom in case this information is not already available.

A spud is a case-hardened steel rod about 2 m to 3 m long and about 20 mm to 40 mm in diameter into which outward-tapering grooves have been machined at regular intervals. Each groove tapers from a maximum depth of 6 mm to zero at the rim of the next one above. The spud is cast or allowed to fall vertically through water with force sufficient to penetrate the deposited sediment and the underlying original soil material. If the water is shallow, it may be driven in by hand. After the spud depth (spud plus line length) is noted, the spud is lifted slowly (so as not to wash out the sediment captured in the grooves), and is examined to determine the depth to the pre-impoundment bottom based on a change in texture, colour, presence of roots, etc. The depth to the top of the sediment deposits is simultaneously determined by using a sounding weight, and the deposit thickness is determined by subtraction.

6.5 Density measurements and sediment samplers

6.5.1 Density measurements

Sediment bulk density can be measured by different methods: namely, by removing a sample of known volume, or by using a gamma density pole, or by multiple-frequency echo sounding. Density measurements and sediment samples are taken along range lines. The number of sample and measurement locations depends on the accuracy desired and the variability of the sediment. The entire depth of each sediment deposit needs to be sampled and sample volume and weight measured accurately to determine sediment accumulation.

6.5.2 Sediment sampling

Sampling devices are described in the ISO 4364 and ISO 9195. Most are various sorts of core-drilling devices (SCS, cylindrical type, etc.), or surficial-scooping devices, suitable for different types of bed material. Piston-type samplers (such as Vibracore) and radioactive probes (such as gamma probes) can also be used.

6.5.3 Multiple-frequency echo sounding

The idea here is to use various echo-sounding frequency ranges: the lower the frequency, the better the impulses penetrate the surface. Consequently, the impulse from a 210 kHz sounder is reflected by sediment density of 1,2 kg/l, whereas the impulse from a 33 kHz sounder is reflected by a density of 1,4 kg/l. It is thus possible, by varying the frequency, to obtain a return spectrum, which can in turn be used to characterize the various layers of sediment. Multiple-frequency echo sounding is still at an essentially experimental stage and would benefit from significant improvements in the field of signal processing. It should also be noted that the aperture angle of the emitted beam varies with the frequency, which means that the signal reflected by each beam does not necessarily come from the same geographical location (x, y). Result interpretation must consequently be restricted to gently sloping areas in order to limit problems involving the different aperture angles of the beam.

The dual-frequency technique (210/33 kHz) is more reliable and is well suited to largely organic sediment; the density of 1,2 kg/l may be located well below the surface of the sediment. On the other hand, in reservoirs where the sedimentation is mainly mineral in origin, the surface sediment naturally exceeds a density of 1,4 kg/l.

Acoustic seafloor classification systems (ASCS) process the acoustic return signals from standard single-beam echo sounders, and can be used to make qualitative estimates of the composition of reservoir deposits. They gather information about bottom type, bottom sediments, and aquatic plants. Different reservoir bottom types can be discriminated by extracting data on bottom roughness (i.e. irregularities in topography) and hardness (i.e. type of substrate – rock, sand, mud, and so forth).

Acoustic reservoir-deposit characterization requires field verification. This can be done either by physical sampling of the bottom using sediment cores or grabs, or through visual observations by divers or underwater cameras. All types of substrate encountered shall be verified to interpret the data accurately and link the acoustic signatures to the reservoir deposit classification scheme. Extensive fine-scale sampling may be required, especially where the deposits are complex. Additionally, these systems require initial calibration in each unique study location in order to interpret the signal returns and classify benthic cover types.

All these techniques, whether based on multiple or dual frequencies, nevertheless require prior calibration using sediment samples such as those described in 6.5.2.

7 Topographic survey using the contour method

7.1 General

The basic objective of this method is to prepare a contour map of the reservoir bed using complete topographic or bathymetric information. For this purpose, spot levels or soundings are taken at predefined points over the entire reservoir bed. A contour map of the reservoir is then prepared with suitable scale and contour interval, from which the capacity of the reservoir at the time of the survey is computed. The difference in capacity between two surveys indicates the loss of capacity due to sediment deposition during the intervening period.

There are quite a few field techniques available for contouring, the application of which depends mostly on the physical features of the reservoir, its operation schedule, working conditions and availability of instruments and other facilities. The commonly used techniques include:

— grid contouring;

— radial contouring;

— circular contouring;

— water-surface mapping.

The basic measurements, carried out in any of the above survey techniques, are for acquiring the x, y and z coordinates at the predefined (grid) points. The methods for acquiring the x and y coordinates are given in ISO/TR 11330.

The z coordinate of points below water level is obtained by depth measurements (soundings). For small reservoirs, soundings are taken either by a sounding pole or by lead line at closer intervals, so that bottom contours are developed with sufficient accuracy. For large reservoirs, depth measurements using echo-sounding equipment are carried out at all grid points of the survey network. Commonly used techniques are explained in ISO 4366. The z coordinate of points above water level may be obtained by a land survey.

A detailed description of procedures and instruments for conducting hydrographic survey is given in IHO's Publication C-13, *Manual on Hydrography*[35].

Recent advances in automated survey techniques have made hydrographic contour surveying economical in smaller and midsize reservoirs.

7.2 Hydrographic survey

Integrated bathymetric systems incorporating a DGPS are also used for hydrographic surveys to digitally map the entire reservoir bottom. The survey system is basically comprised of three components:

a) a positioning system (a GPS in the differential mode for proper positioning of moving survey boat);

b) depth measuring units (digital echo sounder/ bathometer/ transducer for depth measurement);

c) a computer interface, including software for data logging and post-processing of positioning data; a plotter, printer, monitor, etc.

The survey is carried out in a rapid and efficient manner by using GPS in the differential mode for hydrographic surveys, using state-of-the art technology and using a "total station" (see 7.3.2) for topographic surveys on ground. A boat is equipped with the bathymetric equipment, the GPS is mounted on board and a computer is used for the bathymetric survey; its reference station is positioned on a known geographical benchmark. The survey software enables fixing of grid lines, interfacing of the bathymeter and DGPS and taking of the x, y and z values at required intervals/grids. Boat navigation can be controlled by the software so that the boat tracks the grid line accurately. The survey can also be carried out in a random mode. The data collected is then processed and analysed using specially developed software to obtain the results in various forms, e.g. point plots, contour and three-dimensional maps of the reservoir bed, area capacity elevation tables and cross sections of the reservoir.

The line spacing for the bathymetry survey depends on various factors such as the intended use of the data, complexity of the bottom, and the time and effort available. A hydrographic survey is carried out within the water-spread area at suitable line spacing. Data are available all along the lines and hence the entire survey area is covered as desired. A few tie lines in the other direction are also carried out. Similarly, the area above the ground not covered under hydrographic surveys, and up to the maximum water level (MWL), is surveyed by generally taking levels at suitable interval along the range lines laid; this interval is flexible depending on the situation.

7.3 Topographic surveys

7.3.1 General

A topographic survey should be conducted in the area between the existing water level at the time of the survey and the maximum water level (MWL)/full reservoir level (FRL). The survey is carried out around the periphery of the reservoir using suitable grid spacing.

7.3.2 Instruments

a) *Total station* – This system incorporates an electronic theodolite, an electronic distance measurement device and a computer as one unit. The capability of the system to retain data in memory, carry out calculations using its own processor, and finally its ability to create x, y, z files which can be directly transferred to the computer, makes the survey process fast and accurate.

b) *Auto level* – Auto level is used to accurately transfer the z coordinate from a benchmark to the control points in order to control the vertical accuracy of the total station during a topographic survey.

