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Efficiency of Pressurized Rock Traps for Unlined Hydropower Tunnels

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Abstract: Pressurized rock traps are constructed in many hydropower plants to stop sand and gravel from being transported through the turbines. Pressurized rock traps are typically located in the downstream end of unlined headrace tunnels, where the tunnel itself may be one of the sediment sources. This state-of-the-art review presents an overview of research on pressurized rock traps from both publicly available sources and unpublished sources. Limited scientific literature exists on rock traps, and most of the existing literature has previously been unavailable for an international audience. Based on this review, it is concluded that pressurized rock traps should be built with the flow area and sediment deposition volume separated by plates or ribs. Without any separation measures, the sediments risk being re-entrained due to turbulence. This review is separated into three sections: (1) sediment problems and sources of sediments, (2) theory for pressurized rock traps, and (3) design of pressurized rock traps. The recommended design for new pressurized rock traps, including a design flow chart, is provided. Finally, a recommended solution for rebuilding existing pressurized rock traps with an open design into a closed design is also presented.

Keywords: pressurized rock traps; sediment; hydropower; tunnel; desilting basins

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1. Introduction

Particles carried by the water utilized for hydropower production will over time, if they are not removed, cause damage to the turbines, e.g., [1,2]. Therefore, it may be economically feasible to remove particles from the water upstream of the turbines. The particles can be removed through a sedimentation process in facilities commonly referred to as desilting basins, sand traps, or rock traps, depending on the size of the particles to be removed, and convention. This paper presents a review of the design of pressurized rock traps with a special focus on the application within unlined hydropower tunnels. The knowledge gained is then used for a design methodology of rock traps.

The motivation for preventing damage to the turbines is economical. The costs involved in maintenance due to sediments, and the lower-income caused by reduced efficiency must be evaluated against the costs for constructing a rock trap. Nevertheless, this paper is not mainly concerned with the economic aspects, but rather the hydraulic design of rock traps.

Pressurized rock traps are constructed for hydropower plants located in regions with limited fine sediments in the rivers, and they are designed for the removal of sand and rocks primarily transported as bed load. In areas with a high number of fine particles, rock traps can also be used, but above all, the finer sediments must be extracted and flushed effectively, for example in sedimentation basins at the headworks. Pressurized rock traps, on the other hand, are typically found in hydropower plants with unlined tunnels and are placed at the downstream end of the unlined tunnel section at the transition to the steel-lined penstock. At this location, the pressurized rock trap can protect against sediment particles from several sources: (1) particles from the main intake, (2) from one or more secondary intakes, or (3) from the unlined tunnel itself. As pressurized rock traps are designed to capture sediments that are transported as bedload, a suggested rule-of-thumb is that the weight proportion of the inflowing particles with a diameter smaller than 0.3 mm should be less than 30%. This criterion is based on grain size distribution curves from operational unlined hydropower tunnels and pressurized rock traps [3]. It should be noted that this rule-of-thumb assumes that the total amount of particles smaller than 0.3 mm is too small to cause significant damage to the turbine. For cases where the total amount of suspended sediments is high enough to cause significant damage, alternative solutions to reduce turbine wear should be considered.

The published research on pressurized rock traps is limited, partly because the field of research is narrow and partly because very limited research has been conducted within the last 30 years. As a result, engineers risk using outdated guidelines for design and construction. The motivation for the present paper is to mitigate this problem by presenting a review of the existing knowledge within the research area, both theoretical and practical. However, desilting basins and free surface flow sandtraps have been extensively investigated by past studies such as [4–8]. Several textbooks on the design of hydropower have presented discussions of sandtraps and settling basins [9–11]. The basic design principles are similar for pressurized rock traps but owing to the larger target particle size and pressurized flow, the resulting design, construction, and operation are different. General knowledge of sediment transport and erosion is an important part of the design of pressurized rock traps. Thorough and updated overviews of research, history, theory, and knowledge in the field of sediments are found in e.g., [12,13].

This paper starts with an overview of the problems and sources of sediment in hydropower tunnels. Thereafter, relevant theory of rock trap design is outlined and discussed. Furthermore, design criteria and a historical review of rock trap design is presented, before the state-of-the-art is determined. The final chapters contain discussions of previous research, a suggested methodology for design, and the need for new research.

2. Sediment Problems in Hydropower Turbines

This chapter presents an overview of the problems resulting from sediment transport through hydropower turbines, which is the background for constructing rock traps. The volume and characteristics of sediments that pass through the turbines are the main parameters determining the damage potential, in addition to the speed of the water through the turbine [14]. By installing rock traps, the volume of sediments passing through the turbines can be reduced, and thereby minimize the damage. The main modes of turbine damage caused by sediments are described in the following section.

2.1. Hydroabrasion and -Erosion

The main problem from sediments is wear from abrasion and erosion on the turbines, which entails costs such as both maintenance and production loss due to efficiency loss. Sediments cause wear on all types of turbines [2,14,15]. An example from a Pelton turbine is shown in Figure 1. The abrasion and erosion are highly site-specific depending on (1) sediment yield in the river, (2) sediment properties, (3) sediment handling in the power plant, (4) nominal head, (5) turbine type, quality of material and design, (6) turbine operation, and (7) turbine maintenance.

Figure 1. A Pelton turbine with severe sediment wear.

The sediment yield and sediment characteristics (1,2) in the river are usually not possible to control. Sediment yield from the tunnel invert, however, is often possible to control with measures described under Section 3.4. The most important sediment characteristics (2) include particle size, hardness, and shape [2]. The particle size determines the force any given particle will have when colliding with the turbines. The particle hardness and shape (rounded or sharp) may determine how much damage any single particle can inflict. Sediment handling in the power plant (3) can limit the number of sediments that pass through the turbines and can be adapted in the intake, headworks, and rock trap design.

The turbine head (4) has a high influence on the potential of wear on turbines [2,9]. Higher head generally leads to higher flow velocity and increased wear. The turbine design and materials, including coating (5) also affect the resulting damage. The damage potential is related to the relative flow velocity compared to the blade velocity in the runner [2,16,17]. Some detailed studies have quantified the sediments and the correlating wear for specific power plants [15,18], but the results can only be extrapolated to other power plants with very high uncertainty.

Finally, turbine operation and turbine maintenance (6,7) will affect the resulting hydro-abrasive erosion on the turbines. Damage can be reduced by stopping the turbines in periods with high sediment inflow.

2.2. Other Damage Types

The clogging of seals and filters in turbines is a common but less serious damage type. More severe economic losses may be caused by erosion of seals. Erosion of labyrinth seals in Francis turbines will cause a larger amount of leakage losses and thereby reduced power production. Erosion of the guide vane end seals may also cause these not to function, and effectively reduce the efficiency of the turbine.

During the first filling of a newly constructed hydropower tunnel system, the system is prone to severe sediment transport events, especially for power plants with unlined tunnels. Such events are reported to have resulted in significant turbine damage inflicted over just a few hours in the 250 MW Nes power plant and the 52 MW Mel power plant in Norway. The authors are also familiar with incidents after several years of operation of a hydropower plant where large amounts of sediments have been flushed into the turbine during rapid filling of the tunnel system, resulting in the need for manual removal from the Francis turbine house, runner, draft tube, and seals. Such an incident occurred in the 960 MW Tonstad hydropower plant, Norway, in 2012.

3. Sources of Sediments

This chapter discusses the main sources of sediments for pressurized rock traps: (1) sediments from the main intake, (2) from one or more secondary intakes, and (3) from the tunnel itself. A section on field measurements is included to demonstrate some examples of sediment distribution curves from unlined tunnels.

3.1. Sediments from Intakes

Brook intakes and intakes in run-of-river hydropower plants are more susceptible to sediments, compared with reservoir intakes, especially during flood events [19]. Reservoirs may function as large desilting basins and can, over time, accumulate large deposits of sediments. For reservoirs with large regulation height, built-up material may eventually be exposed and erode when the water level is drawn down. In addition, large level variation in reservoirs may also cause side banks to slide into the reservoir. The finer materials will be suspended and may be transported to the intake and into the hydropower tunnels [19].

In cases where the sediments enter the conduit mainly through the intake, it may be more efficient and practical to construct desilting basins directly at the intake instead of pressurized rock traps at the end of the headrace tunnel [19]. This approach is more in line with the traditional way of treating sediments in countries with much higher sediment yield than in Norway, for example, in the Alpine and Himalayan regions [11] and South and Central America [20]. This approach requires the invert in the tunnels to be cleaned or lined with concrete or asphalt as described in the next section.

3.2. Sediments from the Tunnel

In regions with good rock mass quality, tunnels may be constructed unlined with only limited rock support where necessary [21]. This construction method has been widely used in many countries all over the world, among others in Scandinavia, Australia, and the USA. The drill-and-blast method of tunnel construction leaves a lot of muck on the tunnel invert that is prepared as a driveway during construction. For lined tunnels, the remaining muck in the tunnel is separated from the flow and does not impose a problem. For unlined tunnels, the muck is either fully removed, partially removed, or left behind. Any remaining material is exposed to the flow during operation and the finer material will be transported as sediments downstream, and a pressurized rock trap at the downstream end of the tunnel will be necessary.

3.3. Field Measurements

A challenge in pressurized rock trap design is to be able to predict the sediment inflow. To the authors' knowledge, measurements of the total sediment load (suspended and bedload) flowing into a pressurized rock trap do not exist in the literature. There is little accurate knowledge of the correlation between power plant operation and sediment transport at most hydropower plants. A relevant study is conducted at the 64 MW Fieschertal hydropower plant in Switzerland where sediment inflow data is measured and correlated with 3D scans of the Pelton turbines to assess turbine damage [18]. However, there is no rock trap in this tunnel system.

On the other hand, a lot of information exists about the particle size distribution (PSD) of the sediments in tunnels and rock traps from power plants in operation. VR [22] collected the samples from 21 hydropower tunnels after coarse cleaning of the invert, but before commissioning (outlined by the shaded area in Figure 2). It is evident that the materials are poorly sorted, with a significant number of fines (no information about $d < 0.3$ mm). Figure 2 also shows the particle size distribution curve from samples obtained from upstream and downstream in the 55 m long rock trap in Lower Vinstra powerplant in 1968 [23] and upstream and downstream in the 200 m long rock trap in Tonstad powerplant, obtained by the authors in 2018. Several samples were taken at each place, so they were collected to show the range of the particle sizes. The samples taken in the downstream parts of the rock traps (blue plots) consisted of nearly uniformly graded materials with particle sizes mainly ranging between 0.25 mm and 2 mm. The samples taken in the upstream part in the rock traps (red plots) consisted of well graded materials, but with no particles smaller than 0.3 mm. By comparing the PSD curves from the tunnel invert with the curves from the rock trap, it is evident that the materials on the tunnel invert contain higher fractions of both fine and coarse particles than the trapped materials in the rock trap. Eggen [24] concludes that the fine materials probably are passing the rock trap, while the coarser materials are left in the tunnel unmoved.

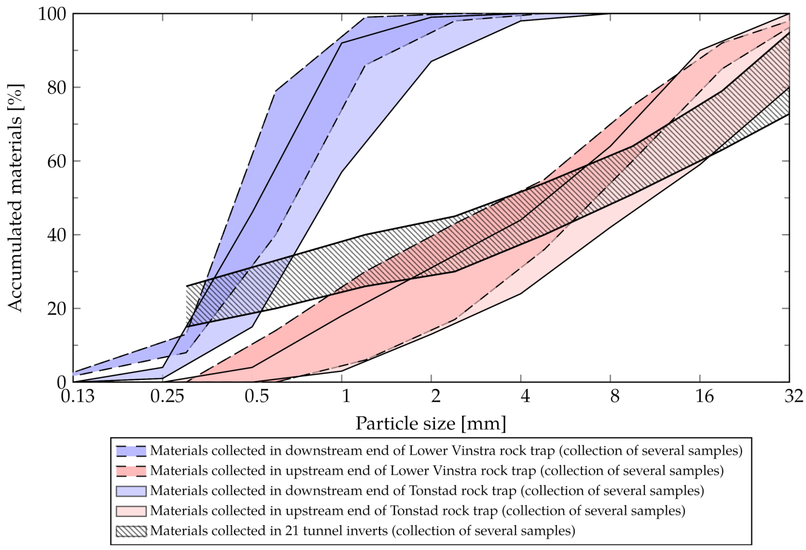

Figure 2. Particle size curve for materials in 21 tunnel inverts (gray area) (adapted from [19]), the rock trap in Lower Vinstra (adapted from [23]) and the rock trap in Tonstad.

In addition to the sediments originating from the tunnel invert, sediments may come from the intakes. One reported case study from Evanger powerplant [25] was investigated in 1980, and samples of sediments were taken several places in the tunnel system and in the reaches upstream of the main intake and twelve secondary intakes. A rock trap has been constructed in the downstream end of the unlined headrace tunnel immediately upstream of the steel-lined pressure shaft. The powerplant was commissioned in 1969 and had been in operation for 11 years at the time of the sampling. Since the time of commissioning, there had been severe turbine abrasion. The investigation revealed that several rivers were flowing through moraine depositions, wherein an average of 40% of the materials had a particle size < 0.25 mm. The materials were taken into the tunnel via brook intakes. It was concluded that the fine materials had no place for settling before they entered the turbines, not even with a state-of-the-art rock trap. In addition, the rock trap was not functioning properly. Only half of the volume was available for sediments, and only sediments with a diameter > 0.6 mm were found to settle.

3.4. Removal of Sediments in Hydropower Tunnels

As mentioned in the introduction, the motivation for the removal of sediments is of the economical kind. The main costs caused by sediment wear on mechanical parts are [22]:

- Maintenance
- Reduced efficiency
- Shortened lifetime, premature replacement
- Production stop at unfortunate times
- Loss of water

The costs mentioned above must be considered against the cost of construction and maintenance (esp. emptying) of sedimentation facilities. For pressurized rock traps, the biggest cost is the excavation of the rock to create room for the sediments.

There are of course other ways to handle sediment problems, and depending on the conditions, they may be better suited than constructing a rock trap. If the sediments can be prevented from entering the tunnel system, it is beneficial for both the power plant and the environment. The headworks could be placed or constructed in a more suitable place, with less risk of sediments entering the tunnel [19]. A sedimentation basin or a dam with sediment flushing capabilities at the intake will in many cases be the best and least costly solution, especially if the sediment yield is high [11]. If the sediments are eroded from a single deposit or area with landslides, the specific area could be protected against erosion [19].

If the sediments originate in the tunnel, as described in Section 3.2, several options for preparing the tunnel before commissioning exists: (1) No cleaning and leave the muck as it is, (2) rough cleaning, (3) thorough cleaning with machines, (4) thorough cleaning by flushing, (5) cleaning by free-surface flow from the intake, and (6) paving the muck on the tunnel invert with rocks, concrete or asphalt [26].

Some of these types of cleaning are illustrated in Figure 3. In the case of no cleaning (1) and rough cleaning (2), substantial amounts of sediments will be left on the invert when the power plant is commissioned. This will require a pressurized rock trap. In the past, it was assumed that the erosion would come to an end after some years of operation [24]. However, experience from several power plants proves that sediment transport is a long-lasting process [27]. One explanation is the forming of armor layers, as discussed under Section 4.4.

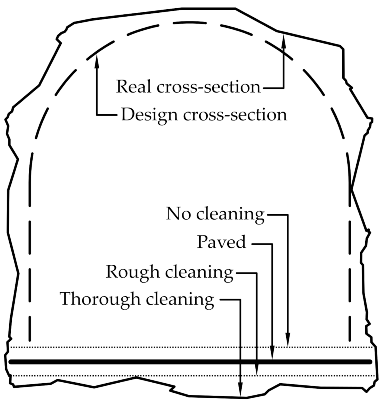

Figure 3. Different methods for tunnel invert cleaning (adapted with permission from from [26] (Copyright 1997 Pål-Egil Rønn).

Thorough cleaning with machines (3), flushing (4), or cleaning by gravity-induced flow (5) may reduce the amount of material significantly to avoid rock traps. This is often the most feasible option for short tunnels. However, for long tunnels, the time needed to clean the invert may not be profitable as the cleaning is a time-critical activity and will delay the commissioning and thus the start of generation of revenue.

Cleaning of the invert by means of gravity-induced flow from the intake (5) has been used for inclined pressure tunnels with success [28]. A free surface flow is applied in the tunnel. The free surface flow will, for a suitable tunnel inclination, have a higher velocity and thus higher sediment flushing capacity than the pressurized flow during normal hydropower operation. The scouring effect of the free surface flow can be used for cleaning the invert before commissioning. This method requires either a suitable tunnel exit or a receiving rock trap in the downstream end of the tunnel with a sufficient volume. One possibility is to construct rock traps not intended for emptying [29] at strategic locations within the tunnel system.

Another measure is to treat the invert with a coating or lining (6). It can be asphalt [24], concrete, or coarse gravel [19] that will create a solid armor layer and prevent erosion of the finer sediments. Of course, in the case of coarse gravel coating, measures must be taken to secure that the flow will not reach magnitudes to erode the gravel, especially during tunnel filling. With concrete or asphalt floor lining, the layer must be thick enough to prevent erosion, and permeable enough to release the pore pressure under the lining [30].

It should be noted that free surface flow with high transport capacity may potentially occur in all headrace tunnels during the filling of the tunnel system. If there is material left in the tunnel after commissioning, then either the filling process must be sufficiently slow, or the pressurized rock trap must be designed to let sediments accumulate. It must be mentioned that emptying and filling will happen many times during the lifetime of any powerplant.

4. Theory for Design of Pressurized Rock Traps

This section of the paper will present the concepts and theory that has been influencing the design of rock traps. First, the most common theory of incipient motion for uniform flow is presented and discussed. However incorrect, this theory has been widely used to estimate diameters of particles transported through the hydropower tunnels and settled in the rock trap. Thereafter, armoring layers and grain sorting are introduced since they influence the stability of particles and thereby the incipient motion.

4.1. Design Criteria

The design criterion for pressurized rock traps has been to "achieve a basin for maximum deposits of bedload" within the allocated volume [31]. In previous research on pressurized rock traps, it was acknowledged that the smallest particles, between 30% and 40% of the total sediment inflow, simply will pass the rock trap without settling [24,32]. The research was focused on optimizing the flow conditions to exploit a specified available rock trap volume for minimum excavation costs versus the time interval between emptying. In comparison, for sedimentation basins, a common design criterion is to select the necessary size to trap all or most of the particles with a size above a certain threshold [8].

An important aspect concerning the design criteria for pressurized rock traps is the filling of the rock trap over time. The trap efficiency will be larger when the rock trap is empty compared to when it is filled, and a full rock trap has lost its function. Designers therefore must select an appropriate filling level as the design situation. Unfortunately, in available technical reports of the design of rock traps, there has been no specified design filling level, or the maximum allowed filling level of the rock trap volume.

4.2. Theory of Incipient Motion

Throughout the last century, several attempts have been made at creating a mathematical model to predict the entrainment, transport, and settling of sediment particles in flowing water [12]. Still, the topic of interaction between water and particles is very complex and not fully understood, and a simple model is most likely impossible to obtain. A common model to describe the movement of particles is the shear stress acting from the flow on the particles. Shear stress can be divided into two parts:

$$\tau = \tau_l + \tau_t, \ [\mathrm{Pa}] \tag{1}$$

where τ_l = viscous stress and τ_t = turbulent stress [33]. The turbulent stress originates in the turbulent vortices that are created along the boundaries of the flow and dissipated through smaller and smaller vortices in the flow. Turbulent stress plays a dominant part in the turbulent flow. Knowledge of both τ_l and τ_t is essential to give an accurate description of the movement and transport of particles. For practical matters, however, the instantaneous shear stress is very difficult to measure accurately, and engineers must often use other, indirect methods, which will be elaborated in the following. In a steady, uniform flow, there must be a friction force balancing the driving force. For an open channel, the driving force is gravity. For a closed conduit, the driving force is pressure. The shear stress will act as a friction force when integrated over a distance, acting in the opposite direction of the driving force. The balance between the driving force and shear friction gives the following equation for mean shear stress:

$$\tau_b = \gamma R_h S, \text{ [Pa]} \tag{2}$$

where τ_b = bed/wall shear stress; R_h = the hydraulic radius and $S = \sin\alpha \approx \tan\alpha = \frac{h_f}{L}$ = slope of the energy line. Equation (2) is usually applied in this form to open channels, but it is also valid for closed conduits. The engineering practice is to apply a formula for friction loss based on the mean velocity $V = Q/A$ where Q is the discharge and A is the cross-section area. This gives an equation for head loss as a function of shear stress along walls and bed. Many empirical equations exist, e.g., Darcy-Weisbach, Manning-Strickler, and Chézy. The Manning-Strickler formula has been widely used for the calculation of head loss in tunnels. It is not as accurate as Darcy-Weisbach, but it is simpler since the friction factor is a pure empirical term, not calculated from conduit and roughness dimensions. The Manning-Strickler formula, as used in several European countries, is

$$S = \frac{V^2}{M^2 R_h^{\frac{4}{3}}}, \text{ [–]} \tag{3}$$

where V = mean velocity and M = Manning-Strickler coefficient. Inserting (3) into Equation (2), gives

$$\tau_b = \gamma \frac{V^2}{M^2 R^{\frac{1}{3}}}, \text{ [Pa]} \tag{4}$$

Shields [34] set a milestone in sediment research with his work. The famous Shields-diagram has the dimensionless Shields parameter on the abscissa, which is defined as

$$\tau_c^* = \frac{\tau_{bc}}{(\gamma_s - \gamma)d}, \text{ [–]} \tag{5}$$

where τ_c^* = dimensionless shear stress; τ_{bc} = critical bed shear stress for initiation of motion, γ_s = sediment weight, γ = water weight, d = particle diameter. The hydraulic radius R_h of an unlined drill and blast tunnel with the standard inverted D-shape is commonly expressed as

$$R_h = k\sqrt{A}, \text{ [m]} \tag{6}$$

where k = a constant that depends on the cross-section shape; A = cross-section area. By inserting (4) and (6) into (5), Lysne [3] developed the following formula for critical particle diameter as a function of velocity, cross section area, tunnel roughness, and particle Reynolds number:

$$d = \frac{V^2}{\left(\frac{\gamma_s - \gamma}{\gamma}\right) k^{\frac{1}{3}} A^{\frac{1}{6}} M^2 \tau_c^*}, \text{ [m]} \tag{7}$$

The roughness, the shape parameter, and the Shields parameter can be set to a new constant, $C = k^{\frac{1}{3}} M^2 \tau_c^*$, so

$$d = \frac{V^2}{\left(\frac{\gamma_s - \gamma}{\gamma}\right) A^{\frac{1}{6}} C} = f\left(V^2\right), \text{ [m]} \tag{8}$$

where $f\left(V^2\right)$ = a function of the mean flow velocity squared. Lysne [3] did model tests to find a formula for critical particle diameter in a tunnel. In several experiments, a constant flow through a smooth-walled tunnel with sand particles on the invert was monitored. After the bed had stabilized, the average flow velocity was measured and plotted as Equation (8). Also included in the plot were field data from the rock traps in two Norwegian hydroelectric power plant tunnels, similar to the data shown in Figure 2. Only the data from the upstream end of the rock traps were used. Lysne found that

$d = f\left(V^2\right) = \frac{V^2}{c}$ with $c = 130$ fit well into Equation (8) for his results from both the lab and the measurements from tunnels [35]. Later experience apparently showed that C may vary in the range 115 to 140 [35]. For the later design of rock traps, formula (8) with $C = 130$, was used extensively e.g., [24,32,36], and it continues to be used by many engineers.

It should be noted that the critical velocity in settling chambers presented by Camp [37] is the same as (8), except that the Darcy-Weisbach friction formula is used instead of the Manning-Strickler formula:

$$d = \frac{f \cdot V^2}{8 \cdot \tau_c^* \cdot \frac{\gamma_s - \gamma}{\gamma}}, \text{ [m]} \tag{9}$$

where f is the Darcy-Weisbach resistance coefficient. Darcy-Weisbach's equation is a more precise formula than the Manning-Strickler equation since f is a function of the relative roughness and Reynolds' number, which again is a measure of the degree of turbulence and is a function of the hydraulic diameter and the flow velocity. In contrast, the Manning-Strickler coefficient is a purely empirical coefficient that is not dimensionless.

Dimensioning of desilting basins as practiced in Switzerland is presented by Ortmanns [7]. The Manning-Strickler formula is inserted in Shields' function for dimensionless shear stress and solved for velocity, which is roughly the same method as used by Lysne [3]. Ortmanns' method is cited by Patt et al. [38].

4.3. Discussion of Combination of Shields' Criterion and Friction Formulas

As shown above, it is tempting and straightforward to combine Shields' parameter and a friction formula, and such formulas are in widespread use. Such a combination gives a relationship for critical particle diameter as a function of mean velocity, roughness, and cross-section area, via the average bed/wall shear stress. For a homogeneous bed in a wide river, the average bed shear stress is causing the total energy slope, and the same bed shear stress is related to erosion or settling of sediments.

However, in a tunnel, the bed comprises only of around 25% to 30% of the perimeter. For such cases, the head loss and energy slope based on roughness and friction factors do not give the information needed to find the bed shear stress for use in Shields' formula (Equation (5)). For a case with disparate roughness in the walls and the ceiling (blasted rock, very rough) and the bed (concrete, much smoother), only data acquired for the near-bed flow velocity profile will suffice for calculating the bed shear stress.

As shown in the previous section, $c = \tau_c^* \cdot M^2 \cdot k$, where τ_c^* is the Shields' dimensionless shear stress, which normally is reported to be between 0.03 and 0.05 [12]. In normal horse-shoe shaped tunnel cross-sections is $k \approx 0.265$. This further results in M to lie in the range between 100 and 130, which is well outside the common domain for the Manning-Strickler formula. It denotes a very smooth surface, for example, acrylic glass, with which the model setup was built. Unlined blasted rock tunnels have a Manning number around 33 to 35, a fact which suggests that the curve fitting result is a mere coincidence.

Additionally, in the analysis, the sediments in the rock trap are used for the determination of the moved particles from the tunnel invert, and the cross-section area and corresponding flow velocity are from the tunnel. The field data contains only samples collected at the upstream end of the rock trap. Data about the finer particles that settled in the downstream end of the rock trap is not mentioned or used. Despite the lack of detailed information of the dataset, it seems unlikely that the data used was representative of the total amount of materials moved from the tunnel invert. In that case, the fitting points from field data seem coincidental, and without any scientific value. Also, a significant number of fine particles are entrained from the tunnel invert as suspended load, but do not settle in rock traps. These particles are not accounted for in the analysis of Lysne [3].

It may seem pedantic to point out these weaknesses of a scientific work that was published over 50 years ago, but to this day, the results are being cited and used by practicing civil engineers. In the Norwegian scientific report [23] that forms the basis for the journal paper, Lysne himself stresses that the results are not as firmly founded scientifically as he would have hoped for. These words of caution seem to have been lost in translation to the English paper.

4.4. Theory of Armor Layers

Armor layers consist of a layer of coarse-grained, interlocked particles lying over fine-grained sediments. Such layers are formed over time when the particles migrate and resettle. The armor layers can protect smaller particles from erosion, and they will retain particles that would otherwise have been eroded and transported downstream by the hydraulic forces.

Based on experience, the top layer of sediments becomes stable when about 40% to 50% of the particles in the layer are larger than the critical particle size for incipient motion [24]. There has been a general understanding that the tunnel inverts with a sediment layer will achieve a stable equilibrium state over time because of armoring layers.

Armor layers in tunnel inverts retain smaller particles in the tunnels of hydropower plants and, thus, influence the influx of particles into the rock trap. The formation of armor layers is a time-dependent process that depends on the power plant operation, the resulting water flow, and particle characteristics. Further, it is challenging to a priori estimate the effect of armor layers on the particle transport in hydropower tunnels.

An important aspect of armor layers in hydropower tunnels is that stable layers can be breached by specific events with higher water velocity such as tunnel dewatering, tunnel filling, or hydraulic transients caused by load changes and the start-stop operations of the turbines. An indication of this effect is reported for a 40-year-old hydropower plant that experienced a significant rise of sediment flux into the rock trap when the operational regime changed towards more load changes and start-stops [39].

The authors argue that armor layers should not influence the design of pressurized rock traps. Armor layers have a positive effect on the flux of particles, but as it is challenging to estimate the features of armor layer formation, it is best to neglect the effect in the design phase. The armor layers do not influence the transportation of the largest particles in the tunnel or the size limit of the smallest particles that will settle in the rock trap. The main effect of armor layers is on the inflow of sediments into the hydropower tunnel and the retention time of particles in the tunnel before they reach the rock traps. The subject will therefore not be further described in this review.

5. Design of Pressurized Rock Traps

This section of the paper presents a historical review and the current state of the art for the design of pressurized rock traps. The aim is to show outdated designs as well as state-of-the-art designs so that the reader can be able to identify good and bad designs. The mainly discussed designs are shown in Figure 4. The best designs are Figure 4a,d.

5.1. Historical Review

The earliest known description of a pressurized rock trap is for the Haas power plant in the USA [40]. However, it is likely that pressurized rock traps were constructed long before this time. The rock trap had a considerably larger cross-section than the upstream unlined headrace tunnel. It was divided into five sections of 24 m lengths with 1.8 m high concrete walls between the sections. The headrace tunnel was horseshoe-shaped with height $\times$ width = 4 m $\times$ 4 m. The rock trap had a height and width of 6.4 m. No record exists of the functioning of the rock trap.

Model tests were done in 1964 for improving rock traps upstream of the Jaybird Powerhouse in the Upper American River Project, CA, USA [41]. Some key requirements for the proper functioning of the trap emerged: (1) No gradual vertical or horizontal divergence of the flow and (2) sediment-trapping cells. The paper concludes with a recommendation for proper trap design. The focus mainly lies on the practical design of the trap, and little emphasis is put on the description of the entering sediments (e.g., grain size distribution). The new rock trap design, called CELSEP ("cell separation"), involves four key elements, (see Figure 4a):

1. No change of cross-section area for smooth and undisturbed throughflow.
2. Avoid abrupt transitions into the sediment chamber section.
3. Horizontal steel plates and rebars for the separation of the flow.
4. Walls between the cells for keeping the trapped sediments in place, horizontally.

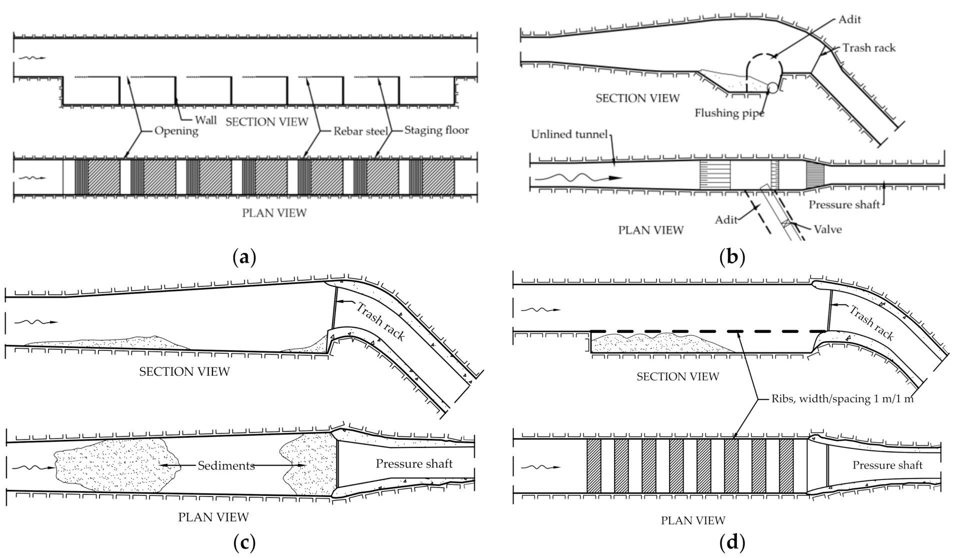

Figure 4. (**a**) CELSEP rock trap (Adapted with permission from [41]. Copyright 1964 ASCE), (**b**) obsolete rock trap, (**c**) open rock trap, (**d**) closed rock trap.

The CELSEP design was reported to give a satisfactory trap efficiency. Another early rock trap design was developed in Norway in the 1950s and the beginning of the 1960s, hereby called the obsolete type, shown in Figure 4b. This design consisted of a short gradual vertical expansion followed by a short pit where sediments should settle. A simple flushing mechanism was provided with a pipe extending from the pit out in atmospheric pressure. These rock traps had several problems. They were too short, and sediments did not have sufficient time to settle. They had a too abrupt expansion, creating a separation of the flow, which prevented a decrease of the velocity, and instead caused the flow to shortcut through the trap like a jet [42]. The flushing mechanism did not work as intended, causing only the sediments in the immediate vicinity of the pipe opening to be transported out. Therefore, the rock traps constructed after the 1960s were more thoroughly researched and tested to develop functioning solutions. At the River and Harbor Laboratory in Trondheim (VHL), several hydraulic scale model tests of rock traps were conducted throughout the period 1960–1990.

A second generation of rock traps is referred to as "open rock traps". The main philosophy of the design is to provide a gradually larger cross-section for the flow velocity to go below the critical transport velocity for most sediments, both suspended and bedload. In this way, transported sediments would settle in the large chamber, and clean water would continue to the power plant. Figure 4c shows an example of an open rock trap. A typical settling pattern in open rock traps is illustrated. The settling is not optimal, as the available volume is not utilized, and the finer particles are typically transported towards the weir situated at the downstream end. Evidently, over time, the finer sediment in the downstream end is transported over the weir and into the turbines. The authors have conducted fieldwork in the operational rock trap in the 960 MW Tonstad hydropower plant (Norway), and have documented sediments on the inside of the trash rack in the downstream end. Figure 5 shows the piling of nearly uniformly sized sand at the downstream end before the weir. Circulating turbulence had lifted the sand at the downstream slope of the pile and sent it to the turbine. This phenomenon was also observed in model tests for the Tonstad rock trap done by TU Graz in 2020 [43].

Figure 5. Picture of sediment deposited before the weir in the downstream end of a pressurized rock trap at the 960 MW Tonstad hydropower plant, Norway. Flow direction from left to right.

The open type rock trap design has several drawbacks, see Figure 6:

- Sediments that deposit in the rock trap are susceptible to resuspension and erosion because of turbulence.
- Variable flow conditions based on the operation of the hydropower plant prevent utilization of the full volume of the sedimentation chamber.
- Unlined tunnels are naturally very rough because of the construction method and irregularities in the rock mass, so smooth transitions of cross-section changes are expensive, difficult, or even impossible.
- The length of the rock trap is of high importance. Longer rock traps (150 m to 200 m) give much better conditions for the settling of smaller particles than shorter rock traps (30 m to 60 m) [24].

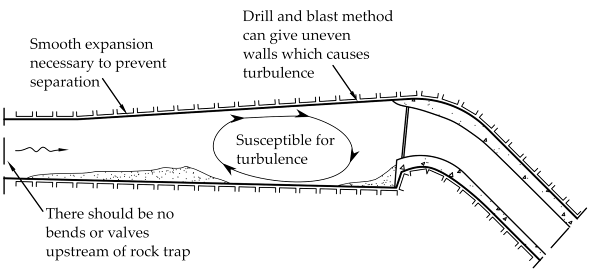

Figure 6. Drawbacks of open rock traps.

For open rock traps to function as desired, there are several requirements of the design and construction [19]:

- They should be placed at least 150 m to 200 m downstream from any bend, gate, or valve. In other words, the tunnel upstream of the rock trap should be straight and without any expansions or contractions. The flow through the rock trap is very sensitive to changes, like bends, entrance adits, or expansions. Virtually all irregularities cause turbulence which prevents sedimentation.
- To get the desired low flow velocity, a smooth transition from the small tunnel cross-section area to the larger cross-section area is vital. If this is not attained, the flow can separate from the walls, and the consequence will be twofold negative: The flow near the walls and invert will be very turbulent, and the flow in the center of the rock trap will be higher than desired, both of which will prevent sediments from settling.

- The drill and blast method of tunneling can cause very uneven surfaces, which will disturb the flow severely, causing reduced settling capability.

Experiences from open rock traps designed with physical model tests show that the model tests might give too optimistic results regarding the trap efficiency. Many of the tested rock trap layouts are located with surge facilities, bifurcations, curves (horizontal and vertical), and contractions or expansions in the rock trap area. These elements may disturb the flow severely, constraining the possibilities to find good solutions with maximum storage capacity and trapping efficiency [44].

Through the experience with the model tests and construction of open rock traps, a new type of rock trap was developed, referred to as closed rock traps (Figure 4d). The closed rock traps are designed with 1 m wide precast concrete ribs spaced 1 m apart as the separation between the main flow and the sedimentation pit. The closed rock traps resemble the CELSEP (Figure 4a) design developed earlier in the USA. Lysne [31], Lysne [44], Tvinnereim [45], Lysne et al. [46] all present several designs of closed rock traps with the sedimentation pit partially covered with ribs and compare them with open rock traps. The closed rock trap is acknowledged as superior to the open type [46], for the following reasons [19], see Figure 7:

- The settled sediments are better guarded from the flow and are less susceptible to re-entrainment.
- The closed type is less sensitive for non-uniform flow, since it prevents large, high-energy turbulence vortices from reaching the sediments. Therefore, there are less constraints than in open rock traps on the upstream placement of bends, constrictions, and other elements that may disturb the flow.

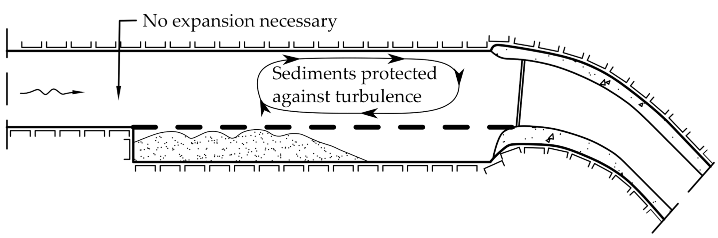

Figure 7. Advantages with closed rock traps.

Closed rock traps can be constructed without an expansion of the flow area and therefore the flow is less prone to turbulence caused by separation. It should be noted that closed rock traps are only efficient for bedload transport. For suspended particles, most of the sediments will pass over the sedimentation pit, as the flow velocity is the same as in the upstream tunnel. The closed rock traps have disadvantages in that they are more expensive than the open rock traps. Small rock traps are more complicated to empty mechanically since the ribs might obstruct access to the settled sediments. However, for larger closed rock traps, the emptying process is not more difficult than for open rock traps, as hauling machines are able to access and drive below the ribs. However, the flushing solution may simplify the emptying procedure for both cases.

5.2. Summary of Rock Trap Designs

Table 1 gives an overview and comparison between the discussed rock trap variants. The dimensions (Length, cross-section area, sedimentation height) refer to existing rock traps, but the local requirements will dictate dimensions if new rock traps are going to be built. For example, have the CELSEP rock traps been built never to be emptied [41,47]. This means that the expected total amount of particles must be computed for the lifetime of the powerplant. The other variants, on the other hand, must be dimensioned for the expected number of sediments in an emptying interval, which ideally is as long as possible. As mentioned earlier, is the expected sediment transport generally hard to compute [19], and must be based on experience and knowledge of the surroundings and tunnel system.

Table 1. Comparison between different types of rock trap designs.

	CELSEP [41]	Obsolete [44]	Open [19]	Closed [19]
Length	>40 m	10–20 m	40–200 m	>15 m
Cross section area	Same as headrace tunnel	~2–5× headrace tunnel	~2× headrace tunnel	Same as headrace tunnel
Sedimentation height	2.7 m	1–1.5 m	~2 m	~2 m
Flushing possible?	Yes	Not working	Yes	Yes
Sediment/flow separation	Yes	No	No	Yes
Emptying procedure	Not planned for	Flushing (does not work)	Mechanical excavation or flushing	Mechanical excavation or flushing
Cross-section expansion	No	Yes	Yes	No
Cost	expensive	Low cost	Low cost	expensive
Sensitive to upstream flow disturbances?	Less	Yes	Yes, esp. long ones	Less
Headloss	Small	Small	Small	Small
Functioning as intended?	Yes	No	If built correctly and carefully	Yes
Recommended?	Yes	No	No	Yes

5.3. Emptying Procedure and Flushing Solutions

The common way to empty rock traps is by mechanical means, i.e., with an excavator, tractor, bobcat or similar. The rock trap must be dewatered, and the machines enter through the tunnel or a separate access tunnel. This procedure is inconvenient as it requires complete dewatering, which results in power plant outage and time-consuming and potentially dangerous excavation work. To avoid such challenges, flushing solutions may be installed.

As part of the 54 MW, Lemonthyme power plant in Tasmania, Australia, a self-cleansing (or scouring) rock trap was constructed in the headrace tunnel [48]. On the top of the cell, along the invert of the tunnel, transverse baffles, 300 mm deep, with a certain spacing, make openings for the sediments to fall into a hopper. The bottom of the pit is shaped like a funnel, with an 800 mm pipe, in the end, leading the materials out of the trap. The design particle size is unknown, but it is obvious that only the bedload will be trapped in the short rock trap. The rock trap was built in 1969, so by the time of the publishing of the article, it had already been in operation for some years, and with good results. It is still in operation and is being flushed for approximately ten minutes every week. Reportedly, the collected sediments from the scour outlet amounts to only 0.25 m^3 in total from 2007 to 2019 (personal correspondence with operator). The design from Lemonthyme was also used for the rock trap built in the Çamabşı tunnel in Turkey [49], but this rock trap did not have flushing capabilities.

Flushing mechanisms commonly used in settling basins, e.g., [10,38,50], have not been used for rock traps. Nevertheless, flushing arrangements for rock traps have been mentioned by Solvik [51] and Lysne [35], with arrangements similar to the flushing mechanism found in the Lemonthyme power plant, see Figure 8. The solution has not been entirely successful, as the excess tunnel below the main tunnel tends to be rather costly.

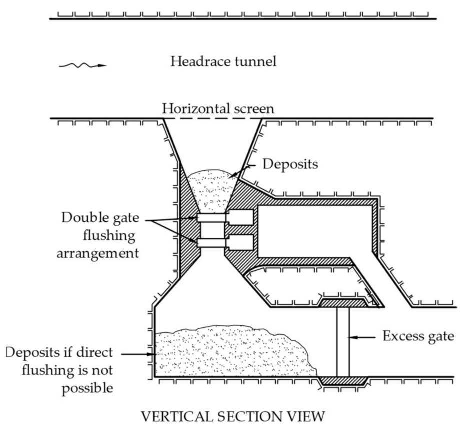

Figure 8. Flushing rock trap with excess tunnel below the main tunnel.

Modern flushing solutions for rock traps as the 4 s solution are described by Støle [52] and Jacobsen [53]. The common feature is that gravity-induced pressure is the driving force. The sediments are collected by slotted pipes placed inside the rock trap and flushed through nearby access. Larger stones can also be removed.

5.4. Flow Conditioners

Flow conditioners also known as calming racks are commonly used at the entrance to settling basins [8,10,11], but this has not so far been seen in pressurized rock traps. As discussed previously, a well-designed rock trap does not preferably have any expansion or contraction that disturbs the flow, hence, the flow conditioner is not required. One study has investigated the use of flow conditioners as an option to improve already existing and poorly designed rock traps with expansion at the inlet [27]. The optimum design of such retrofitted flow conditioners have been investigated by the authors in CFD and physical model tests at NTNU, Norway and at TU Graz, Austria [43,54], but the results were not conclusive and one of the model tests even illustrated an adverse effect from the flow conditioners on the trap efficiency.

5.5. State-of-the-Art for New Pressurized Rock Traps

The rock trap that was developed in 1964 for Jaybird powerhouse, CELSEP, is still regarded as a state-of-the-art design. This design was used in the Snowy Mountains power scheme in Australia [55], and it was the recommended type in the EPRI guidelines for unlined power tunnels [56]. The CELSEP type rock trap design was also implemented in the Karahnjukar power scheme in Iceland, commissioned as recently as 2009 [57]. The rock traps in Karahnjukar were designed with sufficient volume to function as single-use rock traps, without ever being emptied [47].

The closed rock trap, either with or without vertical walls for cell separation, gives a more secure storage of the sediments since the main flow is physically separated from the sediments. They are, however, more expensive to construct than the open type, and research to make more cost-effective rock traps is still warranted. Also, these closed rock traps only capture bedload, and suspended particles will not settle.

Flushing arrangements are regarded as state-of-the-art and are recommended for new pressurized rock traps. Such flushing arrangements mitigate the need for dewatering, the resulting outage, structural stress, and health and safety issues.

5.6. State-of-the-Art for Retrofitting Pressurized Rock Traps

Recent research on the retrofitting of existing pressurized rock traps is published in [58,59]. Several different solutions to improve the trap efficiency of an open type rock trap were tested with CFD and hydraulic scale modelling. Installation of ribs were found to improve the trap efficiency, even when installed in a small part of the downstream end of the rock trap. Installation of flow calming structures was found to decrease the trap efficiency [54,58].

Expanding the volume of the rock trap was found to have a positive effect. For retrofitting, it is especially important to limit the necessary installation time and resulting outage of the power plant. Also, existing structures such as gates, plugs, and concrete diffusors should not be harmed. Therefore, the final recommended solution was to install a short section of ribs inside the existing rock trap volume. A ramp on the upstream side would guide sediments and prevent flow below the ribs. This solution was found in one study to increase the trap efficiency for particles with sizes 0.3–1.0 mm from 0% to over 90%. However, the small volume below the ribs requires that a flushing system is also installed to be able to regularly empty the trapped sediments.

6. Discussion

6.1. Design Criteria

Specific design criteria were not quantified in earlier rock trap research and development. The rock traps were designed based on model tests where the flow and settling pattern of sediments were emphasized. The lack of an explicit criterion makes it harder to decide quantitatively if a rock trap is functioning as intended.

Paschmann [8] summarizes the particle factors that increase damage on mechanical parts, including concentration, size, shape, and hardness. Larger particles cause more damage than smaller particles, and higher sediment concentration causes more damage than low sediment concentration. For a flow with assumed mainly bedload sediment transport, suspended particle concentration is less important, so it seems imperative to prioritize particle removal by size. It follows that a design criterion for rock traps should be to stop a specific amount of a specific threshold particle size, and ideally all particles larger than the threshold particle size.

A useful concept for defining design criteria for pressurized rock traps is the trap efficiency. The trap efficiency is calculated as the ratio between incoming sediment mass and the outgoing sediment mass:

$$\eta = 1 - \frac{m_{out}}{m_{in}} \tag{10}$$

There are several formulas and methods for predicting the trap efficiency as a function of the trap geometry, flow conditions, and particle properties in sedimentation basins [60]. However, rock traps with predominantly bedload transport, and in addition with very limited knowledge of the sediment inflow, cannot be and have not historically been designed with such formulas in mind.

For pressurized rock traps designed for trapping bed load, the threshold particle size is defined by the minimum particle of the incoming bedload. Thus, the design of the pressurized rock trap should be considered in combination with the tunnel cross-section area and the turbine discharge. In some cases, it may even be considered to increase or decrease the cross-section of the entire headrace tunnel to manipulate the minimum particle size of the bed load.

Rock trap design is challenging as the designer does often not know the sediment inflow or the resulting turbine damage it may cause before the facility is put into operation. Hence, rule-of-thumb design based on experience is the typical engineering practice. Both sediment inflow, turbine design, and vulnerability are highly site-specific. Exactly this challenge is the main challenge of rock trap design, and the authors deeply encourage more research on this topic.

6.2. Outlook for Pressurized Rock Traps

The closed type and CELSEP rock traps form a promising basis for new rock traps, and new designs should be based on the principle of separating flow and sediments.

A current trend is that hydropower plants are operated with more frequent start-stop operations as more unregulated renewables are introduced in the power system [61]. The frequent acceleration (and deceleration) may cause higher sediment instability, which is expected to cause more sediment transport in the tunnels. At the same time, several hydropower plants are refurbished and upgraded with higher installed capacity. This can lead to sediment problems and inefficient rock traps [27].

The armor layer is believed to be constantly destabilized by unsteady flow during the start and stop of the power plant, and especially during dewatering and refilling of the tunnels. The armor layer may thus delay the transport of particles but resulting in larger sediment transport after events of dewatering and refilling. It is believed that also the upgrading of turbines in existing hydropower plants might accelerate the erosion of previously stable sediments and armor layers due to the increased maximum flow [27]. The new operation modes might require improved and upgraded rock traps, but this is not known. The effect of new power plant operation styles and the effect of two-way flow on sediments in tunnels and rock traps need to be better understood, and new research is needed.

Retrofitting of rock traps with ribs, flushing solutions, and calming racks may be installed to improve existing rock traps. This topic was addressed in the FlekS project [43], but it is not exhausted, and more research should be done.

New technological breakthroughs, such as CFD and physical model tests with particle image velocimetry (PIV) can be used in a combination with established methods as model tests in future research.

It should be noted that no method is perfectly suited, and compromises must be made. Model tests with sediments in closed conduits are challenging and should be planned and done very carefully. Scale effects will be introduced, affecting both the model fluid and the model sediments [12], app.C. Therefore, one must be cautious when assessing the validity of the results.

CFD is a more time- and cost-efficient way of modeling structures in the waterway, for example rock traps. Many different designs can easily be tested without the costly and time-consuming rebuilding of models. While it can be more accurate than physical models, as scale effects are avoided, CFD also has its limitations. The flow simulations themselves can be accurate enough with both commercial and free programs, and mass sediment transport models for rivers are adequately developed, but the simulation of coarser material like sand, gravel, and rocks has not come as far [12] (p. 651).

For the study of rock traps, where the sediment transport probably is quite low, mass transport models are not suitable. However, discrete phase particle simulations can be used for simulating the trapping effect of rock traps while neglecting re-entrainment and bedload transport.

PIV can be used for accurately studying the flow patterns in specific parts of the rock trap, for example at the entrance or around the ribs in a closed rock trap.

7. Conclusions

Pressurized rock traps are a necessary part of many hydropower schemes, but the recommended designs have not previously been systematically reviewed and summarized. In this paper, the knowledge and state-of-the-art of pressurized rock traps are therefore presented for an international audience. The rock trap designs presented in this work are designed to trap sediments transported as bed load.

Rock traps at the downstream end of unlined hydropower tunnels are critical for reducing damages from sediments on mechanical parts, for example, turbines. The reported experiences are in favor of the closed type or CELSEP type, where the sedimented particles are separated from the flow by means of ribs or plates. The sedimentation basin below the ribs can be divided into individual cells with vertical walls, but this is not strictly required. Open rock traps are in general not recommended, as they can be too unreliable, and the sediments are continuously exposed to the flow. Flushing solutions should be considered. Simple hand-calculations that use Shields' and Lysne's formulas are not recommended, as they do not readily apply for sediments in tunnel inverts. Instead, a combination of CFD and physical model tests will give more reliable results.

The state-of-the-art design of rock traps has been stagnant since the 1970s. New research should be done adopting new techniques like CFD and PIV analysis.

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