SECONDARY WAVE (S-WAVE)

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Synonyms

S wave; Shear wave; Transverse wave

Definition

Secondary waves are elastic shear waves that travel through the Earth.

Discussion

S waves are seismic body waves meaning they travel through the Earth's interior. Their velocity is slower than that of P waves, and they are normally the second major phase to be observed on a seismogram, and are therefore also referred to as secondary waves. In the Earth's crust, S wave velocities are typically 3–4 km/s. S waves are usually larger in amplitude than P waves and may cause strong shaking and/or damage. The particle motion associated with S waves is perpendicular to the direction of propagation. S waves can be subdivided into two groups: SV waves, which are recorded by seismographs on the vertical and radial components; and SH waves, which appear on the tangential component. S waves cannot propagate through liquids or gases, the knowledge of which helped lead to the discovery that the outer core was liquid.

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Cross-references

Body Wave
Primary Wave
Seismograph/Seismometer

SEDIMENTATION OF RESERVOIRS

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Synonyms

Filling up of reservoirs by sediments; Reservoir sedimentation; Siltation of reservoir

Definition

Process of filling up of reservoirs by sediments, which are transported by rivers or overland flows.

Introduction

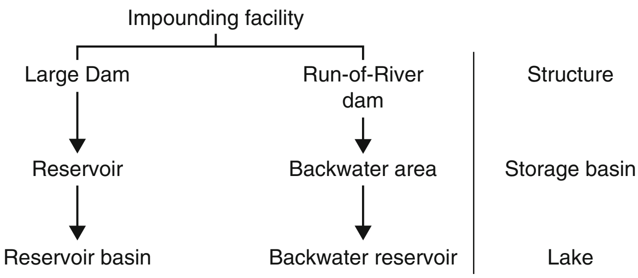
Sedimentation is known as the process which fills up natural lakes and man-made reservoirs by sediments to become the end land again. The main reason for this process is the sediment yield transported by the rivers as suspended or bed load into the reservoirs. Bed and suspended sediment load originate from soil and rock erosion in the catchment area of the reservoir. Suspended fine sediments are also the result of surface erosion as well as of crashing and abrasion of coarser sediments transported by rivers. When entering lakes and reservoirs, the coarser sediments such as sand and gravel settle down and form a delta. The finer suspended sediments are deposited over the whole reservoir. During floods, they are periodically transported as turbidity currents like an underwater avalanche directly from the delta along the reservoir to the deepest point in front of the dam.

Today, the worldwide yearly loss of storage capacity due to sedimentation is already higher than the increase of capacity by the construction of new reservoirs for irrigation, drinking water, and hydropower. In Asia, for example, 80% of the useful storage capacity for hydropower production will be lost by 2035. Thus, the sustainable use of the reservoirs is not guaranteed in long term. In the case of deep and long reservoirs, the sedimentation rate is much below the world mean value. Nevertheless, the sedimentation threatens also these reservoirs since the mentioned turbidity currents are sporadically transporting large volumes of sediments down to the dam. There, the concentrated deposits are hindering the safe operation of the outlet structures as intakes and bottom outlets. Thus, after only 30–40 years of operation, sedimentation has become a serious problem in many reservoirs located even in catchment areas with moderate surface erosion as in the Alps.

The problem of reservoir sedimentation

Reservoir sedimentation is a problem that will keep those responsible for water resources management occupied more than usual during the decades to come. All sorts of impounding structures are concerned: large dams, in the form of fill or concrete dams, as well as river barrages comprising weirs, power plants, locks, impounding dams, and dykes (Figure 1). Impounding facilities are always costly, but this is justified by their various potential uses.

Although the aim behind the efforts to create reservoirs is storing water, other substances are carried along by the water and are usually deposited there as well. This is a result of dam construction, dramatically altering the flow behavior and leading to transformations in the fluvial process with deposition of solid particles transported by the flow. Each reservoir created on natural rivers, independent of its use (water supply, irrigation, energy, or flood control), can have its capacity decreased due to deposition over the years. In an extreme case, this may result in the reservoir becoming filled up with sediments, and the river flows over land again.



Sedimentation of Reservoirs, Figure 1 Classification of impounding facilities.

A reservoir, like a natural lake, silts up more or less rapidly. In actual fact, reservoirs may completely fill with sediments even within just a few years, whereas natural lakes, for example, in the Alpine foreland, may remain as stable features of the landscape for as much as 10,000–20,000 years after they were formed during the last Ice Age.

Reservoir sedimentation reduces the value of or even nullifies the dam construction investment. The use for which a reservoir was built can be sustainable or represent a renewable source of energy only where sedimentation is controlled by adequate management and suitable mitigation measures. Lasting use of reservoirs in terms of water resources management involves the need for reduction of sediment yield and sediment removal.

The planning and design of a reservoir require the accurate prediction of erosion, sediment transport, and deposition in the reservoir. For existing reservoirs, more and wider knowledge is still needed to better understand and solve the sedimentation problem and hence improve reservoir operation.

Consequences of reservoir sedimentation

The accumulating sediments successively reduce the water storage capacity (Fan and Morris, 1992). Consequently, at long term, the reservoir operates only at reduced functional efficiency. Declining storage volume reduces and eventually eliminates the capacity for flow regulation and with it all water supply, energy and flood control benefits (Graf, 1984; International Committee on Large Dams (ICOLD), 1989). Reservoir sedimentation can even lead to a perturbation of the operating intake and to sediment entrainment in waterway systems and hydropower schemes. Depending on the degree of sediment accumulation, the outlet works may be clogged by the sediments. Blockage of intake and bottom outlet structures or damage to gates that are not designed for sediment passage is also a severe security problem. Other consequences are sediments reaching intakes and greatly accelerating abrasion of hydraulic machinery, decreasing their efficiency and increasing maintenance costs.

Sedimentation rate

The worldwide installed capacity of all reservoirs is about 7,000 km^3, whereas 4,000 km^3 can be used for energy production, irrigation, and water supply. (Basson, 2009). The average age of existing reservoirs is about 30–40 years. It is estimated that about 0.8% of the worldwide storage capacity is lost annually by sedimentation. The highest average sedimentation rate is found in arid regions as in the Middle East, Australia, and Oceania as well as Africa (Table 1). A detailed collection of sedimentation rates in regions all over the world can be found in Batuca and Jordaan (2000).

Sedimentation of Reservoirs, Table 1 Average sedimentation rates in different regions (Basson, 2009)

Region	Average sedimentation rate (%/year)
Africa	0.85
Asia	0.79
Australia and Oceania	0.94
Central America	0.74
Europe	0.73
Middle East	1.02
North America	0.68
South America	0.75

In Table 2, the date prediction is given when 80% of the useful reservoir volumes for hydropower production are lost by sedimentation and 70% of the reservoirs for other uses (Basson, 2009), respectively. It may be seen that in Asia, for example, 80% of the useful storage capacity for hydropower production will be lost in 2035. In view of the increasing energy demand, this is a serious problem; 70% of the storage volumes, used for irrigation, will be filled up by sediments already in 2025. This will be the case in the Middle East in 2030 and in Central America in 2040. This underlines that reservoir sedimentations endanger the sustainable energy and food production in many regions in the world.

Sedimentation of Reservoirs, Table 2 Dates when 80% of the useful reservoir volumes for hydropower production are lost by sedimentation and 70% of the reservoirs for other uses (Basson, 2009), respectively

Region	Hydropower dams: Date when 80% filled with sediment	Non-hydropower dams: Date when 70% filled with sediment
Africa	2,100	2,090
Asia	2,035	2,025
Australasia	2,070	2,080
Central America	2,060	2,040
Europe and Russia	2,080	2,060
Middle East	2,060	2,030
North America	2,060	2,070
South America	2,080	2,060

The sedimentation rate of each particular reservoir is very variable. It depends more particularly on the climatic situation, the geomorphology, and the conception of the reservoir including its outlet works.

Reservoir sedimentation by turbidity currents

In long, deep, narrow reservoirs, turbidity currents are often the governing process in reservoir sedimentation by transporting fine materials in high concentrations (Jenzer Althaus et al., 2009). The erosion of the soil within a catchment area is at the origin of the material transported by a river. The erosion process starts in the high mountainous regions and continues in the highlands and plains and ends in the lakes or in the sea respectively where it comes – due to the decreasing flow velocity – to sedimentation. Depending upon the sediment supply from the watershed and flow intensity in terms of velocity and turbulence, rivers usually carry sediment particles within a wide range of sizes. During flood events, the fraction of sediments smaller than sand reaches 80–90 % of the total sediment carried by the river (Alam, 1999), and the total sediment discharge is usually significant. If the sediment concentration is high enough, it may come to turbidity current.

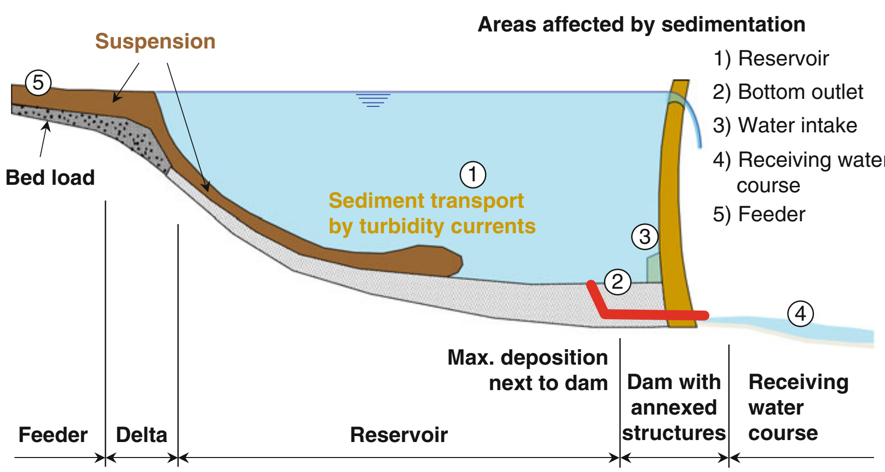
The turbidity currents belong to the family of sediment gravity currents. These are flows of water laden with sediment that move downslope in otherwise still waters like oceans, lakes, and reservoirs. Their driving force is gained from the suspended matter (fine solid material), which renders the flowing turbid water heavier than the clear water above. When a sediment-laden river flows into a large reservoir, the coarser particles deposit gradually and form a delta in the headwater area of the reservoir that extends farther into the reservoir as deposition continues (Figure 2). Finer particles, being suspended, flow through the delta stream and pass the lip point of the delta. If after the lip point of the delta, the difference in density between the lake water and inflowing water is high enough, it may cause the flow to plunge, and turbidity current can be induced. During the passage of the reservoir, the turbidity current may unload or even resuspend granular material. Subsequently, the sediments are deposited along the path due to a decrease in flow velocity caused by the increased cross-sectional area. Fine sediments (clay and silt sizes) are usually the only sediments that remain in suspension long enough, following over long distances the reservoir bottom along the thalweg through the impoundment down to the deepest point in the lake normally near the dam, to reach the outlets. At the dam, the sediments settle out.

Measures against reservoir sedimentation

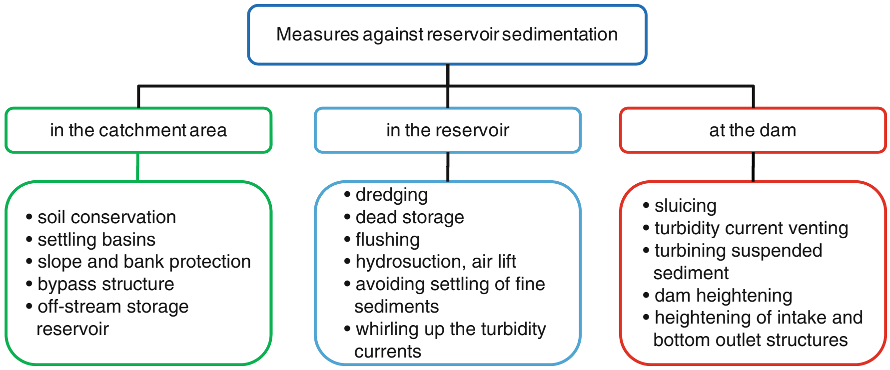
Over the years, several measures against reservoir sedimentation have been proposed (Schleiss and Oehy, 2002). But not all of them are sustainable, efficient, and affordable. For example, raising the height dams and outlet works does not provide a long-term and sustainable solution.

There is a strong need to limit sediment accumulation in reservoirs in order to ensure their sustainable use. Management of sedimentation in Alpine reservoirs cannot be apprehended by a standard generalized rule or procedure. Furthermore, sediment management is not limited to the reservoir itself, it begins in the catchment areas and extends to the downstream river. Every situation has to be analyzed for itself in order to determine the best combination of solutions to be applied. The possible measures are summarized in Figure 3 and grouped according to the areas where they can be applied.

An integrated approach to sediment management that includes all feasible strategies is required to balance the sediment budget across reservoirs (Morris, 1995). Integrated sediment management includes analysis of the complete sediment problem and application of the range of sediment strategies as appropriate to the site. It implies that the dam and the impoundment are operated in a manner consistent with the preservation of sustainable long-term benefits, rather than the present strategy of developing and operating a reservoir as a nonsustainable



Sedimentation of Reservoirs, Figure 2 Areas affected by sedimentation in the surroundings of a reservoir (De Cesare et al., 2001).



Sedimentation of Reservoirs, Figure 3 Inventory of possible measures for sediment management (Schleiss and Oehy, 2002).

source of water supply (Morris, 1996). A sustainable sediment strategy should also include the downstream reaches; therefore, monitoring data should also include downstream impacts as well as sedimentation processes in the reservoir (Morris and Fan, 1997).

The known remedial measures can be subdivided in those taken in the catchment area, in the reservoir, and at the dam itself as shown in Figure 3. Oehy (2003) and Oehy and Schleiss (2007) proposed and studied several technical measures against turbidity currents. Turbidity currents may be stopped and forced to settle by obstacles situated in the upper part of the reservoir in order to keep the outlet structures free of sediments. They can also be whirled up near the dam and intakes and kept in suspension, which allows a continuous evacuation through the turbines (Jenzer Althaus, 2011). In certain cases, fully venting of turbidity currents through outlet structures is possible.

Summary

Today, the worldwide yearly mean loss of storage capacity due to sedimentation is already higher than the increase of capacity by the construction of new reservoirs for irrigation, drinking water, and hydropower. Thus, the sustainable use of the reservoirs is not guaranteed in long term. In the case of alpine reservoirs, the sedimentation rate is much below the world mean value. Nevertheless, sedimentation threatens also these reservoirs since turbidity currents are sporadically transporting large volumes of sediments like an underwater avalanche down to the dam. There, the concentrated deposits are hindering the safe operation of the outlet structures as intakes and bottom outlets. Many possible measures against sedimentation are known from practice, but they are strongly depending on the local conditions. For reservoirs in rather narrow valleys, technical measures, which can govern turbidity currents, are of special interest. The problematic of sedimentation and sediment management should be considered in the early stage of the design of the reservoir in order to obtain sustainable solutions. Although methods for erosion volume estimation and empirical relationships for trap efficiency estimation are available, this is still not the case for many reservoirs built recently all over the world.

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Cross-references

Climate Change
Erosion
Erosivity
Global Change and Its Implications for Natural Disasters
Reservoir Dams and Natural Hazards

SEICHE

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Synonyms

Harbor wave; Long period waves; Tidal wave

Definition

A seiche is a standing wave in an enclosed or partially enclosed body of water. Seiches have been observed in lakes, harbors, reservoirs, swimming pools, bays and seas.

Discussion

The word originates in a Swiss French dialect word that means "to sway back and forth" and was first used by the Swiss hydrologist François-Alphonse Forel in 1890, to make scientific observation of the seiches occurring in Lake Geneva, Switzerland.

Seiches can be caused by meteorological forcing (wind and atmospheric pressure variations), wind waves and swells, seismic activity, landslides, and tsunamis.

Once originated, the wave is reflected from the ends and the water surface oscillates around its rest (horizontal) position. Repeated reflections produce standing waves whose shape corresponds to one of the natural modes of oscillation of the water body, as a function of its geometry.

For a rectangular basin of length L, width W, and depth h, the period of each mode can be evaluated using the generalized Merian's formula:

$$T_{mn} = \frac{2L}{\sqrt{gh}}(\alpha^2 m^2 + n^2)$$

where $\sqrt{gh}$ is the speed of a shallow water wave, $\alpha = L/W$ and m and n define the harmonic nodes in the transverse and longitudinal directions.

Generally, the motion of the water body develops as a combination of the natural modes of the basin. If the forcing is impulsive (i.e., tsunamis or pressure front), the disturbed body of water tends to return at rest after dissipating its energy within a number of free oscillations; if the forcing is periodic, with a frequency close to that of one or more of the natural frequencies of the basin, the body of water can resonate locally amplifying the amplitude of the seiche.

Seiches are often imperceptible to the naked eye due to their usually small amplitude and long wavelength, resulting in a small steepness of the water surface. Small amplitude seiches are almost always present on large lakes; harbors, bays, and estuaries are often prone to seiches with amplitudes of a few centimeters and periods of a few minutes. Seiches can also form in semi-enclosed seas. For instance, in the Adriatic Sea and the Baltic Sea, they contribute to flooding of Venice and St. Petersburg, respectively.

Tsunami can also excite seiches in bays and harbors, and these can in turn be amplified due to the interaction of consecutive tsunami waves with local bathymetric and topographic features, originating very large waves. For instance, the tsunami that struck Hawaii in 1946 had a 15-min interval between wave fronts; since the natural period of oscillation of Hilo Bay is about 30 min, consecutive waves were in phase with the motion of Hilo Bay, and excited a resonant seiche in the bay, which reached a height of up to 26 ft (8 m circa), killing 96 people in the city alone.

Harbors are usually prone to wave-induced seiching (Los Angeles and Long Beach, Rotterdam, Barbers Point and Marina di Carrara) with standing wave patterns resulting in strong localized currents at the nodes (points that experience no vertical motion) reducing the operability of berths and eventually inducing breakage of mooring lines.

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