INNOVATION AWARDS

PRIX DE L'INNOVATION

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Countries / Pays	**Nbr of Papers / Nombre de rapports**
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France	2
Iran	1
Japan	1
Norway	1
USA	1
6 countries / Pays - Total	**7**

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Congress ***Congrès***	**Papers** ***Rapports***	**Number of countries** ***Nombre de pays***
26th - Vienna (2018)	29	10
27th - Marseille (2022)	16	9
28th - Chengdu (2025)	7	6

3) Numbers of Papers per countries / *Numéros des Rapports par pays*

Countries / Pays	**Numbers / Numéro**	**Total**
China	2	1
France	6, 7	2
Iran	4	1
Japan	3	1
Norway	5	1
USA	1	1
6 countries / Pays	**7**	**7**

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RAPPORTS SUR LES PRIX DE L'INNOVATION

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CHENGDU, MAI 2025

DESIGN CHALLENGES FACED IN PETERSON DAM – 100.0FT × 6.0FT - CREST GATE (*)

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SUMMARY

Peterson Station, Milton Station, Clark Falls, and Fairfax Falls make up the 21-MW Lamoille Hydroelectric Project on the Lamoille River. The hydropower plant at Peterson has a production capacity of 6.3 MWe from one unit commissioned in 1948. It is operated by Central Vermont Public Service Corp (CVPS). A previously installed crest gate of 100 ft by 6 ft was used to maintain the water level in river. The gate was damaged and was not able to maintain level in river to run the power station at the desired capacity due to lost water head. CVPS has decided to replace the existing structure, and Rodney Hunt was awarded the responsibility of designing and commissioning a new crest gate.

RÉSUMÉ

Peterson Station, Milton Station, Clark Falls et Fairfax Falls constituent le projet hydroélectrique Lamoille de 21 MW sur la rivière Lamoille. La centrale hydroélectrique de Peterson a été mise en service en 1948 et elle a une capacité de production de 6,3 MW. Elle est exploitée par Central Vermont Public Service

Conception de la vanne de 30 m x 1,8 m en crête du barrage de Peterson

DOI: 10.1201/9781003642428-160

Corp (CVPS). Une vanne de crête de 30 m par 1,8 m avait été installée précédemment pour maintenir le niveau d'eau dans la rivière. La vanne a été endommagée et n'a pas été en mesure de maintenir le niveau de la rivière pour faire fonctionner la centrale électrique à la capacité souhaitée en raison de la perte de charge d'eau. CVPS a décidé de remplacer la structure existante et Rodney Hunt a été chargé de la conception et de la mise en service d'une nouvelle vanne de crête.

1. INTRODUCTION

Crest gates are hydraulic structures designed to control water flow over dams or weirs. They manage water levels, ensure safety during high inflows, and regulate water release for flood control, irrigation, and power generation. These gates open by pivoting downward around a hinge situated just downstream from the dam's peak. Since they open down, they excel at stabilizing the upstream water level. Developed primarily by the USACE, crest gates are used at numerous USACE sites. Typically, they are long and relatively short, although their dimensions can vary slightly from this standard configuration. Like tainter and roller gates, they play a crucial role in water management.

The Bascule® and Pelican® designs were acquired from Allis-Chalmers in 1990 and now belong to Rodney Hunt.

2. PELICAN® GATES (CREST GATES)

- Pelican® gates are typically mounted on the crest of a dam and are hinged along the invert. While there are several variations, all types lower to open and raise to close.
- Fully functional in ice conditions
- Can be fabricated in a number of sections joined in the field to a total of 200 ft or more
- Ideal for flood protection/spillway control

The Pelican® gate design consists of curved plates with internal braces and vertical ribs forming a strong closed shell structure. The gate is supported by a number of hinge brackets (instead of a torque tube), which are attached to concrete at the invert. A stainless-steel pin secures the hinge brackets to the crest gate assembly.

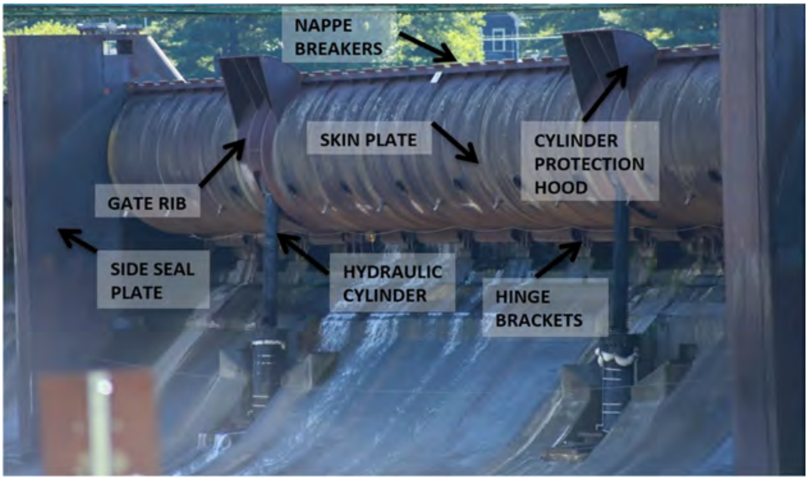

Fig. 1
Installation Photograph of Pelican Crest Gates

3. BASCULE® GATES (CREST GATES)

Bascule® gates are usually mounted on the crest of a dam and are hinged along the invert. There are several different types, but all lower to open and raise to close.

- Fully functional in ice conditions
- Can be fabricated in a number of sections joined in the field to a total of 200 ft or more
- Ideal for flood protection/spillway control

The Bascule® gate design features a flat plate that is reinforced with vertical and horizontal members and is fitted with a single torque tube across the invert. The torque tube is supported by bearings along the invert edge of the gate. A hydraulic cylinder, cable drum hoist, or electric motor-driven cylinder is attached to the arm of the gate with a stem for operation.

Fig. 2
Shop assembly Photograph of Bascule Crest Gates

4. GENERAL DESIGN CONSIDERATION OF CREST GATES

When designing crest gates, several parameters must be considered to ensure they function effectively and safely. Here are the primary design considerations:

- Hydraulic: Crest gates must handle maximum flow, control water discharge precisely, and dissipate energy to prevent erosion and downstream damage.
- Structural: Crest gates must withstand hydrostatic pressure, hydrodynamic forces, debris impact, and ice loads. Materials should be strong and corrosion resistant. The design must ensure flow stability, minimize gate vibrations, and prevent metal fatigue.
- Operational: Design reliable, user-friendly gate mechanisms, including manual, electric, or hydraulic controls. Integrate automated and remote-control systems for efficient operation and monitoring. Ensure easy maintenance, inspection, and repairs. Provide accessibility for operators and maintenance personnel. Include emergency operation provisions for power failures or mechanical malfunctions.

5. DESIGN CHALLENGES FACED IN PETERSON CREST GATE

5.1. Location & role of the dam

Peterson Dam is located near Milton, Chittenden County, Vermont, on the Lamoille River. It impounds water for power generation. The Peterson Dam's hydro power plant has a production capacity of 6.3 MWe, with 1 unit commissioned in 1948. It is operated by Central Vermont Public Service Corp (CVPS).

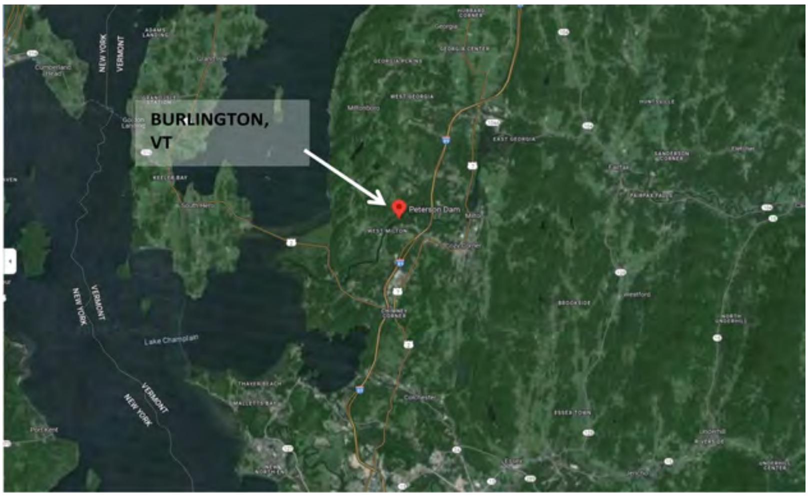

Fig. 3
Geographical location of Peterson Dam

5.2. Purpose of gates replacement

The original 100 ft × 6 ft crest gate-controlled water levels in the river but was eventually damaged, failing to maintain the water level necessary for optimal power station operation and risked catastrophic failure. Consequently, CVPS decided to replace it and awarded Rodney Hunt the responsibility for designing and commissioning the new crest gate.

5.3. DESIGN AND OPERATIONAL ISSUES WITH EXISTING GATES

A 100 ft wide by 6 ft tall steel crest gate was installed around 1948. It is operated by cylinders on lever arms at both ends and was constructed in four sections. The joint at the one-quarter point has failed, causing both adjacent panels to buckle—significant leakages through the bottom sealing and interconnected torque tube and torque shaft. The existing gates were never designed for ice loading. The location of these gates is near Burlington, VT, where gates are typically designed for ice loads ranging from 2,500 pounds per foot up to 5,000 pounds per foot.

Fig. 4
Failed Joint & Leakage through Existing Crest Gate

5.4. DESIGN LOADING CONDITION FOR MODIFIED GATES

The existing gate may not have been designed to handle ice loads, despite the bubbler system in place for ice melting. The new crest gate will be structurally designed to withstand the most severe combinations of loads. The new crest gate will be heavier than the existing gate due to these ice loads, and its design is independent of the existing operational load capacity.

1. Case-01: 6.0 ft hydrostatic head and ice loading of 5,000 lb/ft applied 2.0 ft below the upper pool elevation.
2. Case-02: 6.0 ft hydrostatic head and 2.0 ft overtopping head.

Structural components of the gate-skinplate, vertical girders, horizontal stiffeners, end vertical members, and torque tube—were analyzed using the LRFD (Load Resistance Factor Design) approach. LRFD uses different factors of safety for different types of loads, allowing for a more refined and probabilistic approach to account for uncertainties in loads and material strengths. LRFD allows for more flexibility in design by permitting higher stresses in materials where the risk of failure is low (due to redundancy or lower likelihood of occurrence).

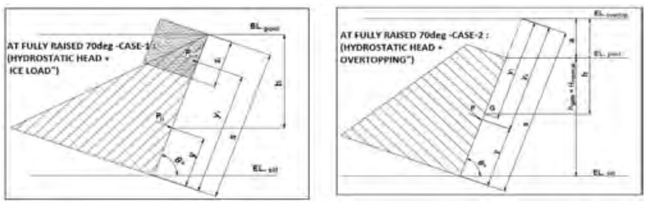

Fig. 5
Loading Condition of Modified Crest Gate

This can lead to more efficient designs compared to ASD (Allowable Stress Design), which typically applies conservative allowable stresses across all conditions. ASD is simpler to apply and understand initially because it uses straightforward allowable stress values. However, LRFD's approach of considering both loads and resistances probabilistically typically that results in more efficient and economical designs for modern engineering practice.

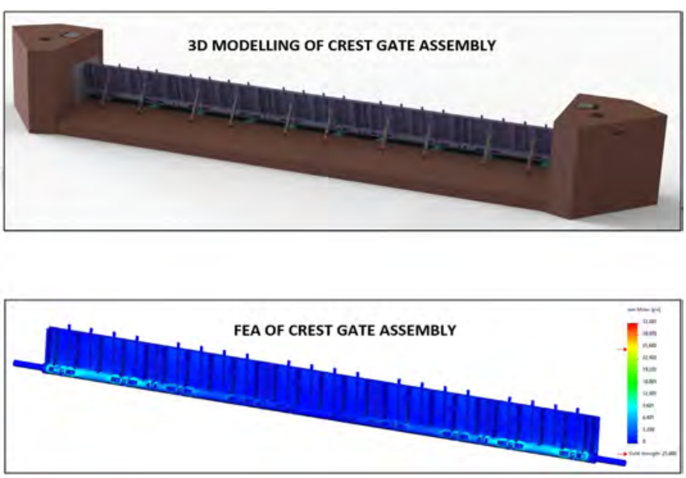

Fig. 6
3D modelling & Finite Element Analysis of Modified Crest Gate

A retrofit civil structures gate 3D model using SolidWorks was also prepared. These 3D models provide a very intuitive but detailed view of the product, helping designers and stakeholders better understand the design and its influence on the civil works. With SolidWorks Designers can create detailed assemblies to analyze how different parts interact and move together. FEA (Finite Element Analysis) was performed on both load cases to evaluate the results in comparison to structural calculations. The image above shows the von Mises stress plots for both loading cases.

Fig. 7
Installation of Modified Crest Gate

6. CONCLUSION

The newly modified gates were analyzed for the worst combination of loading hydrostatic and ice-loading conditions. The gates were fabricated in four segments with 25 ft wide sections. The gates were successfully installed and are now performing the intended function, as shown below.

REFERENCES

[1] ANSI/AISC 360-22: Specification for Structural Steel Buildings

[2] Rodney Hunt. Files & Friday lessons by Rob Kibler, Head of Engineering, Rodney Hunt

[3] Field measurements & photographs provided by the contractor.

COMMISSION INTERNATIONALE DES
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GRANDS BARRAGES
CHENGDU, MAI 2025

DEVELOPMENT OF HIGH CRACKING-RESISTANCE DAM CONCRETE WITH EXPANSIVE LOW-HEAT PORTLAND CEMENT AND APPLICATIONS IN ULTRA-HIGH ARCH DAMS (*)

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SUMMARY

Cracks are major potential hazards that affect the safety and durability of concrete dams, and constructing a world crack-free dam has long been a global engineering challenge. The Baihetan and Wudongde dams, both over 300 meters tall, are ultra-high arch dams that face unprecedented challenges in crack prevention due to their immense scale, complicated construction conditions and harsh natural environment of the narrow and xerothermic valleys where they are located. The cracking risk of the two dams would be exceptionally high if conventional moderate-heat cement (MHC) concrete were used. Our main innovative achievements to overcome the challenge are as follows: (1) We firstly revealed the meso-level cracking mechanism of concrete under xerothermic conditions and proposed a new pathway of improving cracking resistance of concrete by concurrently adjusting both its thermal property and deformation property. This led to the idea of developing expansive low-heat

**Développement de béton de barrage à haute résistance à la fissuration avec du ciment Portland expansif à faible chaleur et applications à des barrages-voûtes très hauts*

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Portland cement (ELHC). (2) We invented ELHC based on four self-developed techniques, which are, a) Optimization of mineral composition, b) adjustment and control of expansion, c) synchronization of high early strength and low hydration heat, and d) industrial calcination. (3) The mixing design for ELHC concrete is low in cement consumption, cement-water ratio and high in fly ash. The temperature rise in ELHC concrete is lower than MHC concrete and the autogenous deformation is expansion, reaching about 10 με at 90d. The cracking resistance of ELHC concrete increases by 40~80% compared with MHC concrete. The temperature control scheme for ELHC concrete is simplified, robust, and efficient.

For the first time, ELHC concrete was extensively used in the construction of the Baihetan and Wudongde hydropower plants, including the dams, powerhouses, tunnels, etc. No cracks have been observed in dams since the construction began 8 years ago, marking a historic breakthrough in dam construction. ELHC and ELHC concrete are China's innovative contributions to the construction of high concrete dams and the broader hydropower industry. They have since been applied to CFRDs, railways and bridges, demonstrating significant potential for further application and delivering substantial technical, economic and social benefits.

RÉSUMÉ

Les fissures sont des dangers potentiels majeurs qui affectent la sécurité et la durabilité des barrages en béton, et la construction d'un barrage sans fissures est depuis longtemps un défi d'ingénierie mondial. Les barrages de Baihetan et de Wudongde, tous deux de plus de 300 mètres de haut, sont des barrages-voûtes ultra-hauts qui font face à des défis sans précédent dans la prévention des fissures en raison de leur taille, des conditions de construction compliquées et de l'environnement naturel difficile des vallées étroites et arides où ils sont situés. Le risque de fissuration des deux barrages serait exceptionnellement élevé si l'on utilisait du ciment conventionnel à chaleur modérée. Nos principales réalisations innovantes pour relever le défi sont les suivantes : (1) nous avons tout d'abord révélé le mécanisme de fissuration au méso-niveau du béton dans des conditions xérothermiques et proposé une nouvelle voie pour améliorer la résistance à la fissuration du béton en adaptant simultanément ses propriétés thermiques et ses propriétés de déformation. Cela a conduit à l'idée de développer du ciment Portland expansif à faible chaleur (ELHC). (2) nous avons inventé ELHC basé sur quatre techniques auto-développées, qui sont, a) l'optimisation de la composition minérale, b) l'ajustement et le contrôle de l'expansion, c) la synchronisation de la force précoce élevée et de la basse chaleur d'hydratation, et d) la calcination industrielle. (3) la conception de mélange pour le béton ELHC est faible en consommation de ciment, le rapport ciment-eau et élevé en cendres volantes. L'élévation de température dans le béton ELHC est inférieure à celle du béton MHC et la déformation autogène est l'expansion, atteignant environ 10 με à 90 jours. La résistance à la fissuration du béton

ELHC augmente de 40 à 80% par rapport au béton MHC. Le schéma de contrôle de la température du béton ELHC est simplifié, robuste et efficace.

Pour la première fois, le béton ELHC a été largement utilisé dans la construction des centrales hydroélectriques de Baihetan et Wudongde, y compris les barrages, les centrales électriques, les tunnels, etc. Aucune fissure n'a été observée dans les barrages depuis le début de la construction il y a 8 ans, marquant une percée historique dans la construction des barrages. ELHC et ELHC concrete sont les solutions innovantes et les contributions de la Chine à la construction de barrages en béton et à l'industrie hydroélectrique au sens large. Ils ont depuis été appliqués aux FCR, aux chemins de fer et aux ponts, ce qui a démontré un potentiel considérable pour d'autres applications et procuré des avantages techniques, économiques et sociaux substantiels.

1. BACKGROUND

Dams and hydroplants are in great need in the world in the 21st century because of the increasing need in water, electricity, flood control and irrigation. Ultra-high arch dam (UAD) is the most important water-retaining structure in mega hydroplant and plays a vital role in flood control, power generation, irrigation, navigation, etc. It's very important to guarantee their safety throughout construction and operation period. Cracks in concrete are major hidden hazards to the safety and durability of UADs. Sayano-Shushenskaya dam (maximum height 245 m), Kolnbrein dam (maximum height 200 m), and other world-known high arch dams, suffered from significant thermal cracking, leading to reduced structural integrity and substantial repair costs [1]. Despite considerable advancements in dam engineering over the past few decades, it still remains a world challenge to build high concrete dams without cracks until the development of the Baihetan and Wudongde dams.

Baihetan and Wudongde hydroplants, located in the southwestern region of China, respectively rank second and seventh in the world in terms of total installed capacity. They both play an indispensable role in the power supply for East China and flood control for the Yangtze River basin. The construction of the two 300m level UADs without any cracks using moderate-heat Portland cement (MHC) concrete in xerothermic valleys remains a significant challenge on a global scale. This is due to several factors, including massive scale in dam body (see Table 1), higher anti-cracking safety requirement (the minimum anti-cracking safety factors for the two UADs are no less than 2.0), complicated construction and harsh natural environmental conditions. If traditional MHC concrete as well as the ultimate temperature control measures were employed, the anti-cracking safety factors for both dams would be no greater than 1.8 and the risk of cracking in the dams would be quite high. Moreover, harsh environmental conditions in the xerothermic valleys, such as dryness (annual average relative humidity is less than 40%), hotness (over 160 days per year the average temperature exceeds 35°C), strong wind (more than 200 days per year the wind speed exceeds Grade 7) and large daily temperature differences (up to 20°C), further heightened the risk of cracking in the two UADs.

Over the past decade, we have dedicated our efforts to overcoming this significant challenge. Our research has led to innovative advancements in cracking and anti-cracking mechanisms, high cracking resistance cement and concrete, and cracking prevention construction techniques.

Table 1
Comparison of Top 10 highest arch dams in the world

RANK	NAME	COUNTRY	MAX. HEIGHT, M	DAM BODY VOLUME, 10,000 M^3
1	Jinping-I	China	305	571
2	Xiaowan	China	292	860
3	**Baihetan**	**China**	**289**	**803**
4	Xiluodu	China	285.5	680
5	Yusufeli	Turkey	275	400
6	Enguri	Georgia	271.5	388
7	**Wudongde**	**China**	**270**	**270**
8	Vajont	Italy	261.6	35
9	Mauvoisin	Switzerland	250.5	211
10	Laxiwa	China	250	368

2. CRACKING MECHANISM AND ANTI-CRACKING PATHWAYS

2.1. MESO-LEVEL CRACKING MECHANISM

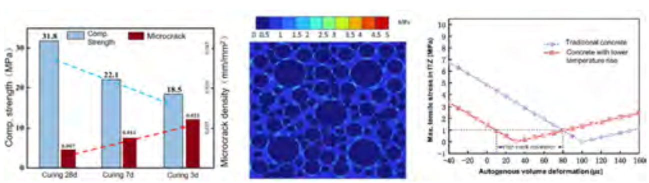

Fig. 1
Properties of concrete with different microcrack density (L), meso-level concrete model (M) and maximum tensile strength in ITZ with different matrix (R)
Propriétés du béton avec une densité de microfissure différente (G), un modèle de béton mésoniveau (M) et une résistance maximale à la traction en ITZ avec une matrice différente (D)

Our previous studies revealed that initial microcracks formed before being subjected to mechanical loading determine the cracking resistance and durability of concrete (see Fig. 1L). Initial microcracks are mostly located in the interfacial transition zone (ITZ) of concrete for it is the weakest link [2]. Meso-level finite element analyses were carried out on concrete to study the effects of deformation and thermal properties of matrix on tensile stress distribution in concrete (see Fig. 1M, Fig. 1R). Results showed that shrinkage in matrix is the driving force of overlarge tensile stress. For traditional MHC concrete in which the matrix has a shrinkage strain of 30 $\mu\varepsilon$, the maximum tensile stress in ITZ could reach 6.5 MPa and the cracking risk is high (generally the tensile strength of ITZ is 1.0 MPa). To reduce the tensile stress level the matrix has to have an expansion of over 80~100 $\mu\varepsilon$, which would lead to instability in dimension of concrete. If the temperature drop from the peak temperature decreases by 4°C, meanwhile the matrix has an expansive strain of 20~30 $\mu\varepsilon$, the maximum tensile stress at ITZ is only 0.5 MPa, leading to a much lower risk of cracking (see Fig. 1M, Fig. 1R). To sum up, the key to producing high cracking resistance concrete is to reduce the temperature rise caused by hydration of cement, as well as to reduce the shrinkage deformation, or to be expansive.

2.2. Anti-cracking pathways

In the past several decades, some progress has been made in either reducing the temperature rise or adjusting the autogeneous deformation to improve the cracking-resistance of concrete.

1. **Current methods to reduce the temperature rise of concrete**. In addition to reducing the amount of cement as much as possible and increasing the amount of supplementary cementitious materials such as fly ash, the essential way is to use cement with low hydration heat. Low-heat Portland cement (LHC) was manufactured and firstly used at a large scale in the construction of Hoover Dam in 1930s [3]. Contrary to standard Portland cement, the content of dicalcium silicate (C_2S, low heat release in hydration) in LHC was high (about 50%) and the content of tricalcium silicate (C_3S, high heat release in hydration) was low (30~40%). The total hydration heat of LHC was thus about 20% lower than standard Portland cement, leading to significant reduction of thermal cracks in dam construction. However, after being applied in Bartlett Dam (1939), Shasta Dam (1945) and Detroit Dam (1953), the application of LHC came to an end because of its shortcomings such as low early strength, large autogenous volume shrinkage and high manufacturing cost. LHC has been replaced by the combination of MHC and fly ash, and is no longer manufactured in the United States. LHC products in other countries such as the UK, Germany, Japan, also have the same shortcomings and couldn't be applied in dam construction extensively.

2. **Current methods to reduce shrinkage of concrete.** Ettringite-based or calcium oxide-based shrinkage compensation concrete, made with either an expansive cement (Type K, M, S) or expansive components (Type K, M, G), is used to minimize cracking caused by drying shrinkage [4]. Since the expansion occurs at early age and doesn't match the cooling and shrinking process of dam concrete, this type of concrete is only used in highway, pavement, bridge, parking structures and so on. Magnesium oxide-based shrinkage compensation concrete (MgO concrete), made with lightly burnt MgO powder (as an additive), showed potential in reducing thermal cracks in dam concrete [5]. MgO concrete has been applied in about 30 small concrete dams in China and the results in minimizing thermal cracks and simplifying temperature-control measures are significant. The reason is that the expansion of MgO after hydration closely matches the shrinking process of dam concrete as it cools. However, due to the difficulties in uniformly distributing MgO powder in dam concrete and concerns that uneven distribution of MgO might cause uneven expansion leading to cracks, MgO concrete hasn't been applied in high dams with heights over 100 m so far.

Based on the above analyses, we came up with the idea of improving the cracking resistance of concrete by concurrently adjusting both its thermal property and deformation property. Our pathway is to develop a new type of low-heat Portland cement which is MgO-based and expansive in autogeneous volume deformation.

2.3. New evaluation indices for cracking resistance

1. Macro-level index-**equivalent volume deformation**. The main strains in concrete can be classified into two types, cracking strain (shrinkage strain caused by cooling or drying) and anti-cracking strain (ultimate tensile strain, autogenous expansion, tensile creep). Therefore a new index called the *equivalent volume deformation* (D_{eq}), is proposed to quantitatively evaluate the real cracking resistance of concrete. It refers to the difference between the total anti-cracking strain and the total cracking strain (see Eq. (1)). The bigger the equivalent volume deformation and the higher the cracking resistance.

$$D_{eq} = w_1\varepsilon_{ult} + w_2\varepsilon_{au} + w_3\varepsilon_{cr} - w_4\alpha\Delta T - w_5\varepsilon_{ds} \tag{1}$$

In Eq. (1), ε_{ult}, the ultimate tensile strain of concrete, ε_{au}, the autogenous volume deformation (negative if the deformation is shrinkage), ε_{cr}, the tensile creep, α-coefficient of thermal expansion, ΔT-temperature drop from the peak temperature during the construction process, ε_{ds}, the drying shrinkage. $w_1 \sim w_5$ are the weight factors and vary from different structural styles and environmental conditions. Take drying shrinkage which occurs only in the surficial 2 cm layer in concrete for example, for the thin-wall structure the weight could be 1.0 or higher, but for dam concrete the weight is much less and could even be set at zero.

We can tell from Eq. (1) that if the autogeneous deformation of concrete is expansion instead of shrinkage and the temperature drop, ΔT, is low, then the cracking resistance is high. The equivalent volume deformation is clear in physical meaning and could be applied in selection of raw materials, optimization of mixing design and comparison in cracking resistance between different concrete.

2. Micro-level index-**microcrack density**. If the relationship between macro properties and microcrack characteristics could be established, then the cracking resistance could be evaluated based on the microcrack structure. Quantitative analysis of micro-cracks in dam concrete represents a significant challenge. Because the representative element size of dam concrete can be as large as 45cm (the max. aggregate size is 15cm for dam concrete), while the width of microcrack can be as small as 1 or 2 μm. A large field of view (greater than 45cm) and high resolution (1∼2 μm) have to be satisfied at the same time for the microstructure-analyzing equipment. Both SEM and CT cannot meet the requirement. Thus we developed a panoramic microcrack imaging and quantifying system [2] for dam concrete, which enables the automatic and efficient quantification of microcrack structure (length, width, density, orientation, etc. at a resolution of 1.6 μm) in large-sized dam concrete slices (>45 cm in side length). A typical panoramic microscopic image of concrete slices can be seen in Fig. 2 L. Based on the quantitative microcrack analyzing technique, we established the relationship between the cracking resistance and microcrack density (see Fig. 2R). For high cracking-resistance concrete, the microcrack density should be no bigger than 0.01 mm/mm^2. Microcrack density is proposed as another index to evaluate the cracking resistance at the micro-level.

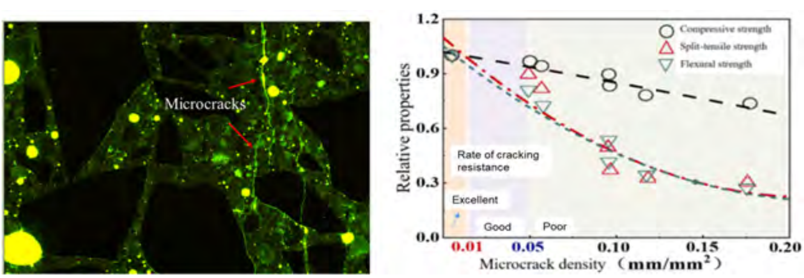

Fig. 2

Typical panoramic microcrack image (L, real size 4.2cm*2.8cm), relationship between the cracking resistance and microcrack density (R)

*Image panoramique typique de microfissure (taille réelle 4.2cm*2.8cm) (G), Relation entre la résistance à la fissuration et la densité des microfissures (D)*

3. DEVELOPMENT OF EXPANSIVE LOW HEAT PORTLAND CEMENT

In order to produce expansive low-heat Portland cement (ELHC) that can be used to prepare high cracking-resistance concrete for high dams, four problems have to be solved. These are, (1) optimization of the mineral composition, (2) adjustment and control of expansion, (3) high early strength, and (4) industrial calcination.

(1) **Optimization of mineral composition.**
LHC was first achieved mainly by lowering the content of C_3S from 45～65% to 20～30%, raising the content of C_2S from around 30% to 45～60%. The total hydration heat of LHC decreased by 15% compared with MHC.

(2) **Adjustment and control of expansion.**
The key is to adjust and control the content of the real expansive source, the periclase (f-MgO) instead of magnesium oxide (MgO). We proposed a technique [6] to quantify periclase precisely, studied the effects of calcination regime on the periclase content in the cement clinker and established the relationship between the expansion ratios and the periclase content (see Fig. 3). As seen from Fig. 3, with the increase of MgO content, the decrease of calcination temperature, the temperature-holding time as well as the cooling rate, the content of periclase increases. Therefore, the periclase-control technique is proposed, which features high magnesium dosage, low temperature calcination, short-term temperature holding and slow cooling. When the content of periclase is no less than 4.0%, the 28 d expansion ratio of cement paste exceeds 0.08%, and the expansion ratio tends to be stable. Accordingly, a threshold of 2.0～3.0% for periclase content in the LHC clinker has been set to ensure the expansion property.

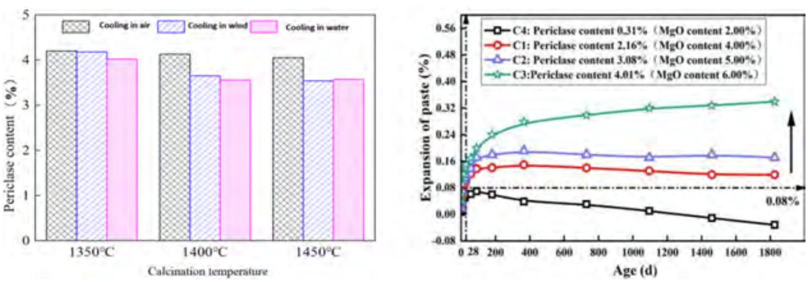

Fig. 3
Periclase content under different calcination regimes (L), relationship between expansion ratio and periclase content (R)
Teneur en périclase sous différents régimes de calcination (G), relation entre le rapport d'expansion et la teneur en périclase (D)

(3) **Synchronization of low hydration heat and high early strength.**

In order to solve the problem of slow hydration and low early strength of cement with high C_2S content, effects of trace elements such as Ba and S on the polycrystalline transformation and crystal structure parameters of silicate minerals in high MgO content LHC clinker were studied [7]. Some of the results are shown in Fig. 4. As seen from Fig. 4, with the increase of trace element content, the content of highly active α'-C_2S and β-C_2S increases, the hydration activity of C_2S is significantly enhanced, and the early strength of cement is thus greatly improved. Therefore ion-doping is used to restrain low-activity C_3S and stable high-activity C_2S, leading to the high early strength without altering the total hydration heat. The compressive strength at 3d could increase by over 25%.

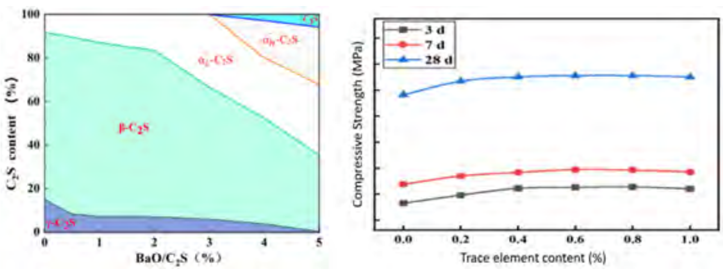

Fig. 4

Type and content C_2S with different BaO/C_2S (L), compressive strength of cement with different trace element content (R)

Type et teneur en C_2S avec différents BaO/C_2S (G), résistance à la compression du ciment avec différentes teneurs en oligo-éléments (D)

(4) **Industrial calcination.**

The cement clinker with expansive deformation and low hydration heat features high content of magnesium, iron and low content of aluminum. Thus, during the calcination process the liquid phase appears early and is large in quantity and low in viscosity, leading to a high difficulty in nucleation of mineral crystals. A series of methods to reduce the eutectic point of the clinker and adjust the surface tension of the liquid phase were proposed [8,9] and applied in the cement factories. A daily production of 2000t on new dry process production line was achieved, with a reduction of 10% in energy consumption and 6% in carbon emission.

Typical mineral compositions of ELHC product are [10], C_2S: 42%~46%, C_3S: 30%~40%, C_3A: 1%~3%, C_4AF: 15%~19%.The final ELHC product features the periclase content of 2.0~3.0% (MgO content in raw materials is 4.0~5.0%).

(5) **Properties of hydrated ELHC.**
As illustrated in Fig. 5, the 3d/7d/28d hydration heat of ELHC is no greater than 210/240/300 kJ/kg, respectively. The 3d/28d compressive strength is greater than 15.5/45 MPa. The autogenous volume deformation is expansive and the 28d expansion is no less than 0.08% while the maximum expansion is less than 0.16% (see Fig. 5L). Compared with MHC, the hydration heat releasing rate of ELHC is lower, the hydration peak time is delayed [11]. The 3d/ 28 d hydration heat is lower by about 20%/15% and the final total hydration heat is lower by 14% (see Fig. 5M). Thermodynamic modelling of the hydration process of ELHC and MHC based on CemGEMS are shown in Fig. 5R. It can be seen that the C-S-H gel content in ELHC increases by over 6.5% and the $Ca(OH)_2$ content decreases by about 20%.

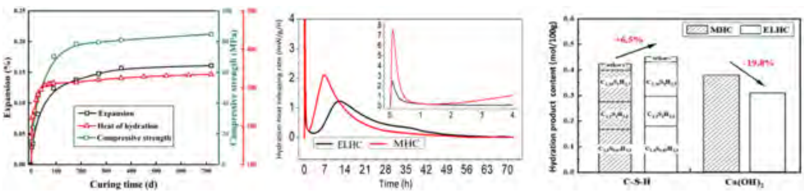

Fig. 5
Properties of ELHC (G), comparison of hydration heat releasing rate (M) and hydration products by thermodynamic modelling between ELHC and MHC (R)
Propriétés de l'elhc (G), comparaison du taux de libération de la chaleur d'hydratation (M) et des produits d'hydratation par modélisation thermodynamique entre l'elhc et le MHC (R)

4. HIGH CRACKING-RESISTANCE CONCRETE AND PROPERTIES

Systematic experimental studies were performed on mixing design of dam concrete based on the raw materials from Baihetan and Wudongde hydroplants.

1. **Mixing design**. The mixing design of concrete in Baihetan and Wudongde dams is guided by principles which are low water consumption, low w/cm ratio, and high fly ash consumption [12]. Comparison in mixing design of dam concrete between some typical 300m arch dams built with MHC concrete are shown in Table 2. It can be seen from Table 2 that the water consumption in Wudongde and Baihetan dams is approximately about 5 kg/m^3 lower, while the cement consumption is 30-38 kg/m^3 lower. The fly ash ratio in Wudongde and Baihetan dam concrete is 5% higher. Overall, the dam concrete in Baihetan and Wudongde dams is economically viable.

Table 2
Comparison of mixing design for typical arch dams

DAM NAME	COMPLETION YEAR	HEIGHT (M)	DESIGN STRENGTH	CEMENTITIOUS MATERIALS	WATER (KG/M^3)	CEMENT (KG/M^3)	W/CM
Xiaowan	2010	292	$C_{180}40$	MHC+30%FA	89	155	0.40
Jinping	2014	305	$C_{180}40$	MHC+30%FA	85	152	0.39
Wudongde	**2020**	**270**	**$C_{180}35$**	**ELHC+35%FA**	**83**	117	**0.46**
Baihetan	**2021**	**289**	**$C_{180}40$**	**ELHC+35%FA**	**79**	122	**0.42**

2. **Cracking resistance.** The properties of the dam concrete in Baihetan and Wudongde dams are shown in Fig. 6 and Table 3. It can be seen that the compressive strength before 90d is slightly lower but exceeds MHC concrete after 90d. Compared with MHC concrete, the adiabatic temperature rise of ELHC concrete is lower by 3～5 °C. The autogenous deformation is expansion, reaching 10 $\mu\varepsilon$ at 90d and stabilizing at around 15 $\mu\varepsilon$ finally. The cracking resistance of Baihetan dam concrete increases by 40～80% compared with MHC concrete. The initial microcrack density in ELHC concrete matrix is as low as 0.005 mm/mm^2 (see Fig. 6R), which meets the criteria for high cracking-resistance concrete.
3. **Durability.** The durability of ELHC concrete is excellent. The results demonstrate that the frost resistance is over F300 and the anti-permeability grade is over W15 [13]. Microstructural analysis shows that the porosity is decreasing gradually from 24% at 7d to 10% at 2a. The pore structure analyses indicate that ELHC concrete at Wudongde and Baihetan dams as well as MHC concrete at Three Gorges dam, are all highly durable concrete [14].

Table 3
Comparison of overall properties between ELHC and MHC concrete

	ELHC CONCRETE			MHC CONCRETE		
	28D	90D	180D	28D	90D	180D
Comp. Strength/MPa	30.1	48.5	55.8	32.6	46.7	49.8
Elastic moduli/GPa	37.2	42.1	43.7	41.4	43.1	43.7
Adiabatic temperature rise/°C	18～22	/	/	22～26	/	/

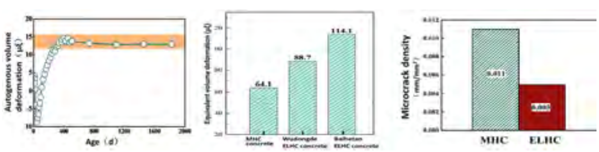

Fig. 6
Comparison of deformation property (L), cracking resistance (M) and microcrack density (R) between ELHC and MHC concrete
Comparaison des propriétés de déformation (G), de résistance à la fissuration (M) et de densité de microfissure (D) entre béton ELHC et MHC

(4) **Nano-level analyses.** Nano-level analyses of the hydration products reveal that compared to MHC, the high-density C-S-H gel in ELHC increases by 32% and the Si-chain length is obviously greater [15], resulting in an increase of 21% in average indentation modulus and an increase of 11% in fracture toughness (see Fig. 7). That explains why the cracking resistance and durability of ELHC concrete are better than MHC concrete.

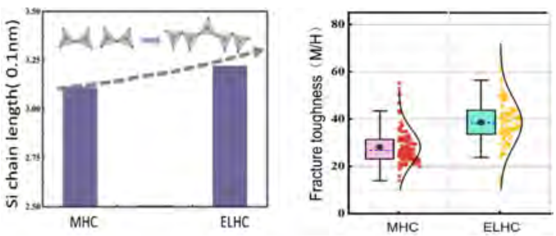

Fig. 7
Comparison of nanostructure features between MHC and ELHC cements
Comparaison des caractéristiques de nanostructure entre des ciments ayant des teneurs en C_2S différentes

5. CONSTRUCTION TECHNIQUES FOR ELHC CONCRETE

Because of the characteristics of low temperature peak, slow temperature rise of ELHC concrete, a series of energy-efficient and highly reliable anti-cracking construction techniques were developed during the construction of Baihetan and Wudongde dams [16]. Our team formulated the first technical specification for ELHC concrete in the hydropower industry in China [17].

1. **Construction techniques**. According to the development process of the properties, the ELHC concrete should be cured earlier and longer than the MHC concrete. A set of construction techniques including demolding time, surficial layer treating method, high-pressure water jetting procedure, etc., are proposed and applied.
2. **Temperature controlling**. The traditional temperature controlling criterion for MHC concrete at the batching plant is strictly 7°C, but for ELHC concrete the criterion could be loosened to 12~16°C. Also for ELHC concrete the secondary precooling of aggregates could be canceled. The energy consumption cost is thus reduced by 13%. What's more, the mid-term cooling and late stage cooling could be initiated 20~30 days ahead of schedule, which can obviously increase the construction speed.
3. **Thick lift construction**. The traditional lift thickness is 1.5~3.0m for MHC concrete, but for ELHC concrete the lift thickness could be 3.0~6.0m for all the dam blocks with the prerequisite that all the maximum temperature is under control. This leads to an increase of 11% in construction speed.

6. APPLICATIONS IN BAIHETAN AND WUDONGDE HYDROPLANTS

The total ELHC consumption in the two hydroplants was 4.66 million metric tons (3.46 million metric tons for Baihetan and 1.2 million metric tons for Wudongde). The total ELHC concrete placed in the two hydroplants was 25.5 million m^3 (18 million m^3 for Baihetan and 7.5 million m^3 for Wudongde). ELHC and ELHC concrete were applied not only in the two UADs, but also in the underground powerhouses, the subsidiary dams, the flood discharging tunnels, etc.

1. **Benefits in dam building.** The cracking resistance safety factors of the two UADs are both greater than 2.0 (see Fig. 8L), meeting the design requirements. No cracks have been detected in either dam since the initiation of the dam construction 8 years ago. Both dams are performing well, standing as iconic examples of high concrete dams without cracks (see Fig. 9), and marking a significant breakthrough in global dam construction. During the construction period of Baihetan dam, six concrete cores longer than 20 m were drilled, with the longest reaching 36.74 m, setting a new world record (see Fig. 8R) for conventional dam concrete. It indicates that the properties of the dam concrete as well as the bonds between two adjacent layers are all excellent. The application of ELHC dam concrete can save over 25 yuan/m^3 in water-cooling process compared to MHC concrete, contributing to a total cost saving of 270 million yuan.

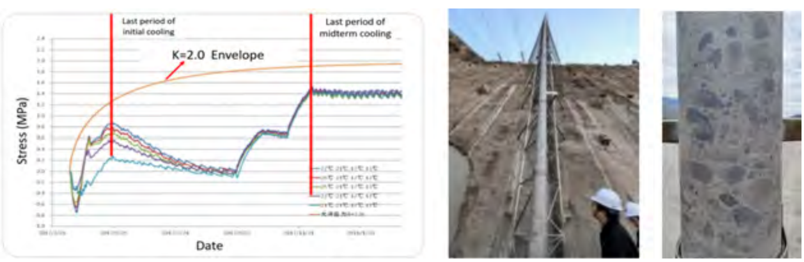

Fig. 8
Cracking resistance safety factors (L) and longest core (R) of Baihetan dam
Facteurs de sécurité de résistance à la fissuration (G) et le coeur le plus long (D) du barrage de Baihetan

2. **Benefits in building other structures.** High abrasion-resistance concrete made with ELHC was first applied in flood discharging tunnels [18]. The ELHC concrete linings in the tunnels are smooth without cracks or defects. They can even be used as mirrors, underscoring the excellence of the construction work. All tunnels have been in operation for three years and have withstood numerous

flood discharges without any signs of damage. ELHC concrete was also applied in the subsidiary dams of the two hydroplants. The subsidiary dam of Wudongde hydroplant is the first ELHC roller compacted concrete (RCC) gravity dam in the world. The maximum dam height is 90.5m and the total ELHC concrete volume of 466,000 m^3. It should be noticed that no cooling pipes were used during the construction but so far no cracks have been found.

7. CONCLUSIONS AND PROSPECT

ELHC developed by our team has advantages of expansion, lower hydration heat, higher early strength, lower energy consumption and carbon emission. ELHC concrete is characterized by its high resistance to cracking, allowing for a simplified yet efficient and cost effective temperature controlling scheme. ELHC concrete could be regarded as a new low-carbon and sustainable building materials for civil engineering.

Fig. 9
Photos of Baihetan dam (L) and Wudongde dam (R) after completion
Photos du barrage de Baihetan (G) et du barrage de Wudongde (D) après l'achèvement

For the first time high cracking-resistance ELHC concrete has been applied thoroughly in the Baihetan and Wudongde hydroplants. The anti-cracking safety factors for the two dams reach above 2.0 and no cracks in dams have been observed since the beginning of the construction 8 years ago. Both dams are operating exceptionally well and have become iconic examples of crack-free dam construction, marking a great breakthrough in the global history of dam engineering. ELHC and ELHC concrete represent China's innovative contributions to high concrete dam construction as well as the hydropower industry. President Rogers, the former president of ICOLD, has recognized the construction techniques employed at the Baihetan and Wudongde hydroplants as being at the forefront of global dam engineering.

In addition to Baihetan and Wudongde hydroplants, ELHC concrete have been applied to various other major infrastructures in China, such as Tiantai pumped storage powerplant (CFRD) in Zhejiang, Jiangmen Underground Neutrino Observatory in Guangdong, Sichuan-Tibet railway and so on. QBT arch dam, with a maximum dam height of 240m, in cold region in Xinjiang is designed as an ELHC dam and is scheduled to begin construction next year. ELHC and ELHC concrete offer significant potential and notable benefits for future infrastructure projects.

REFERENCES & RELATED PUBLICATIONS

[1] ICOLD/CIGB. Bulletin 107. Concrete dams-control and treatment of cracks. ICOLD, Paris, 1997.

[2] LI S., CHEN G., ET AL. Performances of concrete with initial defects under severe environmental conditions. China Railway Press. 2021.

[3] ACI PRC-207.1-21. Mass Concrete-Guide. ACI 2022.

[4] ACI PRC223-21. Shrinkage-Compensating Concrete. *ACI* 2021.

[5] DU C. A review of Magnesium Oxide in concrete. Concrete International. 2005, 27: 45–50.

[6] XU Y., XU L., LI W. Quantitative determination of periclase hydration in high magnesium cement clinker with XRD internal standard method. *Journal of Nanjing Tech University*. 2014, 36(5): 30–35.

[7] WANG J., WANG M., ET AL. A high magnesium expansion low heat cement and a preparation method. ZL201210403083.X. 2012.

[8] LI W. A method to reduce the minimum eutectic point of the low heat Portland cement clinker. ZL201510830883.3. 2015.

[9] XU Y., CHEN X., YANG Y., ET AL. A mineral crystal of cement clinker and its preparation method. ZL201510377455.X. 2015.

[10] LI W., FAN Q., LI X., ET AL. Development and application of specific low heat Portland cement for building ultra-high arch dams. *Journal of hydroelectric engineering*, 2017, 36(3): 113–120.

[11] FAN Q., YANG H., LI W., ET AL. Comparison of thermal and mechanical properties between low-heat and medium-heat Portland cement concrete. *Journal of Changjiang Scientific Research Institute*, 2018.

[12] LI W., LU C. Low-temperature-rise, low-shrinkage, high-crack-resistance and high-durability roller compacted concrete and preparation method. ZL201911330065.1. 2019.

[13] LI W. Scientific reports of cement-based key materials and technologies for energy and road engineering in complex environment conditions. 2016YFB0303600. 2021.04.

[14] LI W., LI S., LI X., ET AL. A durability evaluation method for dam concrete and the equipment and electronic device. ZL202211696944.8. 2022.

[15] ZENG H., JIN M., LI W., ET AL. Assessing the durability performance of high belite cement incorporating fly ash under long-term temperature variations. Cement and Concrete Composites. 2024.152.

[16] FAN Q., ZHANG C., CHEN W., ET AL. Key technologies of intelligent construction of Wudongde and Baihetan super high arch dams. *Journal of hydroelectric engineering*. 2019, 38(2):22–35.

[17] LI W., YANG Z., WANG Z., ET AL. Technical specification for low-heat Portland cement concrete of hydropower projects. DL/T 5817-2021.

[18] LI W., SUN M., LIU Z., ET AL. A preparation method of High strength, high crack resistance and high abrasion-erosion resistance concrete. ZL202011085321.8. 2020.

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ADVANCED CONSTRUCTION SYSTEM OF A^4CSEL FOR AUTOMATED DAM CONSTRUCTION TOWARD THE NEXT GENERATION (*)

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JAPAN

SUMMARY

The new automated construction system founding on the technical components which include modifying ordinal construction machine to autonomous machine, transferring the skilled human operation to the machines and managing the automated construction for high production ability have been invented. We refer it to as A^4CSEL (Quad axel). It has been enhanced by the central remote-control system, which enables the remote management on the automated construction of independent several sites simultaneously by a few engineers.

The applicability and its performance of the new system have been verified in the construction of the highest CSG dam. Significant performances are found in achieving 80 % of labor-saving by the remote operation of the AAC machines and 3 times efficiency in the production, reducing the environmental impact by the 40% to 50 % reduction of fuel consumption of the AAC machines and realizing the safer construction.

It is considered that wider spread of the automated construction increases the productivity of the construction and promptly accumulates required infrastructures as the social foundation, resulting in the upgrade of the status of the construction industry.

**Système avancé de construction automatisée A^4CSEL pour les barrages de la prochaine génération*

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RÉSUMÉ

Un nouveau système de construction automatisé a été inventé, basé sur des éléments technologiques qui comprennent la modification des machines conventionnelles de construction en machines autonomes, le transfert des tâches humaines qualifiées aux machines et la gestion de la construction automatisée pour une productivité élevée. Ce système s'appelle A^4CSEL (Quad axel). Il a été amélioré par le système de contrôle à distance centralisé, qui permet la gestion à distance de la construction automatisée de plusieurs chantiers indépendants simultanément par un petit nombre d'ingénieurs.

L'applicabilité et les performances du nouveau système ont été vérifiées lors de la construction du plus haut barrage en CSG. Des performances significatives ont été constatées dans la réalisation d'une économie de main-d'oeuvre de 80 % grâce à une commande à distance au moyen de machines AAC et un triplement de l'efficacité de la production, une réduction de l'impact environnemental grâce à une économie de consommation de carburant des machines AAC de 40 à 50 % et une construction plus sûre.

La diffusion plus large de la construction automatisée augmenterait la productivité de la construction et accumulerait rapidement les infrastructures nécessaires en tant que base sociale, ce qui contribuerait à l'amélioration du statut social du secteur de la construction.

1. INTRODUCTION

Detailed configurations of a dam depend strongly on the site condition including the geo-mechanical features of the site as well as the functions of the dam. There is no common structural design in terms of the configuration of dams. Many difficulties would be anticipated for the automated construction of dams, while common structures can be assembled in an automated procedure as like productions made in automated factories. Skilled technicians have still work essentially in dam construction. However, it is not easy to recruit necessary skilled technicians for the construction of dams due to the rapidly aging society in Japan. The technical secession from aged skilled technicians to young engineers and technicians is essential for the continuous development of dams, which has been necessary for safer society against increasing natural disasters. Automated machine construction and/or the labor-saving construction method are other options for the solution of such difficulties, which are shared in many countries recently.

As example, the automated construction has been applied in a limited way only for the transportation of mined production in the mining industry. There is no application of the automated machine construction for dams due to the complicated process and the procedure of the concrete placing of dams. The previous method for the machine construction of the dam has been executed by the machine operated by independent operator, which has faced to the difficulties due to insufficient skilled technicians. The remotely controlled machines have shown less efficiency in the construction, even it makes saving in some skilled technicians. In addition, these methods have the shortcoming that these machines must be subject to the degree of the skill of operators. Not-enough skilled technicians have sometimes in less efficiency of the construction as operators. Therefore, not only the involvement of the technique of the skilled technicians but also automated machine construction using autonomous and integrated machines are necessary.

Aiming the industrialization of the construction and incorporating the solutions in the factory production system, the new system for the advanced automated construction has been invented by authors [1]. It is referred to as A^4CSEL (Automated/Autonomous/Advanced/Accelerated Construction system) including automated machine construction, optimizing the construction procedure and integrated management system. This paper introduces the concept and the features of A^4CSEL firstly. Its applicability and performance are verified in the dam construction. A few considerations are prepared for the wider spread of automated construction.

2. BASIC CONCEPT OF A^4CSEL

A^4CSEL founds on three major techniques of Technology 1 (TE 1) to Technology 3 (TE 3) as shown in Fig. 2. TE 1 is the methodology for converting ordinal construction machine to automated construction machine which operate autonomously with the support of additionally equipped various sensers. TE 2 elaborates construction procedure using automated construction machines. The procedure which incorporates the construction techniques of the skilled technicians and those modification processed by AI (Artificial Intelligence) technology regarding the operation of construction machines is simulated for the optimization. It includes operational numbers, kinds and sequence of construction machines based on the area and quantity of the construction amount as the input data for the elaboration. Aiming the high efficiency, TE 3 manages the operation of the automated construction machines. The construction procedure made in TE 2 is processed to the operational parameters for each construction machine. The resultant procedure of each construction machine is measured simultaneously and evaluated by TE 1 and TE 2 for the further optimization of the construction procedure. During the operation of the machines, each machine operates autonomously along with avoiding mutual interference by the equipped sensing function. These technologies enable the automation of the construction by the smart collaboration of each construction machine and higher efficiency of the construction. These are schematically shown in Fig. 1.

Fig. 1
Technologies composing A^{4}CSEL
Technologies composantes d'A^{4}CSEL

3. IMPLEMENTATION OF A^{4}CSEL

3.1. CONVERSION TO AUTOMATED CONSTRUCTION MACHINE (TE1)

The ordinal construction machines have been modified for the automated operation. Sensors such as GNSS sensor, gyro sensor, laser scanner have been equipped for realizing the autonomous operation of these machines. These machines are referred in this paper to as Autonomous automated construction machine (AAC machine). The AAC dump truck has been modified for driving with the electric signal. The AAC bulldozer has been equipped with an interface for the communication with the existing controller for driving, steering and manipulating the blade. The control of the body is ensured autonomously with sensor signal. The AAC roller can be driven with the additional steering devise fixed on the exiting steering handle. Forward and backward movement and the vibration of the roller can be controlled by the electrical signal transmitting to the existing electrical circuit. These communication signals are transmitted by the Wi-fi techniques to each AAC machine. The AAC roller is shown in Fig. 2 as example.

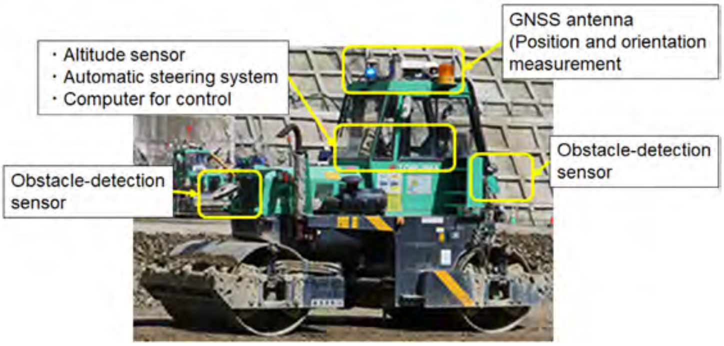

Fig. 2
Modification of ordinal vibrating roller for automated construction
Modification du rouleau vibrant conventionnel pour la construction automatisée

3.2. Management system for automated construction (TE 2 and TE 3)

The management system is invented for the execution of TE 2 and TE 3 functions abovementioned. It consists of construction planning system, construction managing system and machine management system. The alignment of these systems is shown in Fig. 3.

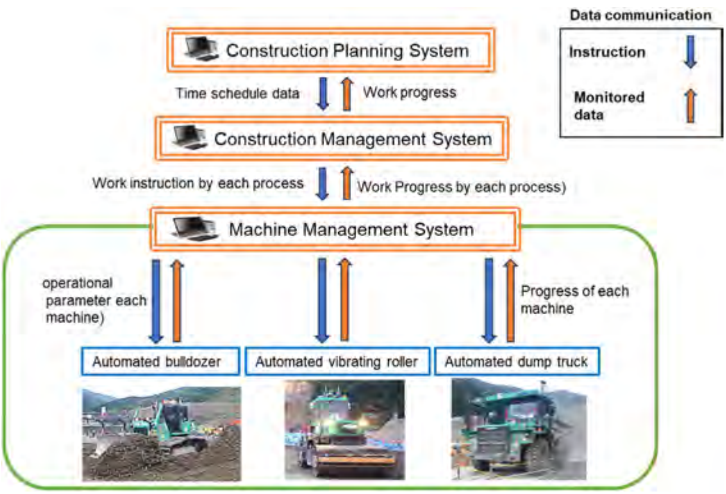

Fig. 3
Automated construction management system
Système automatisé de gestion de la construction

3.2.1. *Construction planning system*

The construction planning system elaborates the construction procedure using the AAC machines. The database of the procedure by the skilled technicians are accumulated and processed into the typical construction procedure using AAC machines aided by AI technique. For the bulldozer, the path and the number of repetitions of spreading are specified for example. Corresponding to the amount of the construction area, quantity, available AAC machines and construction specifications, the allocation for each AAC machine and the total hours for the construction by adopted typical construction procedure are estimated. These procedures are confirmed to be a well construction through the simulation in advance and succeeded to the construction management system.

The construction planning system continuously monitor the results of the construction based on the data transmitted through the construction management system. When the abnormal results of the construction exceeding the threshold of the delay time would be detected, the construction procedure will be examined for the modification of the current procedure.

3.2.2. *Construction management system*

The construction management system instructs the independent procedure (Work instruction) to each AAC machine following the whole construction procedure and the construction restrain by transmitting the data to the machine management system. During the procedure, the construction management system inspects the operation of each AAC machine which are verified according to the original procedure. Next construction procedure is successively instructed on the confirmation of the completion of the current procedure.

3.2.3. *Machine management system*

The machine management system generates operational parameters according to the work instruction by the construction management system for each AAC machine. These parameters include driving routes, manipulation of the blade, vibration of the roller etc. The AAC machines conduct the construction following the work instruction and the operational parameters. The AAC machines will autonomously correct and adjust the construction discrepancy such as the location of unloaded material or the unevenness of the ground aided by AI technique. The machine management system monitors the detailed operational data of each AAC machine for the evaluation of the construction progress. These data also are shared by the construction management system.

3.2.4. *Central remote-control system*

A^{4}CSEL has been upgraded by the development of central remote-control system for higher performance in labor-saving and construction efficiency. As for the verification test, the automated construction of embankment works at three sites including the dam site were simultaneously and remotely operated through the central office situated in Tokyo using the public network facility in 2021 as shown in Fig. 4. The system has been applied in the construction of the Naruse dam since 2023 as described in Chapter 4.

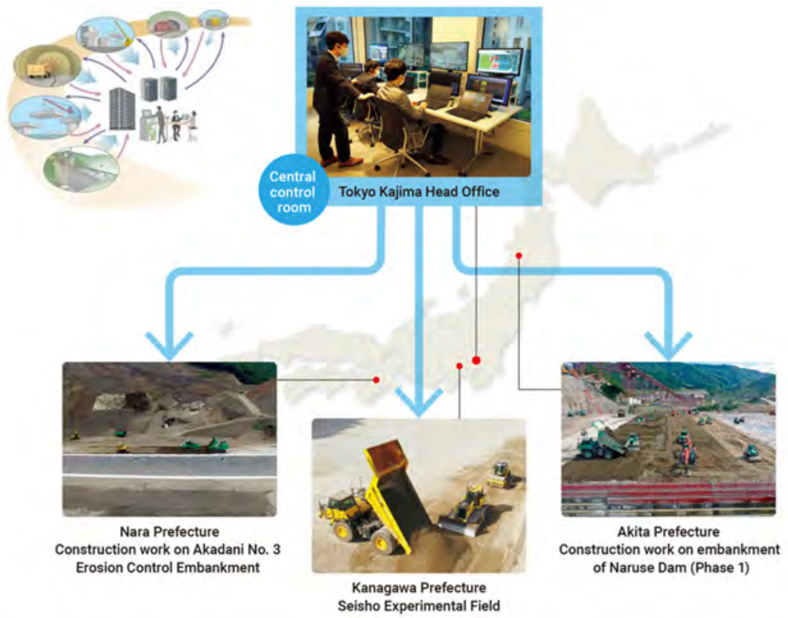

Fig. 4
Central remote-control system for A^{4}CSEL
Système de télécommande centralisé pour A^{4}CSEL

4. APPLICATION TO THE DAM CONSTRUCTION

A^{4}CSEL has been applied for the construction of the Naruse dam of a CSG trapezoidal dam (Owner: Ministry of Land, Infrastructure and Tourism). The performance on the labor-saving, environmental impact reduction, construction quality and safe construction are verified.

4.1. General aspects of the naruse dam

The Naruse dam (referred to as the dam simply) of a CSG trapezoidal dam has been construction for mainly flood mitigation at the north Japan. The dam of 100 m high is the highest CSG dam in Japan. Due to locating at the much snow area, the construction of CSG concrete is limited in 7 months from mid-April to mid-November in a year. The CSG construction has been commenced in October 2017 and will be completed in 2027. The rational construction for ever largest volume of the CSG construction is required using ICT, DX technologies. The general features and the typical section of the dam are shown Table 1, Fig. 5 and Fig. 6, respectively.

Table 1
Major characteristics of the Naruse dam

ITEM	DESCRIPTION
Name	Naruse
Owner	Ministry of Land, Infrastructure and Tourism
Location	Akita pref. (North of main island in Japan)
Purpose	Multipurpose (Flood mitigation)
Type	CSG trapezoidal dam
Dam	114.5 m (High), 755 m (Crest length), 4.85 MCM (Volume) 532.5 m (Crest elevation)
Reservoir	78.5 MCM (Storage volume), 2.26 km^2 (surface area)

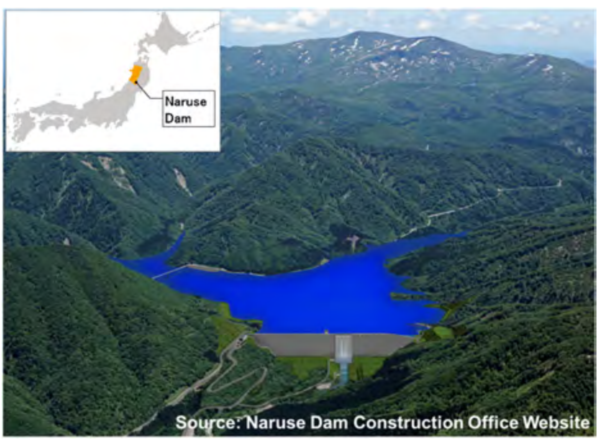

Fig. 5
View of the Naruse dam
Vue du barrage de Naruse

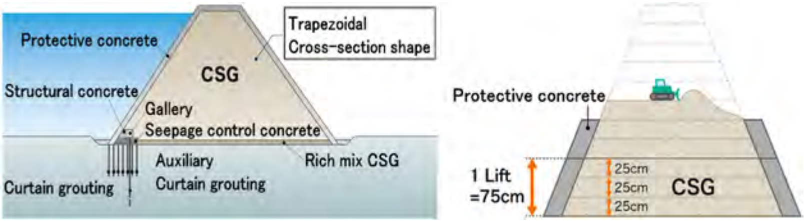

Fig. 6
Typical section of the dam and construction image
Section typique du barrage et image de construction

4.2. Mixing and transportation of CSG concrete

The CSG concrete uses the aggregate of terrace deposit and quarried and crushed material at the areas near the dam. The aggregates are mixed in 50% and 50%, 40% and 60, 30% and 70% with the cement and the water. The quantity of the cement is adjusted at 60kg/m^3 to 160kg/m^3 in each 10kg/m^3 according to the required strength of the dam. Three batching facilities of 360m^3/h capacity are equipped at the site.

The CSG concrete is transported from the batching plant to the right abutment of the dam by belt conveyer of 825 m long and successively flown down to the construction elevation of the dam through three lines of the SP-TOM (Special pipe transportation method [6]). The CSG concrete is again transported by AAC dump truck of 63 ton from the receiver of SP-TOM to the placing area. The situation is shown in Fig. 7.

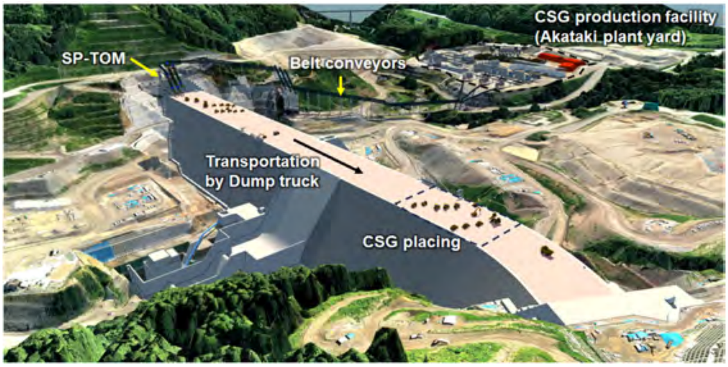

Fig. 7
Construction of CSG concrete
Construction en béton CSG

4.3. Construction of CSG concrete by A4CSEL

It is specified that the placing of CSG concrete is conducted within 6 hours after the mixing. The area of the construction is managed according to the ability of the batching plant and the construction machines used. Three sets of the AAC machines comprising of three bulldozers, four compaction rollers and seven dump trucks are prepared so that CSG concrete is placed at the rate of 750 m^3/h in average. The AAC machines are remotely operated through the wi-fi signals sent by a few IT operators in the control room at the dam site. Various construction information is accumulated in the control room through the construction management system. The construction situation is shown in Fig. 8 as example.

Upper: Overview of CSG concrete construction, Lower left: Unloading and spreading by AAC Dumps truck and AAC Bulldozers, Lower right: Compaction by AAC rollers

Fig. 8
CSG concrete construction by A^4CSEL system
Béton CSG mis en place par le système A^4CSEL

4.4. Performance verification of A4CSEL

The automated construction is realized in the mixing, the transportation and the placing of CSG concrete by A^4CSEL and the management system of the CSG batching plant. The performances of the method are summarized below [2],[3],[4],[5].

The construction area of 94 % of placing lifts is constructed by AAC machines in maximum. The rest is constructed by manually operated machines at especially the area near the upstream and the downstream formworks. It is a future challenge to be tackled. The volume of $1550x10^3m^3$ of CSG concrete have been completed in 2023. It has made the largest monthly record of the placement of $281x10^3m^3$ in May 2024, updating such record significantly. The recent results are accumulated in $4620x10^3m^3$ of CSG concrete. The latest situation is shown in Fig. 9. The performance of A^4CSEL for the CSG dam construction is examined regarding the labor-saving, the construction efficiency, environmental impact reduction, quality assurance and the safe construction.

Fig. 9
Latest situation of the Naruse dam in July 2024, Downstream view
Situation actuelle du barrage de Naruse en juillet 2024, vue aval

4.4.1. *Labor-saving*

The construction procedure of two shifts a day is managed by only three engineers in each shift for the remote operation of 14 AAC machines. It resulted the labor-saving of 79 % compared to the conventional construction method.

4.4.2. *Construction efficiency*

The AAC bulldozer of 16ton-class resulted significant spreading efficiency of 271 m^3/h, while the conventional one is expected in ones of 103 m^3/h. The improvement on the arrangement of AAC machines and the operation procedures have made further development to 322 m^3/h after one year application based on the huge construction data and these analyses accumulated in the automated construction management system.

4.4.3. *Environmental impact reduction*

The fuel consumption of the AAC bulldozer is reduced to 50-60 % during spreading CSG concrete, resulting the reduction of CO2 emission significantly. This is achieved with the reduction of driving length and less idling. The AAC machines drive only the prefixed routes basically. The AAC bulldozer drive only 25 % long for spreading to the conventional one by reducing the distance against the unloaded material for the visual confirmation as shown in the left figure in Fig. 10. The AAC roller reduces the drive length in 19 % by saving the lap width during the compaction of CSG concrete as shown in the right figure in Fig. 10, thanks to the precise operation with the precision of 0.1 m. The AAC machines is operated to be less idling. The operations of all AAC machines are simulated and optimally scheduled in advance for the construction. It enables the AAC machine pauses its operation without idling. The estimation of the fuel consumption for a certain cycle of the CSG concrete construction of 8500 m^3 is made. The results are shown in Table 2. The pauses of AAC machines without idling are counted in 122 times in the cycle. It saved 45.2 litter fuel consumption and will results the save of 22800 litter in the total construction period for the CSG concrete construction. Comprehensively, the fuel consumption for all AAC machines is expected in 40% to 50 % reduction comparing the conventional construction machines for whole construction of the dam.

Table 2
Fuel saving of AAC machines by less idling

ITEM		**QUANTITY**
Construction quantity (m^3)		8,580
Construction hours (h)		23
Fuel consumption (litter）	Conventional case	667.2
	Less idling case (Applied)	622
Fuel saving ratio (%)		6.78

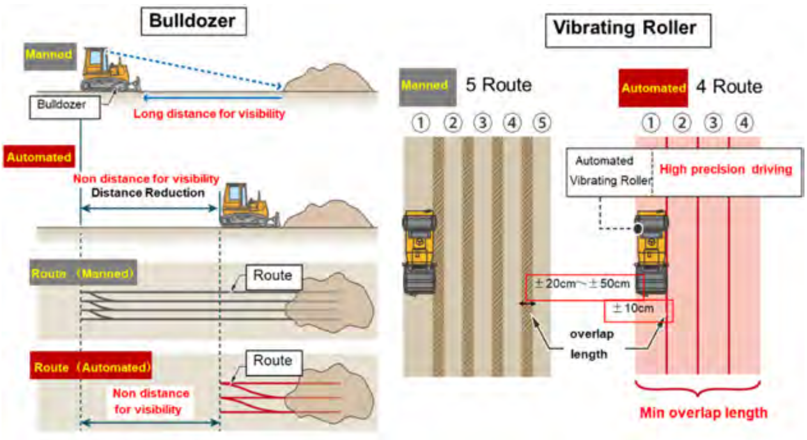

Fig. 10
Driving route of construction machines by human operation and automated operation
Parcours de conduite des machines de construction par opération humaine et opération automatisée

4.4.4. *Quality assurance and safe construction*

Operations by skilled technicians for many dams which involved various situations for the dam construction have been analyzed and incorporated in the automated construction management system. The automated operation of the AAC machines following exactly such operations ensures the same quality of the construction. It has been confirmed by the trial construction in advance. During the construction of the dam, the examination has been periodically conducted for the visual inspection and the unit weight of the placed CSG concrete. The bored cores are shown in Fig. 11. These results verify the high quality of CSG concrete constructed by the AAC machines.

No workers are necessary in the construction area for the construction by the AAC machines remotely controlled. In addition, the AAC machines are equipped for monitoring obstacles around itself which make adequate avoidance for the workers, if any. No human injury accidents have happened during the automated construction using the AAC machines so far. The accident among the AAC machines would not cause human injury accidents due to unmanned operation of these machines. It realizes perfectly safe construction.

Fig. 11
Cores of CSG concrete constructed by the AAC machins
Noyaux de béton CSG construits par les machines AAC

5. CONCLUSIONS

The advanced automated construction system of A4CSEL has been invented aiming the industrialization of the construction of infrastructures. This paper describes the features and the performance of A4CSEL. The main points are summarized below.

1. A4CSEL founds on three technical components which include modifying ordinal construction machine to autonomous machine, transferring the skilled human operation to the machines and managing the automated construction for high production ability.
2. Through the application of the automated construction to the CSG dam, the performance of A4CSEL is verified to achieve 80 % of labor-saving by the remote operation of the AAC machines and 3 times efficiency in the production, reduce the environmental impact by the 40% to 50 % reduction of fuel consumption of the AAC machines and realize the safer construction.
3. It is considered that the spread of the automated construction increases the productivity of the construction and promptly accumulate required infrastructures as the social foundation, resulting the upgrade of the status of the construction industry.
4. For widely promoting the automated construction, followings are future issues:
    1. Developing the electrical control of the machines which have been digitalized
    2. Cost saving for the modification of ordinal machines to automated ones
    3. Strengthening the public network facility especially for small scaled and/ or short period construction
    4. Detailed design of the structure for avoiding the obstacles to the automated construction

ACKNOWLEDGMENTS

We would like to express our gratitude to the Construction office of the Naruse dam, Tohoku Regional bureau of Ministry of Land, Infrastructure and Tourism for the kind acceptance to the application of the A4CSEL system to the dam construction and advises for the adequate execution of its application. We would like to express our gratitude to Dr. Masayuki Kashiwayanagi and Dr. Hiroaki Noguchi of Japan Commission on Large Dams for their strong support and the spot-on suggestions in the manuscription of this paper.

REFERENCES

[1] MIURA S. Advanced production system in the construction industry featured by the automation of construction machines. *The dam digest*, 2019, No.897, No.898. (in Japanese)

[2] MIURA S., IZUSHI Y., HAMAMOTO K. Application of advanced production system in the construction industry of A^4CSEL. *Civil Engineering Journal*, 2021, Vol. 62, No.1. (in Japanese)

[3] MIURA S., IZUSHI Y., HAMAMOTO K. Development and deepening of automated construction system of A^4CSEL. *Civil Engineering Journal*, 2023, Vol. 64, No.1. (in Japanese)

[4] SUGAI T., IZUSHI Y., AOKI H., HAMAMOTO K. Application of automated construction system to the construction of a CSG trapezoidal dam, No.1. *Proceedings of the 76th Annual Conference of the Japan Society of Civil Engineers*, 2021, VI–209. (in Japanese)

[5] SUGAI T., IZUSHI Y., AOKI H., HAMAMOTO K. Application of automated construction system to the construction of a CSG trapezoidal dam, No.2. *Proceedings of the 77th Annual Conference of the Japan Society of Civil Engineers*, 2022, VI–53. (in Japanese)

[6] TASHIRO T., OUCHI H., SAKATA N., WATANABE K. A new conveying method of concrete for the swift construction of large-scaled concrete dams. *Concrete Journal*, 2015, Vol.53, No12. (in Japanese)

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CHENGDU, MAI 2025

DESIGN AND CONSTRUCTION OF BAGHAN RCC DAM FEATURING REINFORCED CONCRETE UPSTREAM FACE AGAINST RCC (*)

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SUMMARY

The Baghan reservoir dam is a roller compacted concrete (RCC) gravity dam with a maximum height of 58 meters and a total concrete volume of approximately 250,000 cubic meters. It is in the final stages of construction in the southwestrn of Iran, an area characterized by very warm climate and low rainfall. The dam aims to meet the critical water needs for both drinking and industrial purposes. Given the challenging weather conditions and the importance of maintaining the reservoir's water supply, special attention was given to the design and construction of the dam's upstream face. The upstream face of the dam was designed with reinforced concrete and constructed in layers, alongside (against) the RCC dam body. Bedding mortar was applied between these layers to enhance water tightness. During construction, flooding did not reveal any significant water leakage, indicating the effectiveness of the sealing system.

**Conception et construction du barrage en BCR de BAGHAN avec parement amont en béton armé*

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RÉSUMÉ

Le barrage de Baghan est un barrage-poids en béton compacté au rouleau d’une hauteur maximale de 58 mètres et d’un volume total de béton d’environ 250 000 mètres cubes. Il est en phase finale de construction dans le sud-ouest de l’Iran, une région caractérisée par un climat très chaud et de faibles précipitations. Le barrage vise à répondre aux besoins critiques en eau à des fins d’alimentation en eau potable et industrielle. Compte tenu des conditions météorologiques difficiles et de l’importance de maintenir l’approvisionnement en eau du réservoir, une attention particulière a été accordée à la conception et à la construction de la face amont du barrage. La face amont du barrage a été conçue en béton armé et construite en couches, contre le corps du barrage en BCR. Du mortier a été appliqué entre ces couches pour améliorer l’étanchéité. Pendant la construction, il n’a pas été constaté de fuite d’eau importante, ce qui indique l’efficacité du système d’étanchéité.

1. INTRODUCTION

Roller compacted concrete (RCC) dams are constructed with upstream and downstream faces that are integral parts of the dam structure. Construction typically begins with placing concrete layers adjacent to temporary and removable forms. These procedures are repeated with strict quality control to achieve smooth concrete surfaces. RCC dams are built in successive layers, which can lead to variations in the upstream face’s design. Initial design considerations focused on methods that accelerate construction, reduce formwork entrapment, ease form installation and removal, and lower labor costs.

Early RCC dams experienced significant issues with leakage, particularly at horizontal joints between layers and vertical transverse cracks. This led to the development of various methods for improving the upstream face of RCC dams, including conventional concrete, precast concrete, geomembranes, or combinations of these systems. Statistical data indicates that conventional unreinforced concrete was the most widely used method [1], [2]. For example, the Javeh Dam in Iran employed conventional concrete alongside RCC in each layer, using additional control joints sealed with mastic to manage thermal cracks [3]. The Shah-Wa-Arus Dam in Afghanistan used similar methods, incorporating waterproof strips in control joints [4].

Baghan RCC dam, which is in the final stages of construction, is located in an environment with very hot and low rainfall climates, inorder to meet the critical needs for drinking water as well as industry wter demand, an reinforced concrete upstream face was proposed and bedding mortar considered at a certain width of the roller compacted concrete body of the dam in the upstream face between layers.

Fig. 1
Construction of upstream face of SHAH-WA-ARUS dam

2. UPSTREAM FACE OF BAGHAN DAM

The Baghan reservoir RCC dam with a maximum height of 58 meters is in the final stages of construction, so that the physical progress of the dam body and its related structures is currently over 98 percent. Figure 2 shows the longitudinal section of Baghan RCC gravity dam and tallest monolith of the dam.

The upstream face of the dam was considered as reinforce concrete face in order to be watertight in the weather conditions of the site and to maintain nice appearance, as well as of the economic issues governing the project. In order to control the thermal cracks caused by the accumulation of concrete and subsequently to minimize the possibility of water leakage from the upstream face, especially due to the very hot climatic conditions of the region, in addition to observing the qualitative issues in the construction, implementation and maintenance of concrete, which is part of the work requirements, it was also taken to reinforce it with minimal thermal reinforcement. This was due to the experience of other similar projects, which sometimes required the addition of many control cracks in the conventional concrete process to reduce thermal cracks, sometimes increasing sealing problems.

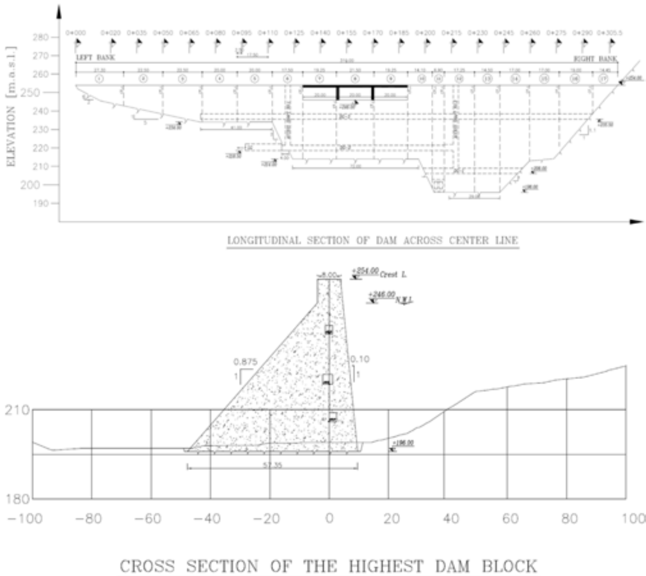

Fig. 2
Longitudinal section of Baghan RCC gravity dam and tallest monolith of the dam

Figure 3 shows construction of conventional reinforced concrete upstream face in Baghan RCC dam, which was carried out next to the RCC.

Fig. 3
Reinforced conventional concrete against RCC system in upstream face of Baghan dam

3. APPLICATION OF BEDDING MORTAR IN RCC ADJACENT TO THE UPPER SURFACE OF BAGHAN RCC DAM

As noted earlier, the upstream face of the dam and the RCC body were constructed in successive layers. Each layer was compacted using rollers to a thickness of about 30 centimeters. To control leakage between layers, bedding mortar was applied at specific intervals from the upstream face. Figure 4 illustrates the use of bedding mortar in the dam's transverse section. The mortar was placed before adding subsequent layers to address potential leakage caused by the reservoir's hydraulic head. The width of the bedding mortar layer increases with the hydraulic head. Figure 4 shows images of the interlayer mortar placement.

Fig. 4
Interlayer bedding mortar placement during construction of Baghan RCC dam

4. PERFORMANCE OF BAGHAN RCC DAM FROM PERSPECTIVE OF THE WATERTIGHTNESS

The Baghan Reservoir Dam has achieved approximately 98% completion. When construction progress reached around 90%, the reservoir was partially filled to preserve water during the last seasonal flooding. At this stage, the lower gallery experienced approximately 20 meters of hydraulic pressure, while the middle gallery was several meters below the water level. Site inspections revealed no evidence of leakage in the galleries or the upstream face. The absence of significant water leakage indicates that the sealing system is functioning as intended. Figure 5 displays images of the reservoir, the gallery surfaces below the water level, and the downstream face after flooding.

Fig. 5
Images of the reservoir, the surface inside the galleries located below the water level and the status of the downstream face after flooding

5. CONCLUSIONS

The Baghan Reservoir RCC dam, with a maximum height of 58 meters, is situated in a region with extreme heat and low rainfall. Due to the region's water scarcity, the dam's sealing system is crucial for minimizing leakage. The upstream face was constructed with reinforced concrete, integrated with the RCC layers, and minimal thermal reinforcement. Interlayer bedding mortar was applied to approximately 10% of the hydraulic head above each layer, extending from the layer level to the normal water level. During the most recent seasonal flooding, the reservoir was filled to more than half its height without any observed leakage, demonstrating the effectiveness of the sealing system.

REFERENCES

[1] DUNSTAN, (1998), RCC Dams (Completed and Under Construction), *1998 World Atlas and Industry Guide of the International Journal on Hydropower and Dams.*

[2] *Facing Systems for Roller-Compacted Concrete Dams & Spillways-PCA publication.*

[3] *Construction Method Report of Javeh Dam Project-Spring of 2010.*

[4] *Final Design Drawings of SHAH-WA-ARUS Dam And Hydropower Project*-May 2019.

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CHENGDU, MAI 2025

INNOVATIVE TECHNIQUE FOR REHABILITATION OF BUTTRESS DAMS (*)

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NORWAY

SUMMARY

This article presents a new method for the reconstruction and strengthening of old buttress dams, where the old dam is used as a shell or formwork for the construction of a new dam. The technique is now the preferred for strengthening existing slab buttress dams in Norway and it has proven to be cost-efficient in cases where construction of a new dam is the only solution. The solution can also be applied at a full reservoir level, a major advantage in many cases.

The new technique was first used at Dam Korkavatn, which was rehabilitated in 2014, where Thomas Konow was the consultant responsible for design and rehabilitation works. The solution results in a stable and safe structure, where the safety factor is greatly increased. The solution also proved to give 40 % cost savings compared to the demolition of the existing dam and construction. The main reason for cost savings is a significant reduction in the necessary concrete volume, which also contributes to reducing the environmental impact.

It is assumed that the solution can be particularly relevant for slender buttress dams such as flat slab buttress dams and multiple arch dams. Examples of how the technique can be applied to these dams are also presented in this paper.

Méthode innovante de renforcement des barrages à contreforts

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It is considered that the technique described in this article can be the preferred solution even though the construction costs of a new dam is comparable, because the safety gained is very favourable compared other traditional dam types.

Due to the many advantages of the design technique for dam Krokavatn, it has now on more than 10 other similar dams in Norway, and it is assumed that the technique is highly relevant for buttress dams outside Norway.

The technique has been registered as Patent no. 335274 by the Norwegian Industrial Property Office (NIPO), with Thomas Konow as inventor. NIPO is the registration authority in Norway for patents, trademarks, and designs. The patent was unbound shortly after approval and is available for anyone to use without any restrictions.

RÉSUMÉ

Cet article présente une nouvelle méthode pour la reconstruction et le renforcement des anciens barrages à contreforts, où l’ancien barrage est utilisé comme enveloppe ou coffrage pour la construction d’un nouveau barrage. Cette technique est aujourd’hui privilégiée pour renforcer les barrages à contreforts existants en Norvège et elle s’est avérée rentable dans les cas où la construction d’un nouveau barrage est la seule solution. La solution peut également être appliquée au niveau d’un réservoir plein, un avantage majeur dans de nombreux cas.

La nouvelle technique a été utilisée pour la première fois au barrage de Korkavatn réhabilité en 2014, où Thomas Konow était le consultant responsable des travaux de conception et de réhabilitation. L’ouvrage conforté est stable, sûr, et le facteur de sécurité est considérablement augmenté. La solution permet aussi de réaliser des économies de 40 % par rapport à la démolition du barrage existant et à la construction. La principale raison des économies de coûts est une réduction significative du volume de béton nécessaire, ce qui contribue également à réduire l’impact environnemental.

La solution peut être particulièrement pertinente pour les barrages à contreforts minces tels que les barrages à contreforts à dalle plate et les barrages à voûtes multiples. Des exemples de la façon dont la technique peut être appliquée à ces barrages sont également présentés dans cet article.

On considère également que cette technique peut être la solution privilégiée même si les coûts de construction d’un nouveau barrage sont comparables, car la sécurité acquise est très favorable par rapport à d’autres types de barrages traditionnels.

En raison des nombreux avantages de la technique de conception du barrage de Krokavatn, il existe maintenant plus de 10 autres barrages similaires en Norvège, et on suppose que la technique est très pertinente pour les barrages à contreforts en dehors de la Norvège.

La technique a été enregistrée sous le numéro de brevet n° 335274 par l'Office norvégien de la propriété industrielle (NIPO), avec Thomas Konow comme inventeur. Le NIPO est l'autorité d'enregistrement en Norvège pour les brevets, les marques et les dessins et modèles. Le brevet a été délié peu de temps après l'approbation et est disponible pour toute personne sans aucune restriction.

1. INTRODUCTION

According to International Commission On Large Dams (ICOLD), Technical dictionary of dams, there are three types of buttress dams:

- Flat slab buttress dams (or deck dam)
- Multiple-arch dams
- Solid head buttress dams

Buttress dams are characterized by a water-tight upstream side that is supported by a series of buttresses on the downstream side. The buttresses transfer the force from the water pressure to the foundation. The buttresses normally have a constant spacing along the dam. Typically, the buttresses are placed at intervals of 5 to 20 meters, depending on the size and design of the dam. Buttress dams are also sometimes referred to as hollow dams because of the open sections between the buttresses on the downstream side of the dam.

In the US, flat slab buttress dams are sometimes called Ambursen dams, since this damtype was patented in the US by the Norwegian engineer Ambjørnsen who immigrated to the US. In Norway, the flat slab buttress dam is also called "Grøner-dam". This is a further development of the Ambursen-dam made by the engineer C.F. Grøner (former ICOLD President). Here the vertical slab joints are placed at the point of zero moment in the slab and thereby reducing the required reinforcement in the slab. Due to these two engineers, Norway and the US are considered to be the countries with the most slab buttress dams worldwide. In Norway there are a total of 240 slab buttress dams whereof 44 are defined as "large dams".

As the age of the buttress dams increases, the need for repair and rehabilitation also increases due to general deterioration and age. In addition, many dams do not meet today's requirements for strength or overall stability, as the required level of safety for dams in general has been increasing over the years. As a result, several of today's buttress dams need rehabilitation and in some cases construction of a new dam may be the only solution.

2. CHALLENGES WITH NORWEGIAN BUTTRESS DAMS

With a few exceptions, all the Norwegian buttress dams are of the type "flat slab" buttress dams.

Most of these dams were constructed during the 1950s and 1960s. The general condition of these dams depends on the age combined with the general quality of the construction works and the environment the structure has been exposed to. Mechanisms that affect the general condition of the structure can be frost and thaw effects, reinforcement corrosion and alkali-aggregate reaction (AAR). Often, a combination of these different deterioration mechanisms is present at the same time.

In addition, the structure needs to have sufficient stability according to today's safety requirements. In Norway, the requirements for the stability changed with the new regulations that came into force in 2001. The present requirements for stability of buttress dams are shown in the table below.

Table 1
Norwegian requirements for stability of slab buttress dams

	FACTOR OF SAFETY FOR	
LOAD SITUATION	**OVERTURNING**	**SLIDING**
Ice pressure (100 kN pr. m)	1,4	1,4
Design flood (Q_{1000})	1,4	1,4
Design flood excluding rock anchor/bolts (Q_{1000})	1,1	1,1
Probable maximum flood (PMF)	1,3	1,1

The new regulations are also applied to existing dams. As a result, many of the existing slab buttress dams do no longer meet the stability requirements against sliding and/or overturning.

In addition, the Norwegian dam safety authorities have an intention to not allow slab buttress dams in the highest hazard class, and this also applies to existing dams.

In Norway, the above-mentioned factors have resulted in an increased number of cases where slab buttress dams need strengthening or rehabilitation. In some cases, decommissioning and reconstruction of a new dam is the only option.

3. RECONSTRUCTION OF DAM KROKAVATN

Dam Krokavatn is 19 m high and has a total length of 100 m, where the main dam is a flat slab buttress dam about 50 m long.

The dam design is typical for Norwegian flat slab buttress dams. It is constructed with an upstream slab inclined at about 50o to the horizontal and supported by 8 concrete buttresses at 5 m spacing. Originally, the upstream deck had a thickness of 0.30 m at the top and increased to a thickness of 0.80 m at the foundation.

At the right abutment, there is a 50 m long concrete gravity spillway. Between the spillway and the buttress dam, there is a corner along the dam axis. Through several years a crack had developed in the concrete wall located at the corner between the buttress dam and the spillway (see Figure 2) and resulted in a large leakage through the crack at full reservoir level.

Fig. 1
Dam Krokavatn. 50 m long slab buttress dam (near side) and the spillway on the far side. Notice that the dam axis has a corner on the far side between the buttress dam and the spillway.

3.1. Dam safety evaluation

In 2012, the dam owner conducted a safety evaluation of the dam, where the overall safety was assessed.

The safety evaluation of the dam identified that it did not meet today's requirements for stability against sliding and overturning. As the dam is a high-hazard dam, the Norwegian dam safety authorities therefore required a reconstruction of the dam.

3.2. Alkali aggregate reaction (AAR)

The dam safety evaluation also concluded that AAR was present in the concrete. This was not a surprise, as observations from the dam showed a relative movement of 15 mm at the buttress wall next to the spillway (see Figure 2), over a length of 8.45 m.

Fig. 2
Cracking of concrete at the buttress wall on the corner between the spillway and the slab buttress dam.

This corresponded to an elongation of 0.18 % and indicated a tensile stress of 360 N/mm2 in the reinforcement. As the characteristic strength of the reinforcement was 400 N/mm2, the tension in the reinforcement was close to yielding, and it was therefore concluded that the reservoir should be restricted to a maximum 2.5 m below the maximum operating level. This section of the dam was only 4 m high, and a collapse of the concrete slab would therefore not have any serious consequences.

3.3. Rehabilitation works

To upgrade the dam, it was decided to use the old buttress walls as formwork to cast new buttresses in every second hollow area, as shown in the figure below. The additional weight from the buttresses would then secure the required stability of the dam.

In addition, a new concrete slab on the upstream side of the old slab was necessary since the load capacity of the slab was not sufficient due to AAR.

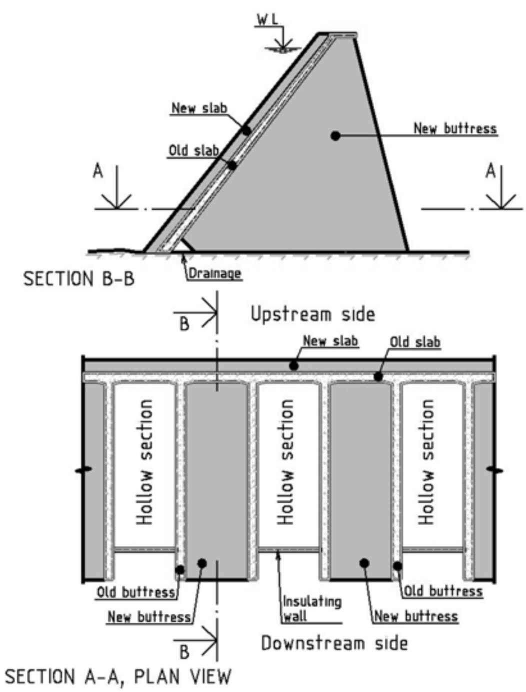

Fig. 3
General arrangements for reconstruction of dam Krokavatn.

After reconstruction, the original dam is only a shell and has no function regarding stability or strength of the new structure.

This solution was by far considered to be the cheapest solution compared to the alternative, which would be the construction of a new dam.

Cost estimates of different solutions are shown below.

Table 2
Cost estimate of different alternatives in 2014 (100 NOK = 11 US$)

ALTERNATIVE	COST (NOK)	COST (US$)	DIFFERENCE (%)
1. Buttress dam – Reconstruction	22 000 000,-	4 400 000,-	-
2. New gravity dam in concrete	31 000 000,-	6 200 000,-	+41%
3. New rockfill dam	41 000 000,-	8 200 000,-	+86%

3.4. Evaluation of stability

Calculations of the dam stability proved that the solution was favourable in terms of stability. This is mainly due to the additional weight from the new buttresses. In addition, the weight of the new upstream slab and a less inclined upstream face also contribute to the improved stability of the dam.

A comparison of the stability before and after reconstruction is shown in the figures below.

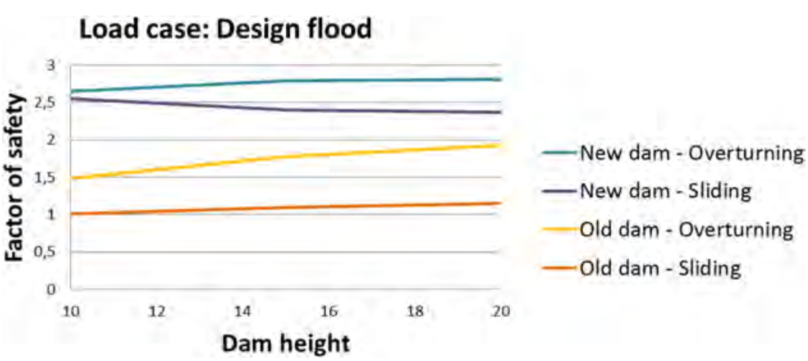

Fig. 4
Computed stability of the existing dam (old dam) compared to that of the reconstructed buttress dam (new dam) for a design flood 0.5 m above normal water level.

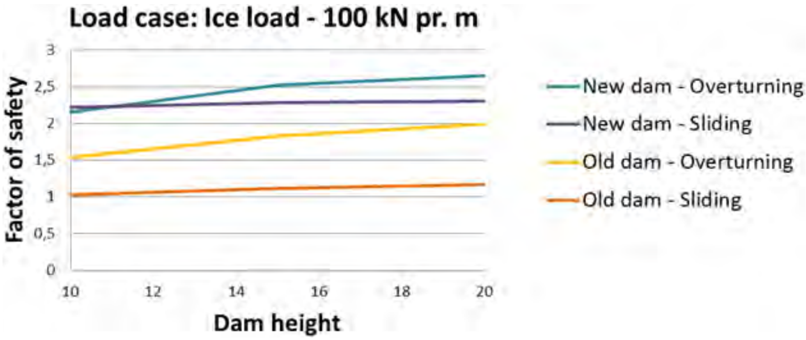

Fig. 5
Computed stability of the existing dam (old dam) compared to that of the reconstructed buttress dam (new dam) for a design ice load of 100 kN pr. m length.

The calculations of stability show that the new dam has a very high level of safety. The factor of safety is higher than 2 and is much higher than the required level of safety in Norway. In general, the factor of safety against sliding is increased by more than 1, compared to the existing dam.

As a simplification, it can be said that the new dam can be looked upon as a combination of a flat slab buttress dam and a solid head buttress dam, where the massive buttresses and the stabilizing weight of the water above the inclined slab together with a reduced pore pressure results in a very safe dam structure.

3.5. Pictures from construction in 2014

As mentioned, the safety evaluation in 2012 concluded that a reservoir restriction of 2,5 m below normal operating level was necessary due to the damages on the dam. The dam owner therefore wanted the reconstruction carried out as soon as possible.

As the dam is in a mountain area, it is not accessible during the winter, and the work must be carried out in the period June to October.

The construction work started in 2014. During the summer a new road of 7 km was constructed, and the new upstream slab was cast. The new buttresses will be constructed during the summer of 2015.

Some pictures from the dam reconstruction are shown below.

Fig. 6
Reinforcement in place on two upstream slabs.

Fig. 7
New slab on the upstream side. Insulation cover of the concrete during hydration was necessary due to the cold climate in the late autumn.

Fig. 8
Dam after rehabilitation where new buttresses are visible on the downstream side.

4. OTHER METHODS FOR STRENGTHENING FLAT SLAB BUTTRESS DAMS

The solution used on dam Krokavatn can be modified to suit other types of flat slab buttress dams, and some of these solutions are described with text and illustrated with figures.

4.1. New slab on the downstream side

The solution is illustrated in the figure below. The figure shows a cross-section D-D of a new buttress where a new concrete slab is constructed on the downstream side of the existing upstream slab. Section C-C shows one possible solution for placing the construction joints and thereby connecting the new buttresses and the new concrete deck. This can be done by casting the new buttresses before cutting through the buttresses of the existing dam.

This solution does not require a full drawdown of the reservoir which can be a great advantage in some cases. The solution may be used on buttress dams where both stability and strength of the structure may be a problem.

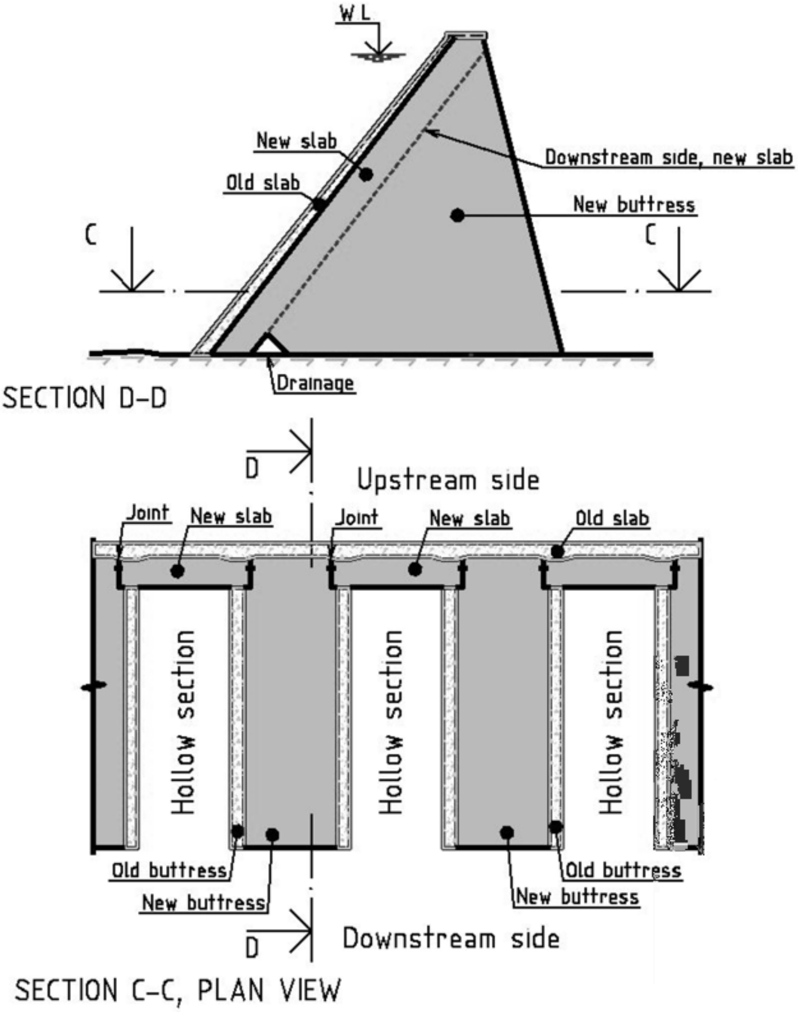

Fig. 9
Reconstruction with a new slab on the downstream side.

4.2. New buttresses only

The solution is illustrated in the figure below. The figure shows a cross-section H-H of a new buttress where a new concrete deck is not required. Section G-G

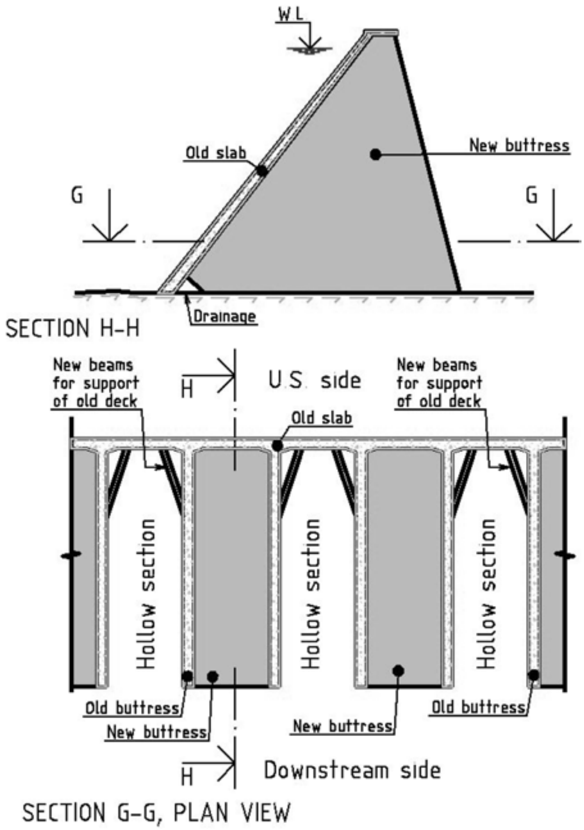

Fig. 10
Reconstruction without a new upstream slab.

shows a plan view with a possible solution for strengthening the slab in cases where this may be necessary. This can for instance be done by installing a row of beams to support the existing slab. This solution requires that the existing upstream slab does not have any major damages or leakages and can still work as an upstream watertight seal for the dam.

This solution does not require a drawdown of the reservoir and can be used where both stability and strength of the structure may be a problem. The new buttress can influence the static load distribution of the existing slab and may result in the need to strengthen the existing upstream slab.

5. STRENGTHENING OF MULTIPLE ARCH DAMS

A multiple-arch dam is designed with the same principles as the flat slab buttress dam, with an inclined upstream face. Normally, this is also a slender dam structure where the vertical weight of the water above the slab gives a major contribution to the stability of the dam.

Multiple arch dams are generally higher than the flat slab buttress dams and have a greater spacing between the buttresses, as the arches can have a larger span than the flat slab. The stresses in the structure and on the interface to the foundation are therefore much higher compared to flat slab buttress dams. On some older buttress dams, FEM analysis has identified unacceptable stresses in these types of dams.

In the following examples, it is illustrated how multiple arch dams can be strengthened with the same method used for dam Krokavatn.

5.1. Reconstruction to a solid head buttress dam

The solution is illustrated in the figure below.

The figure shows a cross-section L-L of a new buttress in a reconstructed multiple-arch dam with a new concrete slab on the upstream side of the existing upstream concrete arch slab. Section K-K shows a plan view where the new buttresses are cast in every second hollow section. The new upstream concrete slab is designed as an upstream buttress head so that the structure can be defined as a solid head buttress structure. The figure shows a constant thickness of the upstream concrete slab; however, the thickness may vary with the dam height and water pressure.

5.2. New buttresses only

The solution is illustrated in the figure below.

The figure shows a cross-section N-N of a new buttress in a reconstructed multiple-arch dam where a new upstream concrete deck is not required, as also illustrated in the plan view (Section M-M). The solution can be used to improve the overall stability of the dam, or where the existing buttresses do not have sufficient

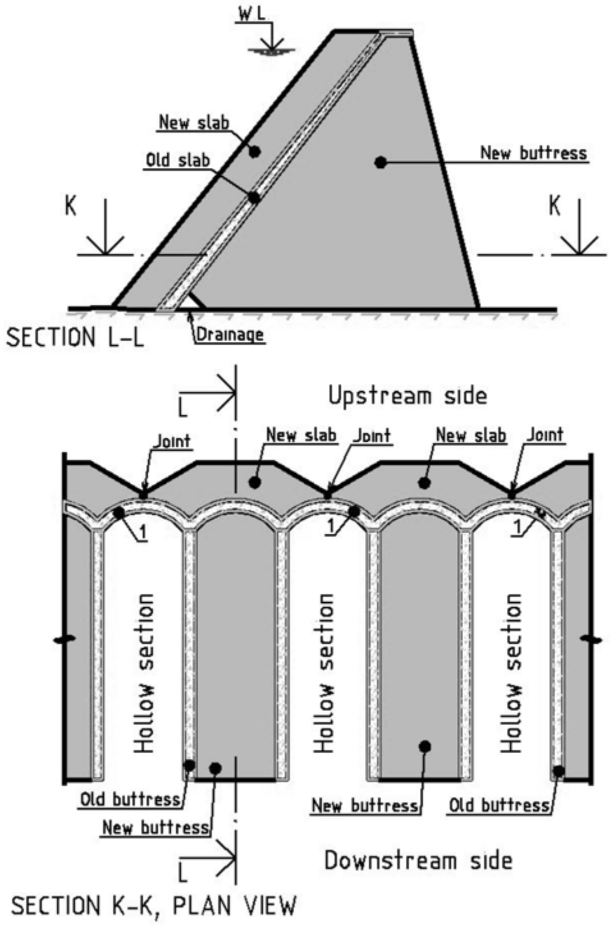

Fig. 11
Reconstruction to a solid head buttress dam.

safety and require strengthening. The solution implies that the existing arches do not have sufficient safety.

To obtain satisfactory waterproofing it is possible to e.g. install a watertight geo-membrane on the upstream side of the dam. It is also possible to construct a new upstream deck at a later stage if this is considered necessary.

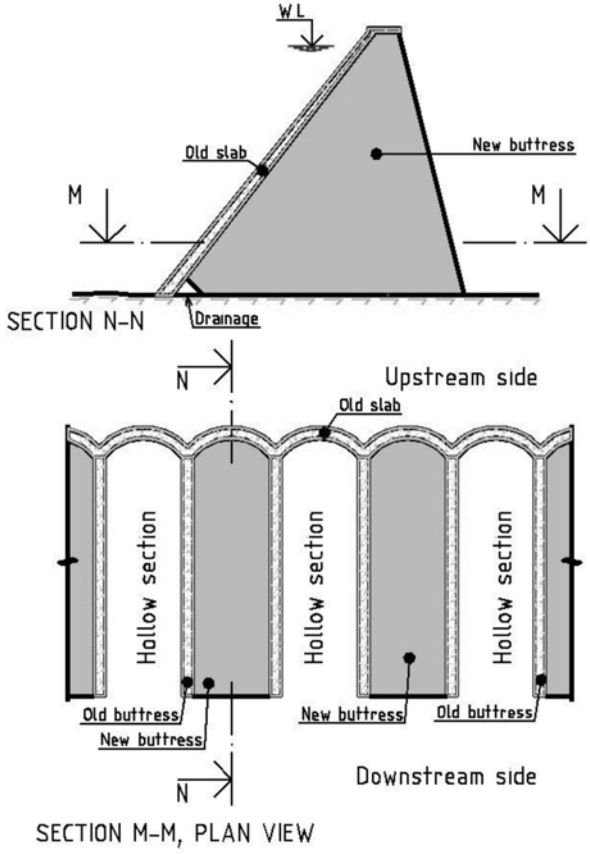

Fig. 12
Reconstruction with new buttresses only

5.3. New slab on the downstream side

The solution is illustrated in the figure below.

The figure shows a cross- section P-P of a new buttress where a new concrete arch is constructed on the downstream side of the existing arch. Section O-O shows one possible solution for placing the construction joints and thereby connecting the new buttresses and the new concrete arch. This can be done by casting the new buttresses before cutting through the buttresses of the existing dam.

This solution does not require a full drawdown of the reservoir which can be a great advantage in some cases. The solution may be used on buttress dams where both stability and strength of the structure may be a problem.

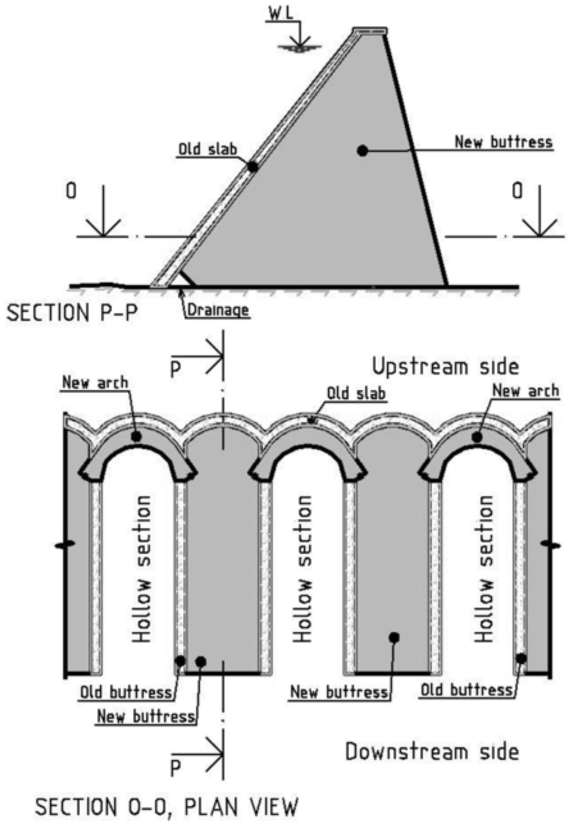

Fig. 13
Reconstruction with a new arch on the downstream side.

6. CONCLUSION

As the age of the buttress dams increases, the need for repair and rehabilitation also increases due to general deterioration and age. In addition, many dams do not meet today’s requirements for strength or overall stability, as the required level of safety for dams in general has been increasing over the years. As a result, many of the existing buttress dams need rehabilitation and, in some cases, construction of a new dam may be the only solution.

This paper presents a new technique for the reconstruction of buttress dams where new buttresses are cast in between the buttresses of the existing dam. As a simplification, the solution can be illustrated as a combination of a flat slab buttress dam and a solid head buttress dam, where the massive buttresses and the stabilizing weight of the water above the inclined slab together with a reduced pore pressure results in a very safe dam structure.

The technique is presently being used on flat slab buttress dams in Norway and the article gives a brief description of the safety evaluation and rehabilitation works of this dam.

The design of this dam has proved that the solution is very favorable in terms of stability. This is mainly due to the additional weight from the new buttresses. In addition, the weight of the new upstream slab and a less inclined upstream face also contribute to the improved stability of the dam.

On dam Krokavatn, the solution has proven to be cost-efficient compared to construction of a new dam, which was the only alternative solution.

The technique described in this paper may be the preferred solution even though the construction costs of a new dam are comparable, since the safety gained by this technique is favorable compared even to a new dam.

REFERENCES

[1] T. KONOW. Innovative technique for strengthening old buttress dams and multi-arch dams. Hydropower & Dams, 2015, Issue n. 3.

[2] T. KONOW. New innovative technique for strengthening old buttress dams and multi-arch dams. USSD Annual conference, US Louisville 2015.

[3] T. KONOW. New innovative technique for strengthening old buttress dams and multi-arch dams. Hydropower ‘15, Norway, Stavanger June 2015.

[4] The Norwegian Industrial Property Office (NIPO), Patent no. 335274, Inventor: Thomas Konow.

Commission Internationale des
Grands Barrages

Vingt-Huitieme Congres des
Grands Barrages
Chengdu, Mai 2025

STEP ET ELECTROLYSE DE L'EAU SUR PRISE DE BARRAGE (*)

Joseph Antoine PAOLI

France

SUMMARY

The innovation file for the 2025 ICOLD Prize, written by engineer Joseph Antoine Paoli, proposes an integrated solution for the sustainable management of dams in the face of current climate challenges. This innovative project is based on a two-pronged approach: a system for self-cleaning dam intakes to limit siltation and a water purification process by electrolysis, producing oxygen, ozone and hydrogen. In addition to preserving water quality, this technology ensures energy autonomy thanks to a pumped-storage system (WWTP) and floating photovoltaic energy. By combining purification, renewable energy and sustainability, this solution is intended to be economically viable and environmentally responsible, thus meeting the challenges of eutrophication, water storage and energy transition.

RÉSUMÉ

Le dossier d'innovation pour le Prix CIGB 2025, rédigé par l'ingénieur Joseph Antoine Paoli, propose une solution intégrée pour la gestion durable des barrages face aux défis climatiques actuels. Ce projet innovant repose sur une double approche : un système d'auto-curage des prises de barrage pour limiter l'envasement et un procédé de purification de l'eau par électrolyse, produisant oxygène, ozone et hydrogène. En

**PSP and water electrolysis on dam intake*

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plus de préserver la qualité de l'eau, cette technologie assure une autonomie énergétique grâce à un système de pompage-turbinage (STEP) et à l'énergie photovoltaïque flottante. En alliant purification, énergie renouvelable et durabilité, cette solution se veut économiquement viable et écologiquement responsable, répondant ainsi aux enjeux d'eutrophisation, de stockage d'eau et de transition énergétique.

1. PRESENTATION

Les changements climatiques se manifestent partout dans le monde par deux phénomènes extrêmes et contradictoires : de longues périodes de sécheresse alternant avec des pluies intenses, provoquant des ruissellements et des charriages importants. Ces crues, de plus en plus violentes, induisent un envasement significatif des barrages, réduisant ainsi les volumes d'eau stockés. Les dépôts de matériaux lourds s'accumulent en queue de retenue, tandis que les sédiments plus fins se mélangent aux débris végétaux pour former des vases épaisses au fond des bassins, parfois jusqu'à obstruer les prises d'eau. Sur les barrages de grande hauteur, les méthodes de curage traditionnelles – dragues, pelles hydrauliques, suceuses – sont souvent difficiles à déployer et coûteuses tant sur le plan technique que financier.

Par ailleurs, l'élévation des températures, l'agriculture intensive et l'extension des zones urbaines et rurales entraînent une dégradation accrue de la qualité des plans d'eau. Les barrages, retenues collinaires et réservoirs deviennent vulnérables à l'eutrophisation, avec une prolifération d'algues et l'apparition de cyanobactéries.

Face à ces défis, il est essentiel d'adopter une conception et une gestion des barrages plus résiliente, permettant de stocker davantage d'eau et d'en assurer une meilleure qualité. Cela passe par deux axes complémentaires d'amélioration.

Le premier, « par le haut », repose sur l'installation d'évacuateurs de crues de surface de type labyrinthe, qui permettent non seulement une meilleure évacuation des eaux excédentaires mais aussi un gain en volume de stockage grâce à une légère élévation de la tranche supérieure du plan d'eau.

Le second, « par le bas », concerne la prise d'eau des barrages ou des retenues collinaires, qui constitue le point de prélèvement et de transfert de l'eau stockée. Depuis plusieurs années, j'ai concentré mes recherches sur la problématique de l'envasement en développant un système d'auto-curage des prises de barrage, en intégrant progressivement le principe des STEP (Stations de Transfert d'Énergie par Pompage).

En parallèle, j'ai orienté mes travaux sur la purification de l'eau grâce à l'injection d'oxygène et d'ozone, produits par électrolyse, directement dans les plans d'eau ou au niveau des prises des barrages. Par ailleurs, la production d'hydrogène issue de l'électrolyse est valorisée en tant que source d'énergie, renforçant l'autonomie énergétique de ces installations.

Mes innovations, toutes brevetées, s'appliquent à une configuration spécifique des prises d'eau dans les barrages, et sont détaillées dans ce rapport technique. Ces solutions intégrées visent à garantir la durabilité des infrastructures hydrauliques, à préserver la qualité de l'eau stockée et à répondre aux nouveaux défis posés par le changement climatique.

2. RAPPORT TECHNIQUE

Sur les barrages en enrochements, la vidange de fond et la prise d'eau sont assurées par une conduite unique, généralement posée dans une galerie sous le remblai. La figure n°1 représente le côté amont où le culot avec la violence des crues actuelles a tendance à se remplir rapidement, empêchant ainsi la manœuvre de la vanne de vidange. L'envasement grandit alors irrémédiablement, voire peut obstruer la crépine.

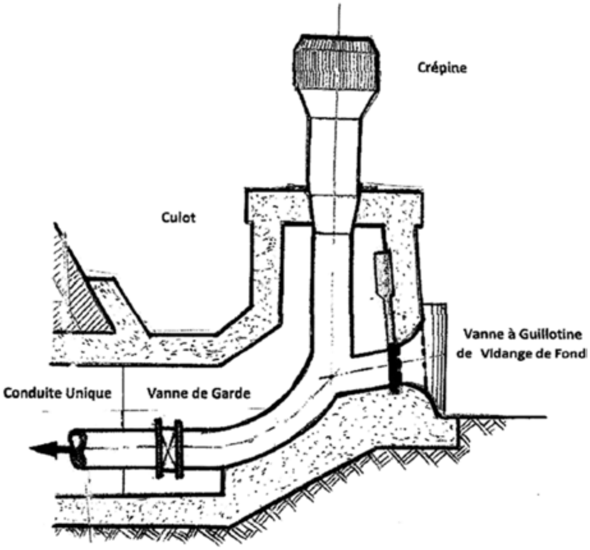

Fig. 1
Prise dans la configuration initiale

Prise d'eau Innovante

1/ La Fonction d'Auto-Curage

Comme indiqué sur la figure 2, La zone d'intervention possible sur la prise se situe au-dessus de l'ouvrage en béton armé du fond. Selon le niveau d'envasement il peut être nécessaire de rehausser le fût supportant la tulipe d'entonnement avec la crépine. La partie envasée, abandonnée définitivement est considérée comme une tranche morte.

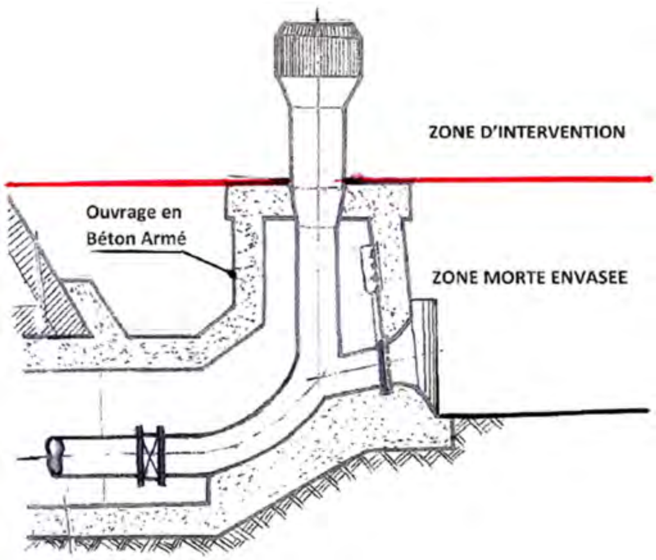

Fig. 2
Tranche morte

Le but premier est d'assumer la fonction d'Auto-Curage, en mettant sous la tulipe d'entonnement, sur le fût un système hydromécanique particulier, dont le fonctionnement est basé sur mon procédé « Jetting-Aspiration-Pompage », (Acronyme J.A.P, correspondant à la fois à son intitulé, aux initiales de mon prénom composé et de mon nom), ayant fait l'objet d'une protection industrielle à l'INPI / MD N° 601629 du 10/10/2018.

Le dispositif intitulé « Prise de Barrage pour le Dévasement avec Auto-Curage », consiste à empêcher l'accumulation des dépôts au droit de la prise d'eau, en utilisant celle-ci pour évacuer les éléments solides fins. Il sert à prélever l'eau du fond des barrages la moins chargée possible. Ce qui implique selon les cas quelques rejets de ces éléments fins, ne procurant aucune pollution par le fait d'une dilution progressive, correspondante à leur composition d'origine.

Les appareillages positionnés dans la zone d'intervention pré-indiquée à la figure 2, intègrent les phases d'Auto-curage par dans le sens :

- Passant du prélèvement, des succions avec forte aspiration, constituant des hydro-éjections,
- Inversé, des projections de jets de puissance variable venant d'un pompage extérieur, pulvérisant les envasements consolidés.

Entre l'ouvrage en béton armé et la tulipe d'entonnement est mis sur la partie rectiligne du fût, le dispositif suivant :

1. Une vanne de garde, dite de sectionnement de la prise,
2. Un tuyau torique crépiné, cerclant le fût, comprenant au minimum deux tronçons isolés, appelé « Anneau de curage à compartiments, fonctionnant à flux réversibles »,
3. Chaque compartiment est relié au fût avec leur vanne, dite d'isolement du compartiment,
4. Sur chaque tronçon de liaison au fût est raccordé un by-pass de petit diamètre, permettant d'effectuer d'une part l'hydro-éjection et d'autre part la manœuvre en pression équilibrée des vannes.

Toutes les Vannes (5 au total, pour 2 compartiments / le tuyau torique crépiné) sont du type immergé, avec des commandes déportées dans la galerie de visite, ou dans un petit local sur le couronnement du barrage.

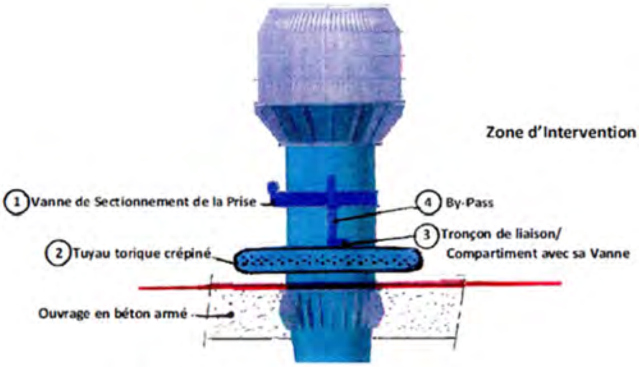

Fig. 3
Prise de barrage pour dévasement avec auto-curage

L'auto-curage à partir du tuyau torique crépiné est déduit d'une part de l'analyse physique des atterrissements constituant le culot et de valeurs remarquables, à la suite d'expérimentations. Ce qui impose de vider le barrage. Avec une barge partiellement échouée, équipée d'un godet, de matériels de forages, sont effectués des prélèvements à proximité de la prise dans le fond comblé. Les caractéristiques physiques en fonction de la profondeur comprennent :

- La teneur en eau (%),
- La Densité (KN/m3),
- L'indice de plasticité (%),
- La teneur en MO (%),
- % passant à 80 μ,
- % passant à 2μ.

L'angle de glissement interne à une profondeur $\leq$ 2m du toit de l'envasement et celui de l'envasement consolidé au niveau de la vanne à guillotine de vidange du fond, déterminent un angle moyen. Il sert au traçage du cône naturel qui s'établit autour du tuyau torique crépiné. Celui-ci est implanté à une distance égale à 3 fois le rayon du fût. Les loupes de glissement sont définies à partir des caractéristiques physiques relevées des matériaux du culot consolidé, par la méthode géotechnique des cercles de glissement. Quant au débit total d'auto-curage, il est compris entre Qe/4 et Qe/8, où Qe est le débit d'exploitation maximum du barrage. Avec 2 compartiments (voir figure 4) le débit par compartiment est alors de moitié. Par ailleurs pour avoir un fonctionnement sans cavitation des vannes papillon N° 1, N° 3 et N° 4, il faut vérifier que la vitesse à leur droit ne dépasse pas 4 m/s.

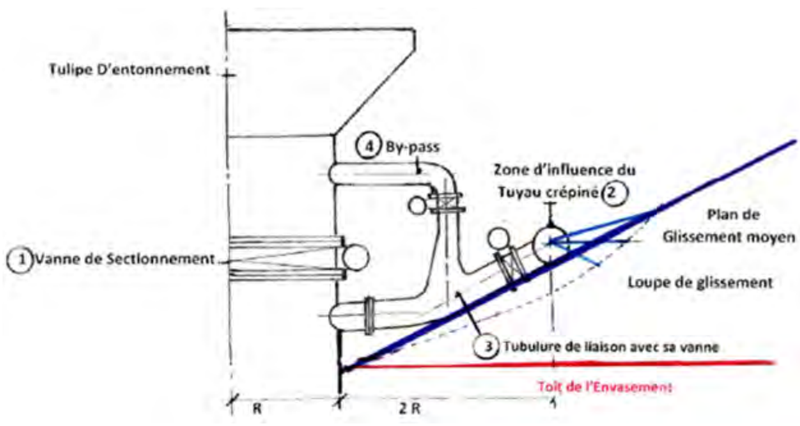

Fig. 4
Coupe longitudinale d'un compartiment du tuyau torique crépiné

Le fonctionnement du tuyau torique crépiné, compartimenté, est conçu de manière réversible. Les éléments principaux ont rapport au nombre de trous et à leur positionnement. Ils doivent permettre dans le sens passant de faire un filtrage des fines sans colmater le compartiment de l'anneau. La vitesse de passage de l'eau au niveau des trous est prise à 2 m/s (diamètre courant = 14 mm).

L'utilisation dans l'autre sens de l'anneau crépiné en Jetting, est primordiale pour le curage. Elle a été particulièrement étudiée et expérimentée. J'ai développé une méthode hydro-géotechnique, dont la représentation graphique est précisée sur la figure 5.

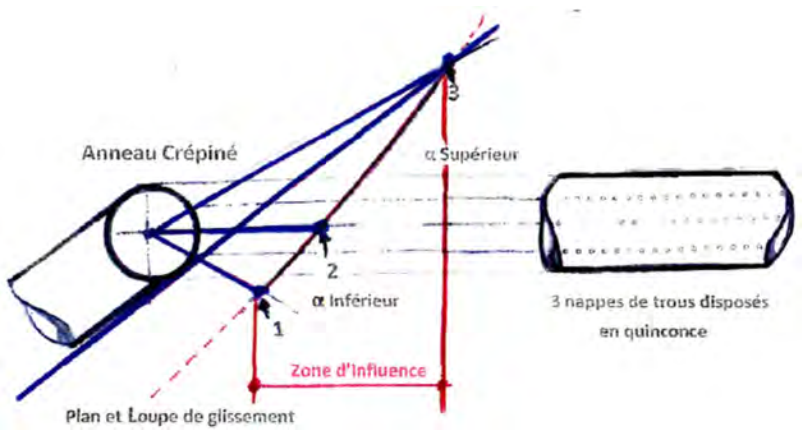

Fig. 5
Conception du Jetting

Le but est de pulvériser par des jets d'eau sortant de l'anneau crépiné, les matériaux fins et d'éviter ainsi tout dépôt consolidé autour. Les jets se répartissent selon trois trajectoires. La trajectoire centrale n°2 est positionnée à l'horizontale. Les deux autres n°1, n°3, sont déterminées par rapport au plan et la loupe de glissement, correspondant aux données géophysiques relevées par les sondages dans le culot comblé.

Pour saper l'agglomération et la consolidation des matériaux fins autour de l'anneau, les jets sont définis par leur débit, mais surtout par leur pression de sortie dans l'eau boueuse. Selon la nature et la teneur de l'eau chargée, la « force d'impact dans ce milieu » s'estompe à une courte distance, de l'ordre d'1m à 2m.

Le Jetting est d'autant plus efficace que les jets sont puissants, avec une pression supérieure à celle statique par rapport au plan d'eau. Selon sa hauteur, le différentiel de pression doit-être de + 4 bars à + 6 bars à barrage bas et de + 2 bars à 3 bars à barrage plein. L'objectif est de créer un cône évasé, empêchant les atterrissements de venir contre la prise, entre le pied du fût et l'entonnement et donc de pérenniser son fonctionnement, avec un curage progressif complètement intégré à l'exploitation de l'ouvrage.

METHODE D'UTILISATION

*En exploitation courante (Voir Figure 6)

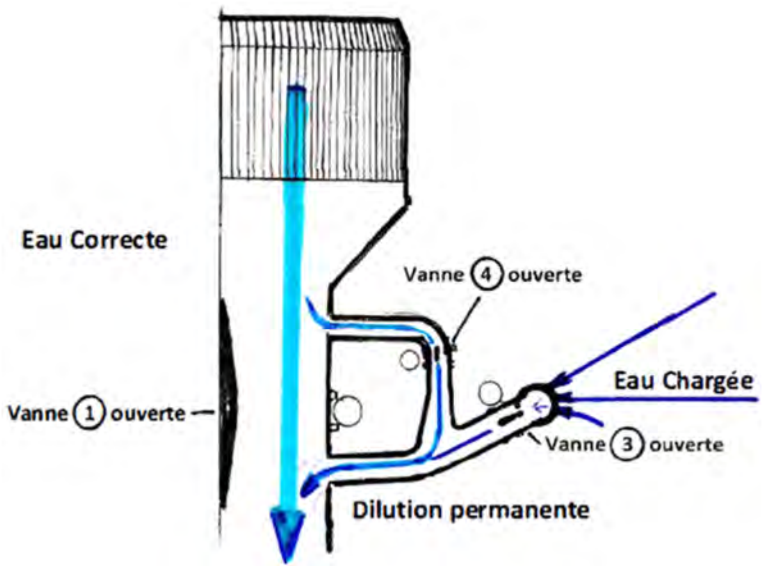

Fig. 6
En exploitation courante

Toutes les vannes immergées sont ouvertes. L'eau propre empruntant le by-pass, aspire l'eau chargée passant par l'anneau crépiné. Les éléments fins se dissolvent de manière continue, en petite quantité dans le flux du fût, correspondant au débit appelé d'exploitation. Sur les barrages à vocation principale agricole, ce système favorise une irrigation naturellement plus fertilisante.

*Pendant les arrêts réguliers d'exploitation

Cette période est mise à profit pour pratiquer à un nettoyage plus intensif de la partie sous l'entonnement de la prise. Celui-ci se déroule en deux phases.

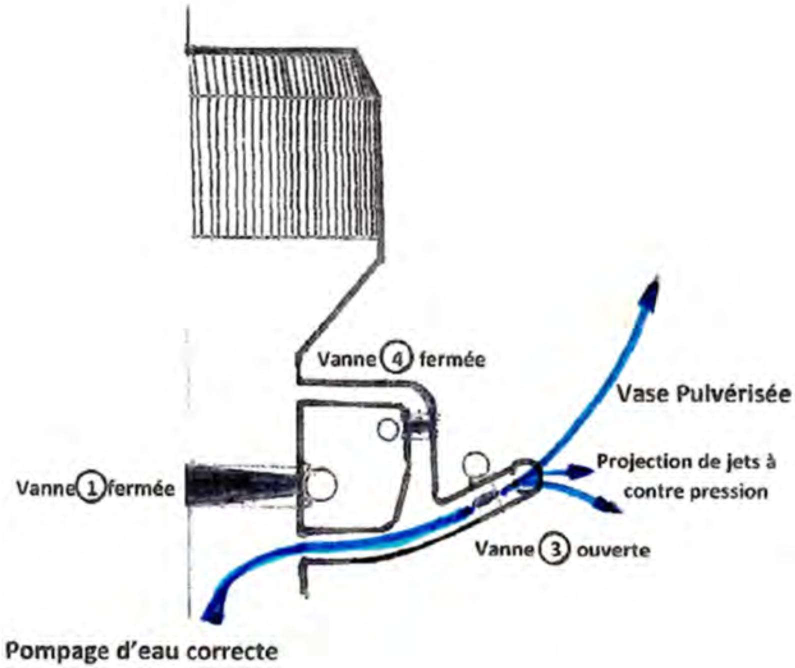

Fig. 7
Jetting en phase 1

Dans un premier temps : (Voir Figure 7)

Les vannes immergées N° I et N° 4 sont fermées. Les compartiments crépinés de l'anneau sont activés en écoulement inversé. Les volumes annuels utilisés sont très faibles, eu égard la capacité de stockage du barrage (de l'ordre de 1/1000).

Pour assurer ce Jetting, un pompage immergé dans la partie supérieure du plan d'eau, là où elle est claire, pourrait être installé et raccordé sur chaque compartiment de l'anneau crépiné. Les jets servent à déraciner d'éventuels petits branchages venus se ficher dans les trous, ou à décolmater certains, mais surtout à disloquer la vase autour de l'anneau. Les éléments fins sont pulvérisés au-dessus. Cette opération est d'une durée assez brève.

Dans un deuxième temps : (Voir Figure 8)

Afin que l'eau boueuse ne se décante pas dans le culot, cette opération s'enchaine rapidement à la précédente.

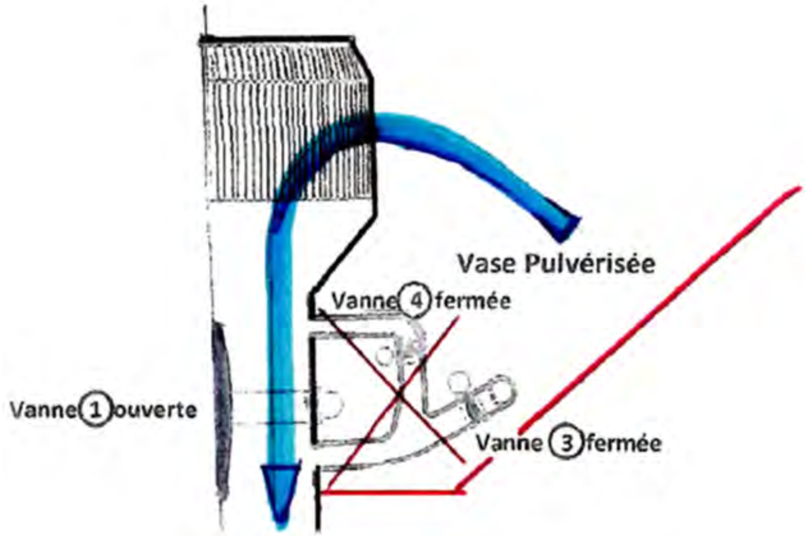

Fig. 8
« Chasse » en phase 2

Elle consiste à créer un effet de chasse en réouvrant la vanne immergée N°1, et en isolant le compartiment de l'anneau crépiné par la fermeture de la vanne immergée N°3.

C'est l'ouverture de la vanne de vidange, située au pied aval du barrage, (généralement du type « Jet Creux ») qui effectivement le déclenche.

Les chasses rejetées dans le thalweg à l'aval du barrage, fortement consommatrices d'eau, sont limitées en nombre.

Le nettoyage autour de la prise se poursuit avec des cycles équilibrés de Jetting-Rinçage, réduits en volume transféré et en récupérant l'eau filtrée de rinçage.

Ainsi est favorisé un usage réversible plus intensif de l'anneau crépiné (même positionnement des vannages que celui de la Figure 7), avec l'adjonction d'une réserve équipée d'un pompage-réversible.

C'est un fonctionnement en STEP. L'ensemble des Installations est représenté sur la Figure N° 9 suivante.

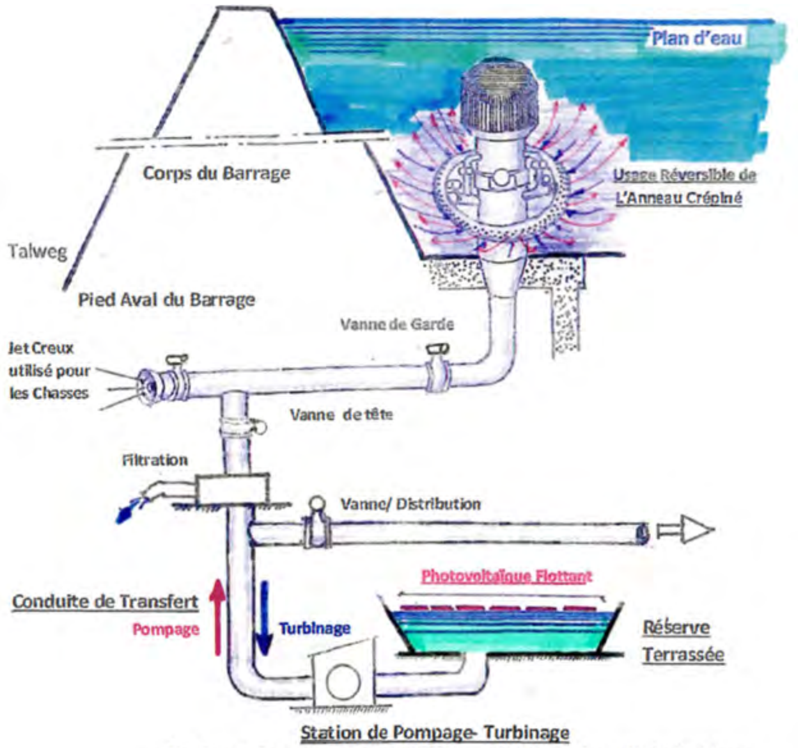

Fig. 9
Curage optimisé en STEP

Contrairement aux systèmes de chasse, ce procédé de curage du fond du barrage utilise une très faible quantité d'eau de rinçage pour la filtration. Le volume journalier d'eau pompée correspond à celui de l'eau de rinçage. Le débit admissible à travers le tuyau torique crépiné, calculé pour une vitesse d'eau de 1,6 m/s, et réparti sur la durée maximale d'ensoleillement journalier, détermine le volume optimal de la réserve basse à construire. Cette réserve est équipée d'une centrale photovoltaïque installée sur le plan d'eau, qui alimente le pompage. L'eau de rinçage, quant à elle, est turbinée au remplissage de cette réserve.

L'alternance entre le pompage solaire et le turbinage entre les deux réservoirs en dénivelé forme ainsi une véritable Station de Transfert d'Énergie par Pompage (STEP). Sur une année, ce système permet en moyenne d'effectuer 14 % du pompage ou jetting et 10 % du turbinage ou rinçage. Ce curage présente de nombreux avantages : il peut se dérouler sur plusieurs heures, avec un débit d'eau adapté aux caractéristiques de l'anneau crépiné, et génère même un revenu grâce à la vente d'électricité produite lors du turbinage. L'efficacité de ce système de curage surpasse donc largement celle des méthodes classiques.

Pour réduire l'investissement de la Station de Pompage-Turbinage, j'ai appliqué ma conception brevetée (référencée page 11). Traditionnellement, les équipements de pompage (pompes centrifuges, mono-roue, multicellulaires) diffèrent de ceux utilisés pour le turbinage (turbines Kaplan, Pelton, Francis), rendant les coûts de turbinage plus élevés. Mes brevets reposent sur une réversibilité complète des systèmes hydrauliques et électriques. En utilisant des pompes centrifuges à vitesse variable, qui, en inversant le sens de l'eau, se transforment en turbines efficaces également à vitesse variable, nous optimisons la performance. Le moteur asynchrone, qui entraîne la pompe, fonctionne en générateur lorsque celle-ci agit en turbine inversée. J'ai simplifié le circuit hydraulique et optimisé le traitement des régimes transitoires, réduisant considérablement les éléments hydromécaniques et les structures en béton armé nécessaires pour le génie civil. Grâce à cette approche, mes brevets permettent de diminuer d'au moins 30 % les coûts d'investissement selon la puissance installée, rendant ainsi le fonctionnement de la STEP avec auto-curage totalement optimisé.

2/ La fonction Purificatrice

Le lessivage des sols, l'utilisation intensive d'engrais et le rejet d'eaux usées insuffisamment traitées provoquent une eutrophisation des plans d'eau et la prolifération estivale de cyanobactéries. L'apport de phosphore en particulier stimule la croissance de la biomasse algale. Avec des périodes de chaleur prolongée, notamment entre le printemps et l'automne, le différentiel de température entre la surface et le fond des plans d'eau s'accentue, favorisant la biodégradation en profondeur.

Ce processus entraîne une réduction de l'oxygène dissous, ainsi qu'un relargage dans les sédiments de fer et de manganèse ; ce qui dégrade la qualité de l'eau, en particulier pour les barrages destinés à la production d'eau potable. La mise en place de traitements conséquents devient alors indispensable.

Actuellement, on utilise des systèmes d'aération, comme l'introduction d'air comprimé en profondeur. Cependant, ces installations sont coûteuses à construire et à maintenir : elles nécessitent de vastes réseaux de canalisations perforées ou des aérateurs hypolimniques ancrés en profondeur. De plus, ces procédés sont énergivores et peu efficaces : la faible teneur en oxygène de l'air (20 %, le reste étant principalement de l'azote) limite son impact, tandis que l'azote favorise le développement algal. Pour enrayer ce cycle d'eutrophisation et de dégradation, il est essentiel de maintenir une concentration stable d'oxygène dissous de 5 mg/L en tous points du plan d'eau. L'injection contrôlée d'oxygène pur est donc la solution la plus adaptée, bien que sa mise en œuvre semblât autrefois difficilement réalisable en raison des coûts de production et de diffusion.

Depuis 2018, je me suis consacré à développer une solution plus performante. En collaboration avec le groupe NGE, nous avons abouti à un procédé breveté en 2021 (brevet n° 21/05585) intitulé Amélioration de la Qualité de l'Eau et Production d'Hydrogène. Cette innovation utilise l'électrolyse pour générer sur place de l'oxygène (O2) et de l'ozone (O3) issu de ce dernier pour traiter l'eau. En parallèle, l'hydrogène (H2) produit est valorisé pour le stockage d'énergie ou la mobilité. Cette triple production d'O2, O3 et H2 sur les réseaux d'eau, avec une utilisation intrinsèque d'O2-O3, est rentable dans un temps de retour court inférieur ou égal à 5 ans. Si l'injection d'O2 et/ou d'O3 est assez facile à faire sur les conduites d'eau, il n'en est pas de même sur les barrages, vis-à-vis de la disparité d'introduction. Cette difficulté est surmontée en différentiant leur injection par :

- Un Robot Subaquatique Automatisé (acronyme RSA) agissant sur le plan d'eau,
- La spécialisation de la Prise d'eau, dénommée Prise d'Eau Purificatrice (acronyme PEP).

Cette « PEP » représentée sur la Figure 10 est en fait le perfectionnement de la prise de curage en STEP vue précédemment, avec l'O2 injecté sur l'anneau crépiné, l'O3 sur la conduite de distribution et à part la valorisation de l'H2.

Les fonctions d'Auto-Curage en STEP et de purification par électrolyse de l'eau se distinguent par leur remarquable synergie. Les mouvements d'eau décrits dans la Figure 9, en dehors des périodes d'exploitation, contribuent à une aération naturelle du fond autour de la prise. La conception de la prise, avec son anneau crépiné compartimenté, offre une solution multifonctionnelle et économique pour le curage et l'injection d'oxygène (O_2). Lors de l'exploitation, la recharge progressive en O_2 ceinture la prise au fond, créant une colonne d'eau de qualité autour de ce point de prélèvement essentiel. L'ozonation parachève la purification de l'eau brute et constitue un pré-traitement efficace pour l'eau potable. L'ozone (O_3), puissant désinfectant et biocide, est généralement produit à partir de l'oxygène contenu dans l'air. Ici, il est fabriqué à la demande directement à partir de l'O_2 généré par électrolyse, réduisant ainsi la consommation énergétique et doublant sa production. L'hydrogène (H_2) généré parallèlement trouve une rentabilité sur place en servant de moyen de stockage énergétique pour produire de l'électricité via une pile à combustible, tout en permettant un ravitaillement pour la mobilité locale. Pour alimenter le pompage d'eau de nettoyage, l'électrolyse O_2-H_2 et la production d'ozone O3, la principale source d'énergie verte privilégiée est le photovoltaïque flottant installé sur la réserve basse aménagée, complétée par le turbinage de l'eau de rinçage. Ce système énergétique est prévu pour être autonome en électricité et même positif en énergie grâce à la vente de l'électricité et de l'hydrogène produits.

En somme, cet ensemble *“STEP et Électrolyse de l’eau sur Prise de barrage”*, qui pourrait sembler complexe au premier abord, révèle une cohérence de fonctionnement impressionnante face aux défis climatiques actuels. Cette conception repose sur des principes d’efficacité, de durabilité et d’intégration énergétique, répondant ainsi aux problématiques environnementales de manière proactive.

En optimisant la gestion de l’eau, ce système contribue à maintenir la qualité des ressources aquatiques et à prévenir l’eutrophisation, réduisant la prolifération des cyanobactéries.

De plus, l’autonomie énergétique offerte par le photovoltaïque flottant, l’hydroélectricité et la production d’hydrogène permet non seulement de réduire l’empreinte écologique de l’installation, mais également de générer des revenus additionnels, rendant le système économiquement viable et écologiquement responsable.

Par cette approche innovante et intégrée, le projet se positionne en modèle de gestion durable des infrastructures hydrauliques, offrant des solutions robustes aux défis climatiques futurs. Il témoigne de l’importance d’une vision holistique dans le domaine hydraulique, où la synergie entre purification, production d’électricité, d’hydrogène et stockage d’énergie permet de maximiser l’impact environnemental positif.

Avec ce procédé, nous disposons d’un levier puissant pour contribuer à la préservation des ressources en eau et soutenir les transitions écologiques et énergétiques de demain.

COMMISSION INTERNATIONALE DES
GRANDS BARRAGES

VINGT-HUITIEME CONGRES DES
GRANDS BARRAGES
CHENGDU, MAI 2025

NESSIE®: AN INNOVATIVE SOLUTION FOR SUSTAINABLE SEDIMENT MANAGEMENT IN RESERVOIRS (*)

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FRANCE

SUMMARY

This report chronicles the development of the NESSIE robot, led by Raphaël Gaillard and Stéphane Caffo, representing Watertracks and EDF respectively, within the framework of the innovation partnership initiated between the two companies in 2018.

The creation of NESSIE addresses a clearly identified need: to provide complementary means to traditional dredging vessels to meet regulatory requirements for sediment management, without compromising storage opportunity or the management of water resources in reservoirs, particularly for hydroelectric production.

This article outlines the key stages in the development of this innovative solution. It will begin by reviewing the sedimentation issue and the identification of the need, followed by a description of the developed solution and its application through two typical examples. It will then remind the innovation process, concluding with the prospects offered by this technological advancement.

**NESSIE®: une solution innovante pour la gestion durable de la sédimentation dans les réservoirs*

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RÉSUMÉ

Ce rapport présente le développement du robot NESSIE, mené par Raphaël Gaillard et Stéphane Caffo, représentant respectivement Watertracks et EDF, dans le cadre du partenariat d'innovation initié entre les deux entreprises en 2018.

La création de NESSIE répond à un besoin clairement identifié : fournir des moyens complémentaires aux navires de dragage traditionnels pour répondre aux exigences réglementaires en matière de gestion des sédiments, sans compromettre les possibilités de stockage ou la gestion des ressources en eau dans les retenues, notamment pour la production hydroélectrique.

Ce rapport expose les étapes clés du développement de cette solution innovante. Il commence par un rappel de la problématique de la sédimentation et de l'identification du besoin, suivi d'une description de la solution développée et de son application à travers deux exemples typiques. Il rappelle le processus d'innovation et conclura sur les perspectives offertes par cette avancée technologique.

1. IDENTIFYING THE NEED

1.1. The challenge of sedimentation in reservoirs

Sedimentation in reservoirs is a pervasive issue affecting water storage facilities worldwide. Over time, rivers and streams transport sediments—comprising silt, sand, and organic matter—that accumulate in reservoirs. This accumulation reduces water storage capacity, impairs dam functionality, and can lead to operational challenges.

Globally, this buildup results in an annual loss of approximately 45 billion cubic meters of reservoir capacity, affecting water availability and shortening the lifespan of dam infrastructure. In regions with high sediment influx, such as mountainous areas, reservoirs can rapidly fill with deposits, obstructing water intakes and leading to costly maintenance.

1.2. Review of existing sediment management strategies

To manage sediment accumulation in dams, operators periodically perform flushing or dredging operations, depending on the specific scheme. Dredging of fine sediments typically involves pumping and diluting the material before discharging it downstream. While this method aligns with sediment continuity criteria mandated by water agency regulations, it is associated with significant costs and operational challenges.

Key issues include:

- **Water Loss:** The process consumes substantial amounts of water for dilution, which is then released downstream, leading to resource wastage.
- **Reservoir Constraints:** Maintaining stable water levels to accommodate floating dredging vessels can limit reservoir operations, affecting energy production and storage capabilities.
- **Operational Losses:** The inability to optimize production during dredging activities can result in operational inefficiencies.
- **High Costs:** The expenses associated with dredging operations can be considerable, and in some cases, the operational losses may surpass the direct costs of the dredging work.

Additionally, the technical complexity of dredging and its potential impact on reservoir operations necessitate careful planning and execution to minimize disruptions and maintain efficiency.

To maintain sediment levels in dams, operators carry out periodic flushing or dredging operations, according to scheme type. The dredging of fine sediment is mostly done using a pumping and diluting technique discharged downstream. This technique has the advantage of meeting the criteria of sediment continuity required by Water agency regulations, but it is very costly. It also causes considerable operational losses: loss of the water used to dilute the sediment (suspended matter or wash load) downstream from the dam, constraints on the reservoir, inability to optimise production. The cost of dredging can be high (worksite) and, in certain cases, operational losses are greater than this cost. Dredging is complex from a technical point of view and can have a significant impact on the reservoir operator since floating dredging vessels may need a stabilized water level to fulfil with their dimensions and that constraint can drive to losses in energy placement or storage opportunity.

Traditional sediment management methods, like flushing and dredging, are expensive and can disrupt local ecosystems, underscoring the need for sustainable and continuous sediment management technologies in the hydropower industry.

1.3. Benefits of maintaining sediment continuity beyond the dam

Removing sediments from watercourses involves several energy-intensive processes, including excavation, dewatering, and transportation. These activities contribute to increased carbon emissions and resource consumption. Additionally, they can disrupt aquatic ecosystems, leading to habitat loss and biodiversity decline. Additionally, stringent regulations govern sediment removal processes, necessitating substantial administrative efforts, comprehensive feasibility studies, and strict compliance measures to mitigate environmental impacts.

Whereas ensuring sediment continuity downstream of dams offers significant environmental benefits:

- **Habitat Preservation:** Continuous sediment flow maintains riverbed structures essential for aquatic habitats, supporting diverse species and ecological balance.
- **Nutrient Distribution:** Sediments transport nutrients vital for downstream ecosystems, enhancing soil fertility and promoting vegetation growth.
- **Erosion Control:** Sustained sediment supply prevents excessive erosion of riverbanks and coastal areas, safeguarding landscapes and human settlements.

1.4. Specifications of the desired technology

The diverse conditions and constraints associated with sediment management necessitate the development of highly adaptable solutions. Such flexibility ensures that a single approach can be effectively applied across various structures, including dams, rivers, and channels. This adaptability not only streamlines operations but also enhances the efficiency and sustainability of sediment management practices across different environments.

To effectively address the challenges of sediment management in reservoirs, the desired technology should encompass the following specifications:

- **Versatile Sediment Handling:** Capable of pump-dilution dredging for a wide range of sediment particle sizes, from fine to coarse, including highly consolidated materials and various debris types.
- **Integrated Operational Control:** Seamlessly linked to the operation of electric production units, enabling adjustable dredging activities based on wash load concentrations and available dilution flows.
- **Deep-Water Functionality:** Designed to operate efficiently at depths exceeding 100 meters, accommodating significant fluctuations in water levels without compromising performance.
- **Lightweight and Manoeuvrability:** Engineered for easy handling using lightweight equipment, facilitating deployment and retrieval in diverse operational settings.
- **Energy Efficiency:** Optimized for low energy consumption, ensuring sustainable operation and minimizing the environmental footprint.

By meeting these criteria, the technology will provide a comprehensive and adaptable solution for sediment management, enhancing the efficiency and sustainability of reservoir operations.

2. SOLUTION DESCRIPTION

NESSIE was conceived as a swimming pool robot, scaled to operate within the dimensions of the pool it services.

What does NESSIE, the underwater dredging robot?

NESSIE ® stands for**: N**ew **E**nvironmental **S**ystem for **S**ediment **I**nnovative **E**vacuation. She is the very first ever made underwater low impact dredging robot.

She has been designed to dredge fine sediment and dilute them in a controlled and measurable way for downstream release without any water waste of hydro-power production loss.

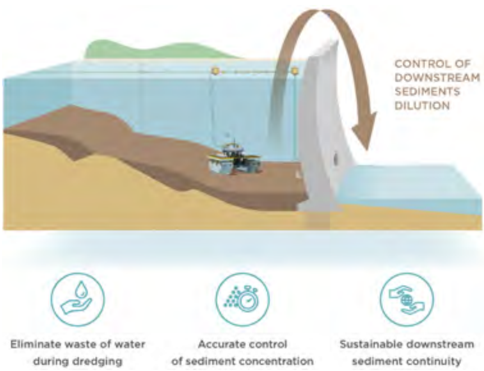

Fig. 1
NESSIE working principle

As NESSIE can work at any depth, she does not impose any constraint on the water level of the reservoir.

Therefore, periodic dredging can be envisaged with NESSIE: A new way of tackling lake sedimentation and its negative side effects.

- She helps to erase the dams' impact on sediment continuity while respecting downstream dilutions.
- Energy production during dredging is NOT affected at all.

2.1. NESSIE specifications

NESSIE is an underwater dredger that crawls over the sediment at the bottom of the reservoir using two caterpillars equipped with ballasts.

NESSIE is equipped with an automation system which allows to follow a dredging plan and to regulate its production in terms of flow and dry matter concentration according to programmed instructions.

NESSIE performs dredging by dilution pumping:

- She dredges the sediments and mix them with water: 10 to 25% dry material into water, and
- She pumps the mixture in a pipe to the discharge point, which can be a river, or the dam's turbines, or any other place up to 1 km or more if needed.

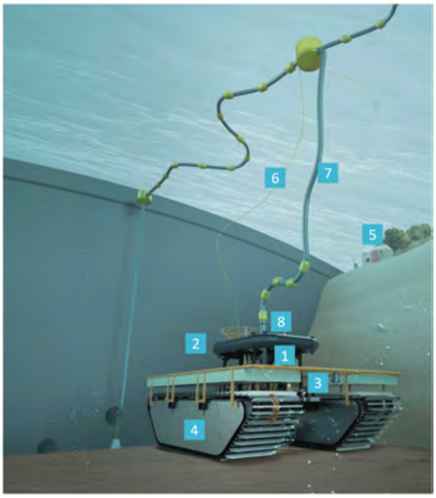

Fig. 2
NESSIE technical features

1. *130KW dredging pump,*
2. *Adjustable buoyancy for diving and ascent,*
3. *Obstacle detection sonar,*
4. *Ballast tracks, to adjust the weight and grip according to the nature of the silt*
5. *Remote control station,*
6. *Power and data cable,*
7. *Dredging pipe,*
8. *Dredge flow and density sensors.*

- NESSIE dimensions are 5.5 x 6.5 metres and 4.10 meters high.
- Her weight in air is about 17 metric tons and can be regulated between +4 and -1 tons in water.

NESSIE main performances:

- Working depth: 1.5 to 300m,
- Dredging pump output: up to 1200m^3/h
- Control and monitoring from distance, without operator on water,
- Working on demand 24/7,
- Positioning accuracy $<$10cm,
- Electrical power needed: 440kw,
- Low impact: discreet, silent and clean.

NESSIE's dredging pump has a dredging head, or cutter, located in the centre of the machine between the tracks.

The dredging device is fitted on an elevator assembly that allows to dive the dredging tools lower than the caterpillars' bottom.

Fig. 3
Cutter positioning system

Several types of dredging tools can be adapted to the robot to comply with different material and environments:

- **Double rotary cutter**

Each cutter rotates opposite to the other: this avoids generating a heading drift and maintains the same efficiency in forward or backward movements.

Fig. 4
Double rotary cutter

- **"Pac-Man" dredging-head designed by WATERTRACKS**

The "Pac-man" head is a Watertracks innovation, specially developed for sediments that may contain any type of log jam made by trees, leaves stones or other kind of rubbishes. This specific cutter avoids any clogging of the dredging process by reducing small debris to make them pumpable, or by avoiding bigger rubble to enter in the suction nozzle.

Fig. 5
Watertracks' Pac-Man Dredging head

3. QUALIFICATION : INDUSTRIAL DEMONSTRATOR IN LE SAUTET DAM

In the fall of 2020, NESSIE was qualified during an industrial demonstrator on the EDF's LE SAUTET lake near Grenoble – France.

During the qualification, NESSIE was controlled from the lake bank and from Watertracks' office in Marseille.

This chapter details NESSIE operational qualification by EDF, and therefore, NESSIE dredging operations process that could be implemented for any dam worldwide.

"LE BARRAGE DU SAUTET", located in the French Alps, is a curve gravity concrete dam of 128m height that was built on "Le Drac" River in 1930. Its water capacity of 108.00 hm^3 is quite reduced because of tens of meters of sediment piled up in its bottom.

As for any dredging work, some weeks before the start of the dredging operations and after a site survey, EDF and WATERTRACKS agreed on the dredging strategy based on recent bathymetry and the last dredging experiences in the same lake.

EDF qualification process for NESSIE included the following 8 steps:

- **Step 1: NESSIE ease to be transported and assembled one site**

WATERTRACKS organised the transport of equipment to site with standard trucks, performed the site installation and prepared NESSIE for operations.

Fig. 6
Site access and installation view

Two standard trucks are needed to transport NESSIE on site.

Fig. 7
Two trucks to transport NESSIE

It takes three hours to mechanically assemble the robot on site.


Fig. 8
NESSIE assembly in progress

The surface required for the assembly of NESSIE is 100m2. She can be ready for work within two days on site.

- **Step 2: NESSIE ability to be towed to dredging area and back to maintenance area,**

NESSIE crawls autonomously into the water. She floats in 4m depth. Then, she can be towed by a small boat to reach the dredging area.


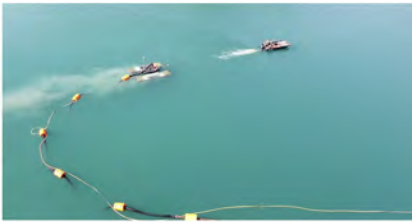

Fig. 9
NESSIE crawling down in the water and then towed while floating

- **Step 3: NESSIE ability to self-dive and self-ascent in the water column,**

NESSIE uses its ballasting system to float dive and surface in the water column. Before diving, it is necessary to locate a clear landing zone to avoid, for example, a landing on a tree.

NESSIE reached a depth of 54 meters in a minute and a half, which makes a descent speed of 0.6m / s. She surfaces at the same speed.

She qualified she was able to smoothly dive vertically 60m depth and then ascent back to the surface only using its own ballasts.

Fig. 10
What is seen from the surface when NESSIE dives

- **Step 4: NESSIE dredging sensors qualification,**

The main sensors used for dredging production measurement are flow and density meter. Two sensors have been marinized by Watertracks to be fitted on the robot as close as possible to the outlet of the pump. The combination of flow meter and density of slurry, with the application of a conversion law gives the instant production of dredged dry material.

To qualify the embedded sensors on NESSIE, two calibrated reference sensors were fitted on the dredging pipe 450m after the outlet of the pump in a measurement container placed on the shore of the lake.

Additionally, several series of dredging pulp samples were taken to be analysed in the laboratory in order to verify all the measurements.

Recorded measure data of the embedded sensors on NESSIE and reference sensors in the container were compared with a time offset corresponding to the length of dredging pipe between the measure points. This comparison is illustrated by the following curves that show a very good match.

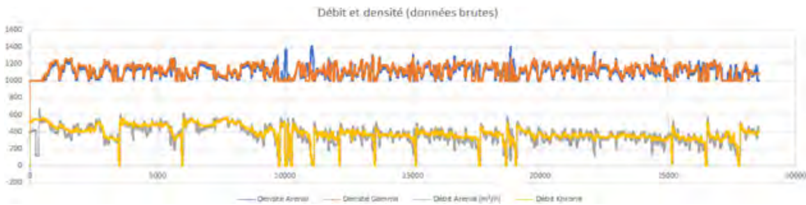

Fig. 11
Production measures comparison curves

- **Step 5: NESSIE underwater positioning system validation,**

NESSIE underwater positioning in a reservoir requires the combination of three different systems that are redundant.

- º The robot is equipped with an inertial fibre optic heading unit which guarantees a very high-quality heading and gives roll and pitch of the machine. It also measures its ground speed.
- º Using both heading and speed, NESSIE location is computed with an accuracy compliant with dredging operations.
- º From surface to 7 meter-depth, NESSIE positioning is done using a D-GPS sensor on a mast allowing one centimeter positioning accuracy.
- º Beyond 7 meter-depth, NESSIE positioning is done with an hydride system done from D-GPS buoy and acoustic triangulation system underwater. This system can give the position of the machine at 10 cm in a silent environment. In the “noisy” underwater working environment it happens that acoustic localization is lost from time to time. In this case, NESSIE monitors her movement using estimation and may input correction in its trajectory when a new point is clear again.

The results of the production at the end of the demonstration shows that NESSIE was precisely located whatever the water depth during the qualification process.

- **Step 6: NESSIE production composed of two different phases,**

After some preliminary tests of diving, crawling, dredging, measurements and settings, two areas have been defined to carry out production tests.

- **First phase of dredging: high production**

The objective of this first phase was to produce in large quantities. It was therefore necessary to dredge 10,000m^3 of sediment in five days for 24 hours a day, that is to say without stopping the machine. The area is a rectangle of approximately 40m by 100m, reaching 10,000m^3, which represents a dredge depth of approximately 3m in the centre, due slope effect on the sides.

This first phase lasted a day longer than expected due to a little failure that was repaired on site.

According to NESSIE sensors, 9 500 tons or approximately 9,500m^3 of dry material were extracted. Over five full days, or 120 hours, an average of 80 tons of dry matter per hour. NESSIE is controlled by dredging with a setpoint of 110 tons/hour.

It therefore automatically manages its production by varying its speed of movement by taking an average value over 30 seconds of the measurement.

During this first phase, NESSIE was active 85% of the time.

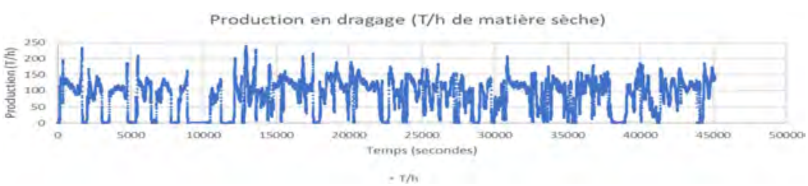

Fig. 12
Example of production records in t/H of dry material

- **Second phase of dredging: shaping the sediment**

The objective of this second phase was to respect a complex dredging shape, defined by EDF, on the bottom of the lake. The requirement was to obtain a prism with 3 / 1 slopes and a defined depth. The planned dredging time was five days, for 16 hours per day.

The desired geometric shape was achieved earlier than expected.

A dredging plan was predefined in advance in order to respect the shape constraint, so production stopped once all the passes and dredging lines were completed.

This second production phase lasted 70h, which gives a total efficiency of 46T / h. The shape constraint added to the small surface area required more manoeuvres than in the first phase to change dredging lines.

As a result of these constraints, during the second phase, NESSIE was active 60% of the time.

- **Step 7: NESSIE bathymetric results post-dredging,**

A bathymetric survey was carried out on December 14th, 2020, by a sub-contractor as a third party. They provided us with bathymetric results and related 3D views. For the initial depth, a 2019 bathymetry provided by EDF was used as reference.

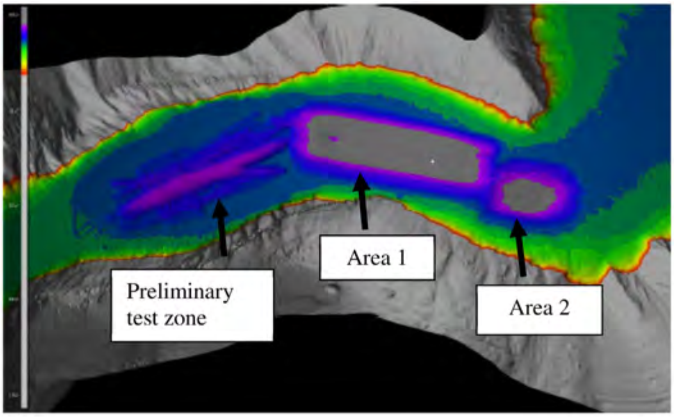

Fig. 13
Bathymetric result in dredging areas

The production areas 1 and 2 are well marked and we find the desired geometric shapes.

The depth of the dredged area varied from 0 to 4.6m.

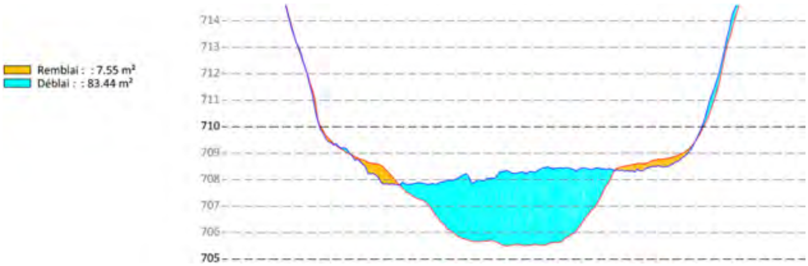

Fig. 14
Profile view of dredging in area 1

The blue part represents the “cut” ie the section removed on this cut. The yellow-orange part represents the “backfill”, that is to say the sediments that have been deposited between the two bathymetries (June 2019 and December 2020). Slopes of 4/1 (14 °) to 3/1 (22 °) have been achieved.

The dredged areas are between 709 and 706 metres, or about 3m of material removed.

According to the cubature report provided by the subcontractor, approximately 14000m^3 of sediments were dredged over an area of approximately 10 000m^2.

- **Step 8: NESSIE emergency surfacing via separate autonomous inflating balloons.**

In case of serious breakdown including total loss of communication with the robot, it is possible to send acoustic signal underwater that generates the two emergency balloons inflation to surface the robot.

The emergency surfacing system, from 54 metre-depth, was qualified at le Sautet lake.

4. RESEARCH AND DEVELOPMENT JOURNEY

To develop NESSIE, the authors and their teams undertook a comprehensive research and development process. This journey began with identifying technological barriers, followed by prototyping and testing various concepts, ultimately culminating in the assembly of a groundbreaking solution.

4.1. Three technological barriers to overcome

When Watertracks presented its proposed solution, three technological barriers were identified:

4.1.1. *Enabling a submarine vehicle to traverse fine sediment without becoming stuck*

At that time, attempts to maneuver underwater vehicles over soft sludge had failed. For instance, the French Research Institute for Exploitation of the Sea (Ifremer), a public institution dedicated to marine science and technology with a focus on sustainable ocean development and protection, experienced an incident where a submarine vehicle became stuck in fine sediments on the ocean floor during their last trial.

4.1.2. *Controlling dredging rate measurements to ensure compliance with dilution guidelines using onboard sensors*

To synchronize the dredging vehicle with the production rate, it was necessary to install sensors on the dredging pipe as close to the pump as possible. This proximity was essential to avoid delays caused by the distance between the pump and the sensor. Consequently, it was necessary to equip the underwater crawling vehicle with these sensors. At that time, no physical sensors for flow and density measurement in a pipe had been marinized.

4.1.3. *Preventing dredging head blockage by obstacles*

The sediment floor at the bottom of reservoirs is often littered with various obstacles, including organic materials like leaves, branches, or wooden logs; minerals like stones; or miscellaneous debris. An autonomous underwater dredging vehicle would be impractical if it had to surface frequently due to suction head clogs. Watertracks committed to developing a specialized cutting suction head designed to avoid or reduce encounters with subaquatic obstacles, thereby preventing blockages in the pumping system.

4.2. Try and fail process

To address these challenges, three subsystems were prototyped and tested in real-world environments. Each module was built separately, tested, and improved through a trial-and-error innovation process. Once all subsystems were de-risked, they were assembled to produce the first prototype of NESSIE. All activities were conducted at Watertracks‘ premises in the South of France and tested on actual EDF dam sites.

Each of these modules were built separately, before being assembled to produce the first prototype of NESSIE. All the activities were carried out on the Watertracks premises in the South of France and tested on actual EDF dam sites.

The development timeline includes:

- **2016:** EDF issued a European tender for the study and design of an automatic dredging robot.

- **2017:** Three competitive projects conducted feasibility studies on two pilot sites.
- **2018:** EDF entered an innovation partnership with Watertracks to develop the NESSIE Solution.
- **2019:** The Nessie Robot prototype underwent testing on EDF dams.
- **2020:** The first industrial demonstration of Nessie was performed.
- **2021:** Commercialization of the solution commenced.

4.3. Breakthrough solution

This innovation process resulted in a robotic solution that led to the filing of two patents, attesting to its innovative nature. We consider it a breakthrough solution.

The R&D journey is reported in more details in reference 9].

5. INDUSTRIAL DEVELOPMENT

In conclusion, it is essential to highlight the broader implications of the NESSIE robot's innovation by illustrating its applications, the subsequent development of related robotic technologies, and the potential impact of these advancements on global sediment management practices in reservoir maintenance.

Applications of NESSIE examples:

- **Alisgiani Reservoir, Corsica:** NESSIE was utilized to manage sediment accumulation, ensuring optimal water storage capacity and maintaining the ecological balance of the reservoir.
- **Plan d'Aval Dam:** The robot performed dredging operations, facilitating the dilution of sediments through turbine systems, thereby enhancing the efficiency of hydroelectric power generation.

5.1. Other robots issued from NESSIE

Building upon the success of NESSIE, further innovations have led to the development of specialized robots tailored to specific sediment management needs:

- **LISIE:** A compact robot designed for precise dredging operations near dam structures and security installations, ensuring minimal disruption to critical infrastructure.

- **SUPER NESSIE:** A larger-scale NESSIE robot engineered to handle substantial sediment volumes, suitable for extensive dredging projects in large reservoirs.

5.2. Perspectives

The advancements in robotic sediment management technologies present significant opportunities for reservoir maintenance worldwide.

- **Diversification in France:** Organizations such as EDF Hydro, CNPE, CNR, and OEHC are exploring the integration of these new robotic solutions to enhance their sediment management strategies.
- **International Expansion:** Initial efforts are underway to introduce these technologies in Switzerland, with plans to extend their application to other countries facing similar sedimentation challenges.

6. CONCLUSION

The NESSIE robot represents a significant advancement in sediment management for hydroelectric reservoirs. Designed to operate at varying depths, it enables precise dredging of sediments without disrupting reservoir water levels, thereby minimizing constraints on energy production. Its ability to maintain downstream sediment continuity while minimizing environmental impact meets current regulatory requirements. The partnership between EDF and Watertracks, led by authors Raphaël Gaillard and Stéphane Caffo and initiated in 2017, has overcome major technological challenges, resulting in an innovative patented solution. Successful industrial demonstrations, notably at Le Sautet dam, and commercial operations since 2021 attest to NESSIE‘s operational effectiveness. NESSIE has initiated a panel of subaquatic dredging robots, including LISIE and SUPER NESSIE, with more developments anticipated. These innovations pave the way for sustainable sediment management, harmonizing industrial performance with environmental stewardship.

REFERENCES

[1] ANNANDALE, G. W. (2013). *Quenching the Thirst: Sustainable Water Supply and Climate Change*. North Charleston, SC: CreateSpace Independent Publishing Platform. ISBN 1480265152.

[2] International Hydropower Association (IHA). (n.d.). *Switzerland - Solis*. Retrieved from https://www.hydropower.org/sediment-management-case-studies/switzerland-solis

[3] KARMACHARYA, S. K. (2019, June). Physical modelling of pressurized flushing of non-cohesive sediment using lightweight material. *Journal of Physics: Conference Series*.

[4] AELBRECHT, D. (2022). Climate change at the heart of 27th ICOLD Congress in Marseille – May 28 / June 3, 2022. *27th ICOLD World Congress - France*. Retrieved from https://cigb-icold2022.fr/en/

[5] RIGAUD, V. (2003). *Les robots dans les milieux extrêmes : l'émergence des robots sous-marins*.

[6] Ifremer. (2017). *De nouveaux robots autonomes pour mieux observer l'océan*.

[7] Futura Sciences. (2015). *Un nouveau robot pour l'exploration des grands fonds marins*.

[8] Mer et Marine. (2017). *Ifremer : Un nouveau drone ultra-profond pour la cartographie et l'inspection*.

[9] STEPHANE CAFFO, RAPHAEL GAILLARD AND FREDERIC GAUCH; 2019; Hydro 2019 (Porto); Development of an innovative ecological and economical dredging robot solution (NESSIE® solution).