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Sediment bypass tunnels to mitigate reservoir sedimentation and restore sediment continuity

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ABSTRACT: Worldwide, a large number of reservoirs impounded by dams are rapidly filling up with sediments. As on a global level the loss of reservoir volume due to sedimentation increases faster than the creation of new storage volume, the sustainability of reservoirs may be questioned if no countermeasures are taken. This paper gives an overview of the amount and the processes of reservoir sedimentation and its impact on dams and reservoirs. Furthermore, sediment bypass tunnels as a countermeasure for small to medium sized reservoirs are discussed with their pros and cons. The issue of hydroabrasion is highlighted, and the main design features to be applied for sediment bypass tunnels are given.

1 INTRODUCTION

By impounding natural watercourses, dams alter the flow regime from flowing water to a body of standing water, which favors reservoir sedimentation. Without adequate countermeasures ongoing sedimentation may lead to various problems such as (1) a decrease of the active volume leading to a loss of energy production or of water available for water supply and irrigation; (2) a decrease of the retention volume in case of flood events; (3) endangerment of operating safety due to blockage of the outlet structures; and (4) increased abrasion of steel hydraulics works and mechanical equipment due to increasing specific suspended load concentrations. Besides these operational problems a lack of sediments in the downstream river stretch may result in river bed incision. Particularly, with more severe legislation such as the revised Swiss water protection law that has come into force in 2011, the exigencies regarding ecology have increased. One of the goals is to restore the longitudinal continuity of sediments wherever possible at reasonable expense. For many smaller reservoirs, particularly in mountainous conditions, Sediment Bypass Tunnels (SBTs) may counter these negative effects by connecting the upstream and downstream reaches of dams and reestablishing sediment continuity, as proven by a number of cases worldwide, particularly in Japan and Switzerland (Auel & Boes 2011, Fukuda et al. 2012). However, due to high flow velocities and large bed load transport rates, hydroabrasion is a frequent phenomenon present at SBT. Due to the fact that abrasion requires continuous maintenance and causes high annual costs, adequate countermeasures such as using High-Performance Concrete (HPC) and/or optimization of hydraulic conditions for invert protection should be already taken into account at the design phase (Hagmann et al. 2012).

2 RESERVOIR SEDIMENTATION AND COUNTERMEASURES

In analogy to natural lakes, artificial reservoirs impounded by dams fill up with sediments over time. Depending on local site conditions such as size, topography, landform, hydrology and geology of the catchment basin, as well as size and shape of the reservoir this process may last from a few years to several centuries. On a worldwide scale, typical sedimentation rates per country vary between a few tenths up to more than three percent (Fig. 1),

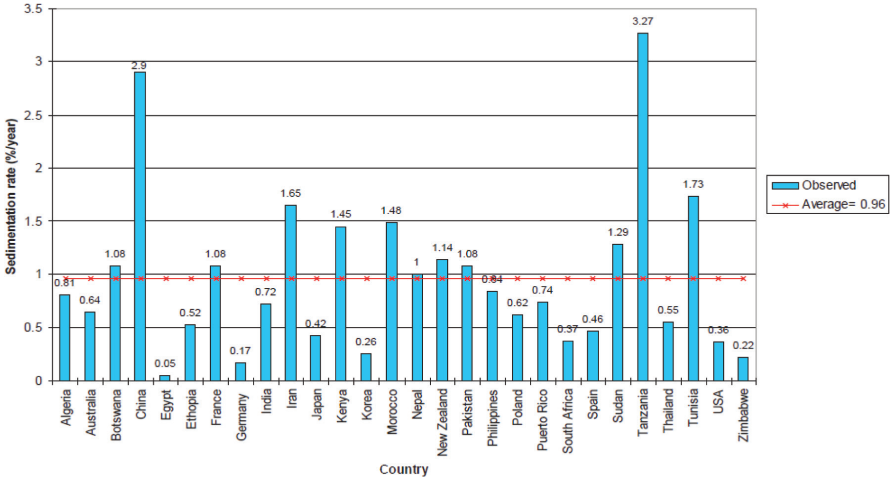

Figure 1. Observed sedimentation rates for various countries worldwide (after ICOLD 2009).

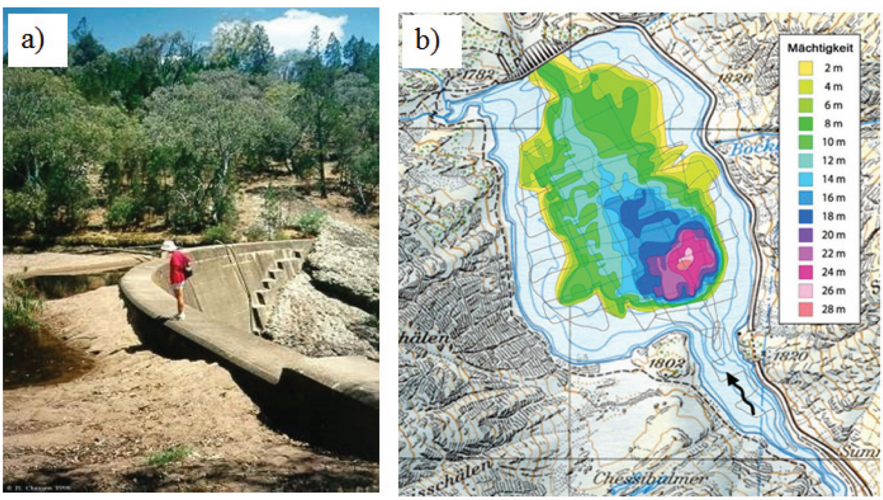

Figure 2. (a) Fully-silted *Koorawatha* reservoir in Australia (Chanson 1998), (b) aggradation depths in *Räterichsboden* reservoir from 1950 to 2001 (Bühler & Anselmetti 2003).

putting the sustainability of reservoirs into question if no adequate countermeasures are taken. The Koorawatha reservoir in Australia, for instance, has quickly experienced considerable sedimentation after commissioning in 1911, so that it lost its main purpose for railway water supply (Fig. 2a). Although such a high rate of sedimentation hardly occurs for Central European conditions, some alpine reservoirs also show a significant aggradation process. The aggradation depths in the Räterichsboden reservoir in the Swiss Alps amounted to 28 m after 50 years of operation (Fig. 2b).

From a hydraulics and sedimentology point of view the deposition process of bed load or suspended load in a reservoir is described by the relationship between discharge, flow velocity or bed shear stress and particle properties e.g. size, density and settling velocity. The aggradation pattern in a reservoir therefore depends on the kind and amount of incoming sediments as well as the geometry and operation mode of the reservoir. Typically, due to decreasing flow velocities and thus turbulence intensities aggraded sediments become finer from the

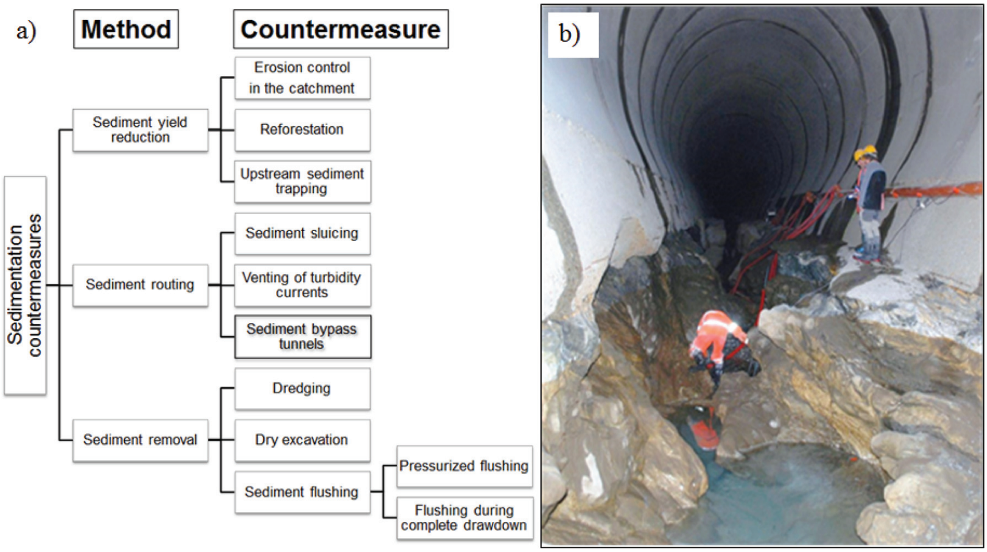

Figure 3. (a) Reservoir sedimentation countermeasures (adapted from Sumi et al. 2004), (b) invert abrasion at *Palagnedra* SBT, Switzerland (photograph by C. Auel).

upper reach of the reservoir towards the dam. A common approach distinguishes between delta formation at the upper reach of a reservoir caused by coarse sediments (bed load) and the aggradation of fines in the deeper water zone further downstream which is often highly affected by density currents in the case of rather narrow and elongated reservoirs of steep bottom slope (Schleiss et al. 2010, Boes 2011).

Reservoir sedimentation causes a number of negative impacts on dams. Firstly, when reaching the dam it may endanger the functionality of both intake structures and bottom outlets. Blockage of the latter must be avoided, as these constitute an important safety element of dams. Secondly, the effective net volume available for the purpose of the reservoir, e.g. power production or flood protection, is reduced over time due to proceeding sedimentation. Thus aggradation of fines results in an immediate negative impact, whereas accumulation of coarse material has a long-term negative impact on reservoirs.

To keep or restore the original reservoir volume the necessary measures are (I) prevention of sediment input, (II) routing of incoming sediments and (III) removing aggraded sediments *a posteriori* (Fig. 3a). Whereas the former have a preventive character, i.e. they impede sediments from being transported into a reservoir; the two latter methods are retroactive, as they deal with sediments that have already been transported into the lake. Sediment bypass tunnels belong to the routing method, as they convey sediments around a dam into the tailwater. SBTs are mainly operated during flood events and connect the upper and lower river reaches and reestablish the pre-dam conditions in terms of sediment transport (sediment continuity). In general, such measures should be taken as early as possible to maximize their efficiencies, i.e. in the planning and design phases of dams and reservoirs. Unfortunately, despite knowledge on the reservoir sedimentation process countermeasures have often been postponed or not adequately been considered in the past, restricting the choice of efficient measures at a later stage.

3 SEDIMENT BYPASS TUNNELS

According to Auel & Boes (2011) a SBT consists of a guiding structure installed in the reservoir, an intake structure with a gate, mostly a short and steeply sloped acceleration section, a mild sloped bypass tunnel section, and an outlet structure. Depending on the location of the intake structure, i.e. whether at the head or within the reservoir, there are basically two different types of SBTs. For type A, the inflow takes place under free surface conditions at the delta, while for type B it is usually pressurized located below the pivot point of the aggradation body. The tunnel invert has to be steep enough to avoid sediment deposition and at the same time it should be as mild as possible to limit the flow velocities in order to prevent invert abrasion. For existing SBTs in Japan and Switzerland, the bed slope varies between 1 and 4% (Auel & Boes 2011).

SBTs feature several advantages over other countermeasures. Firstly, they have positive effects regarding ecological aspects, because sediment conveyance may significantly decelerate or even stop river bed erosion and increase the morphological variability downstream of a dam. Mainly sediments provided from the upstream river reach are conveyed through the SBT since remobilization of accumulated sediments in the reservoir hardly occurs. The sediment concentration in the tailwater of the dam is thus not affected by the reservoir itself and of natural character. Secondly, SBTs have been proven as an effective countermeasure against reservoir sedimentation amongst others. For instance, the type A SBT of the Asahi Dam in Japan has greatly reduced the severe aggradation in terms of accumulated sedimentation volume after commissioning in 1998 (Fig. 4). Even during an exceptionally large flood caused by a typhoon in 2011 the routing of sediments around the dam helped to limit the inflow of sediments into the reservoir.

Whereas typically, the bed load deposition may be completely solved with SBT, the deposition of fines depends on the design discharge of the tunnel. The higher the recurrence interval of the SBT operation, the higher the share of the incoming suspended load that may be conveyed through the tunnel and the smaller the amount of fines entering the reservoir. The main drawback of SBT is related to economic considerations. The implementation of SBT is not only costly from an investment perspective, but also requires regular maintenance. Due to high flow velocities with peaks in the range of 12 to 20 m/s (Auel & Boes 2011) and high sediment transport rates, invert abrasion is generally a severe problem, requiring costly repair works and maintenance (see Fig. 3b). For this reason SBTs should be considered as a convenient measure for small to medium-sized reservoirs with capacity-to-inflow ratios, i.e. the ratio between the annual inflow and the total reservoir volumes, of about 0.003 to 0.2 for the Swiss and Japanese SBTs (Sumi & Kantoush 2011). For such reservoirs bed load aggradation and delta formation are more critical problems than the problem of sedimentation of fines since a large amount of incoming fines stay in suspension due to the relatively short residence time and are discharged via the outlet works. Moreover, major tunneling costs favor their use at smaller reservoirs due to short SBT lengths.

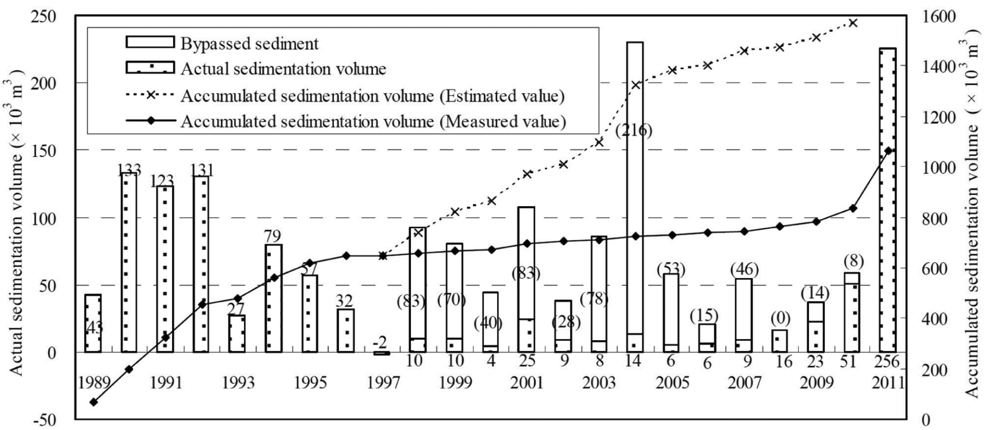

Figure 4. Development of reservoir sedimentation volume at *Asahi* reservoir, Japan, prior to and after commissioning of an SBT in 1998 (Fukuroi 2012).

4 HYDROABRASION AT SEDIMENT BYPASS TUNNELS

As stated above, abrasion is a serious concern in most SBTs. The extent of damages along the wetted perimeter, i.e. mainly on the invert and the lower parts of the tunnel walls, typically increases with increasing unit sediment load, particle size and distribution and flow velocities i.e. shear stress as well as quartz content in the mineralogical composition of the sediments.

Hydro-abrasive damage on an invert of a hydraulic structure occurs when the flow induced bed shear stress exceeds a critical value and hence numerous particles start impacting. Depending on the flow conditions particles are transported in sliding, rolling or saltation modes and cause grinding, rolling or saltating impact stress on the bed and thus wear on the bed (Fig. 5). According to Sklar & Dietrich (2001, 2004) the governing process causing abrasion is saltation, whereas sliding and rolling do not cause significant wear. Therefore, for an optimum SBT design, hydraulic conditions, particle size and distribution and hence particle transport modes must be determined. The rolling, saltation and suspension probabilities of different particle sizes are also important since the transport mode directly affects the particle impact energy on the bed. They are determined using the relationship between probabilities of transport modes and Shields number (Hu & Hui 1996, Ancey et al. 2002, Auel et al. 2014a). For a given particle size and flow induced shear stress, particle transport modes and their probability as well as expected particle abrasion mechanisms can be obtained to optimize the hydraulic condition and to choose the invert material type for a SBT.

Auel et al. (2014b) show that mean particle and impact velocities for rolling and saltating particles linearly increase with flow velocity independent of particle size. Large particles possess a large particle mass, thus higher impact energy is transferred by these particles on the surface (Auel et al. 2014a and 2014b). Consequently, a combination of large particle size and high flow velocities results in high mean invert abrasion, which is clearly confirmed in Figure 6. Depending on the invert material and transported sediment properties, the abrasion depth varies and in general typical mean abrasion depths range from microns to some millimeter per operating hour for some Swiss and Japanese cases (Jacobs et al. 2001, Kataoka 2003, Sumi et al. 2004, and Fukuroi 2012).

The results from *Runcahez* SBT indicate that mean abrasion depth per hour increase with decreasing compressive and bending tensile strengths of the invert concrete (Figs. 6a and 7). Moreover, despite slightly larger particle size and higher design velocity compared to *Runcahez* SBT, the mean abrasion depth per hour on *Pfaffensprung* SBT is smaller than in *Runcahez*. This result reveals a strong effect of invert material properties on abrasion depth, e.g. the higher the compressive and bending tensile strengths, the less the abrasion depth (Fig. 7). Comparison of *Runcahez* SBT with *Asahi* SBT shows the effect of design velocity on abrasion depth (Fig. 6b). Although the concrete compressive strength is smaller for *Asahi* than for *Runcahez* (Fig. 7a), the high mean abrasion depth per hour in *Asahi* SBT in comparison to Runcahez SBT is mostly attributed to the high design velocity despite much smaller particle size, i.e. d_m = 50 mm for *Asahi* vs. 225 mm for *Runcahez* (Fig. 6a). Note that the bed-load rates are not known for both SBTs.

One of the important findings from the study in *Pfaffensprung* is the high hydroabrasion resistance of granite compared to the implemented concrete invert, as the mean abrasion per hour on the granite plates is five times less than on the concrete invert (Fig. 7a). This may

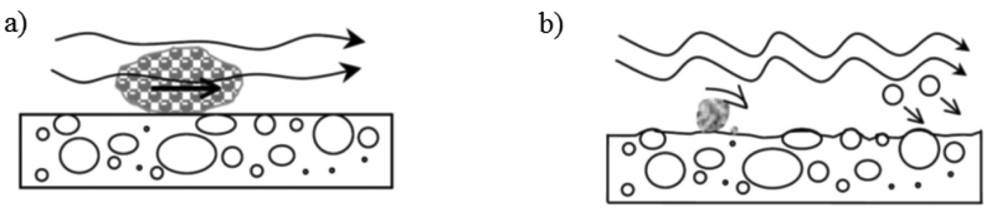

Figure 5. Abrasion processes of hydraulic systems' surfaces: (a) grinding, (b) combination of grinding and impingement (Jacobs et al. 2001).

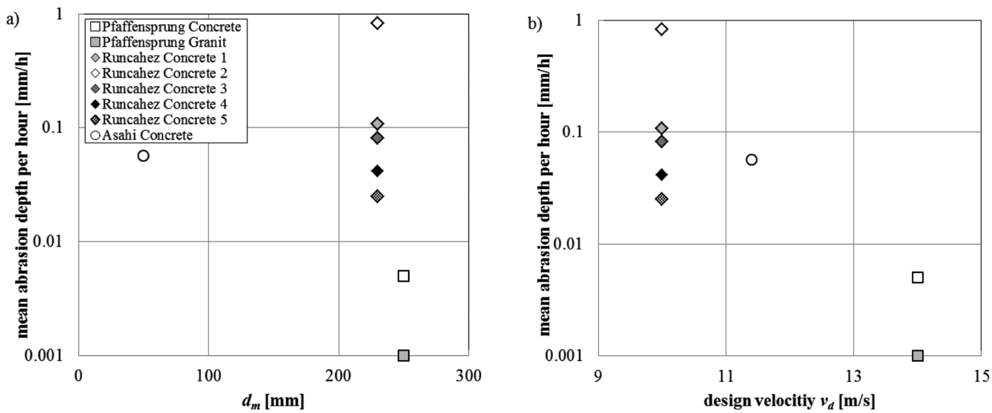

Figure 6. Observed mean abrasion depths per operating hour as functions of (a) particle diameter d_m and (b) design flow velocity v_d.

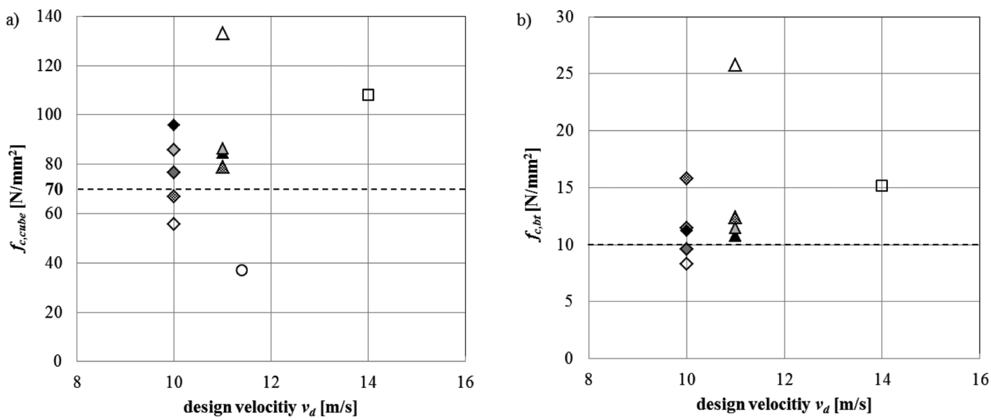

Figure 7. (a) Compressive strength determined at cubes and (b) bending tensile strength of invert concrete applied in various SBTs (data from studies mentioned above); symbols are the same as in Figure 6.

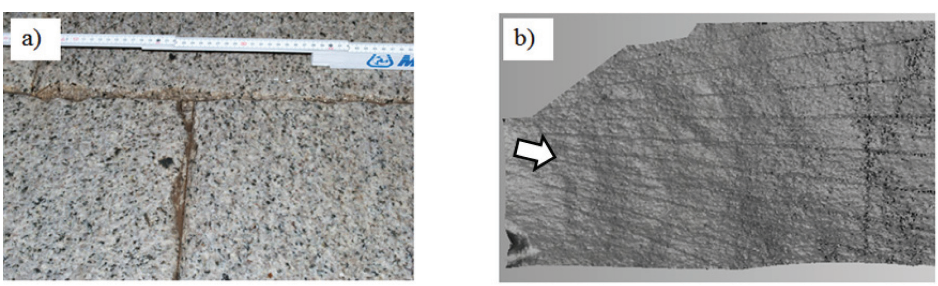

Figure 8. Abrasion patterns at *Pfaffensprung* SBT: (a) grooves forming along joints of granite plates, (b) undulating invert at HPC test field (steel-fibre HPC with $f_c > 70$ N/mm²).

suggest that granite is a better choice as an invert material over HPC. However, the cost of granite should be carefully considered at SBT design phase.

The results of the study carried out in *Pfaffensprung* SBT in 2013 show that the damages typically take place in the form of grooves along the joints of basalt and granite plates (Fig. 8a), while a wavy pattern of abrasion occurs on the HPC (Fig. 8b). In order to further reduce the abrasion on the granite, this result suggests that such plates should not be implemented in parallel to the main flow direction.

Whereas natural stone material, e.g. granite or cast basalt plates, usually have a high abrasion resistance against pure particle grinding action, their brittleness favors fracturing by impinging particles in case of saltating sediments. In the latter case, either steel or cementitious material such as HPC generally show a better resistance. As steel linings are often too costly for abrasion protection of large areas such as in SBTs, HPC becomes an interesting and economical alternative.

Based on a long-term field study performed at *Runcahez* SBT in Switzerland between 1995 and 2000 (Jacobs et al. 2001), the decisive material characteristics of hardened HPC are the compressive strength (f_c > 70 N/mm^2 at 28 days, Fig. 7a), the bending tensile strength ($f_{c,bt}$ > 10 N/mm^2 at 28 days, Fig. 7b), and the fracture energy (>200 J/m^2 at 28 days).

5 DESIGN OF SBT

To reduce the negative effects of hydroabrasion at SBTs, (i) an optimum hydraulic design to limit the strong particle impact forces and (ii) a selection of sustainable and optimum abrasion-resistant invert lining material are recommended measures. Aspect (i) demands for the following, among others:

- A tunnel cross section with plane invert geometry should be chosen, i.e. archway and horseshoe profiles with horizontal bed rather than circular ones, to avoid stress concentrations.
- Whenever possible, bends in plan view should be avoided to reduce shock waves and secondary currents, which cause locally high specific sediment transport rates. For instance, in Solis SBT the sediment transport at the tunnel outlet is concentrated on the orographic right side as a result of a bend further upstream (Fig. 9a).
- Keep the bed slope as mild as possible without endangering sediment aggradation.

As to aspect (ii) the following should be accounted for, among others:

- If most of the particles are transported in rolling or sliding motion with only minor saltation, abrasion processes are expected to be mainly grinding and only weakly impinging. Hence using natural stones such as granite and cast basalt as invert lining material is a good solution. As the joints should not be parallel to the flow, the use of hexagonal plates is recommended (Fig. 9b). The plates should be embedded into a special mortar.
- If saltation is expected to be the main particle transport mode and/or the sediment is rather coarse with high flow velocity, HPC with compressive strength above 70 N/mm^2 (i.e. C70/85 and higher) and a bending tensile strength above 10 N/mm^2 is preferable. Concrete curing is critical and should be carefully performed. For more details, see Jacobs et al. (2001).

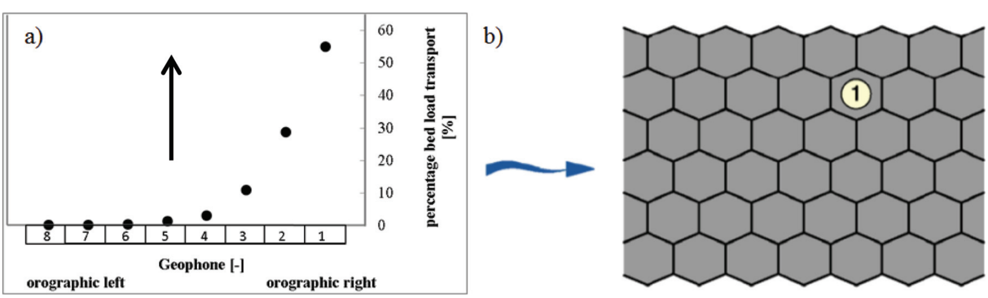

Figure 9. (a) Measured sediment transport using 8 geophones for the 2013 flood event at *Solis* SBT; (b) schematic plan view of a thin pavement of hexagonal natural stone plates (Jacobs et al. 2001).

6 CONCLUSIONS

Reservoir sedimentation is a serious worldwide problem threatening the sustainability of reservoirs and negatively impacting dam safety. SBTs are effective countermeasures for small to medium-sized reservoirs provided that hydroabrasion is accounted for from the very beginning of the planning stage by optimizing the hydraulic design and by applying adequate invert material. Depending on the transport mode of the sediment which is determined by the hydraulic characteristics of the tunnel flow, cast basalt and granite plates or HPC and steel linings are recommended.

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