COMMISSION INTERNATIONALE
DES GRANDS BARRAGES

VINGT-SIXIÈME CONGRÈS DES
GRANDS BARRAGES
Autriche, juillet 2018

TWO YEAR OF PERFORMANCE OF A PENSTOCK ANCHORED BY PU-FOAM

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1. INTRODUCTION

Due to a high number of new small hydro projects (SHP) in the last decade many cost-reducing innovations have been developed [1]. Still, the conduit system remains the most costly item in the SHP, representing 40 – 60% of the total investment cost. In the same period, electricity prices in Europe have dropped and further cost-saving innovations must be made to maintain SHP as one of the alternatives for feasible new renewable energy.

Today, the construction of buried penstocks is based on the principle of gravel/crushed rock as backfill, and anchoring of bends with concrete thrust blocks. With SHPs often located in remote areas without pre-existing connection to the main road network, the transportation of materials for penstock construction has to be carried out by constructing new access roads or by helicopter, which is both time consuming and costly.

Penstock BV (now HydroFoamer Ltd) invented a method using polyurethane foam (PU-foam) as a replacement for gravel and rockfill. The PU-foam concept was presented internationally in 2017 in [2] after the commissioning of the first full scale penstock constructed using this concept. The project at Lille Måsevann was a development project; a brief program to study and follow up the quality and performance of the penstock was implemented. This paper describes the performance of the penstock in two full seasons of pumping. Since completion in November 2016 the penstock has performed perfectly well without any indication of unexpected behaviour.

2. THE PU-FOAM CONCEPT

The main motivation of the concept is to lower cost of buried penstocks with the same safety or better. Applied at straight sections of the penstock, the main purposes of the foam are:

- To provide mechanical protection of the pipe, against sharp edged gravel and stones
- To allow more native soil material to be used as backfill, reducing the amount of transported or locally-crushed gravel/aggregate and reducing the need to dispose of unused excavated material
- To increase the periphery towards the native soil material (normally not a critical condition)

In bend application, the function is different; the PU-foam act as a structure exposed to tensile stress and absorbs the hydraulic forces from the bend. In addition, the effect s of adjacent 'straights sections' are still taken into consideration as part of the bend system. This lower the costs of bends by eliminating the demand for expensive on site constructed concrete blocks.

Fig. 1
PU-foam used as backfill

3. PU-FOAM

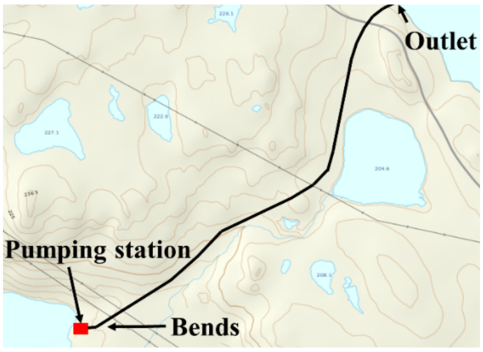
The quality and the performance of rigid closed-cell PU-foam for outdoor use is briefly described in [2]. The foam typically expands up to 30 times, and is 70 % cured 10 minutes after the initial reaction, although the reaction profile can be controlled by manipulation of pressure and heat. In order for the foam to expand, a blowing-agent is needed. The most commonly used blowing-agent is water – an eco-friendly blowing-agent where no harmful gasses are released into the atmosphere.

Rigid closed-cell PU-foam is normally divided into two categories; 'pour foam' and 'spray foam'. The main difference between the types is the proportion of mixing between the components and the way they are applied to the object. For experimental purposes and to optimize the total concept of anchoring of penstocks by PU-foam both methods have been fully tested in lab and in the field. Both the behavior of the foam and the procedure for application is very different and requires two very different set of equipment and set-up of the working teams. The experience from both quality and speed of construction will be discussed in later parts of the article.

No prior findings indicate that the foam, after curing, has a negative effect on the environment [4]. Cured foam is considered 'inert' and does not react easily with other substances in any natural environment. During application of the foam, health and safety measures need to be met. This certificate information has not been possible to verify during the rather short available lifetime of this specific penstock.

4. THE PENSTOCK AT LILLE MÅSEVANN

The penstock at Lille Måsevann is the first of its kind that uses PU-foam as backfill at parts of the penstock. Lille Måsevann is a pumping station for lifting water with maximum discharge 1,4 m^3/s from Lille Måsevann reservoir up to Store Måsevann reservoir. The water is further used in the 50 MW Adamselv hydropower project and increases the annual energy output with 7 GWh. Construction took place during the summer and fall of 2016 and were commissioned by a start-up and sudden shut down at the 24. November 2016, see Figure 6. The pumping station conduit consists of an 1130 m long, buried DN800 and 900 GRP pipe. Approximately 1/3 of the total length, including two bends, was covered by foam. A map showing the penstock alignment can be seen in Figure 2a. On the same Figure 2b, the penstock both with and without PU-foam is shown, before application with gravel.



a)

b)

Fig. 2

a) Map of the penstock alignment b) The penstock at Lille Måsevann (from west

Three different methods were used to apply the foam to the penstock; 'Open formwork' (Figure 3a), 'Closed formwork' (Figure 3b) and 'Spray application' (Figure 3c).

Both methods using formwork is developed for 'pour foam' material. The open formwork application gave dry conditions in the formwork and controllable curing conditions see Figure 3. The closed formwork application is a better concept on the way to automatize the construction process but there is still large challenges to overcome about the quality, see Figure 3. The direct spray application is a manual based process with limited speed of construction but with very good conditions to control the curing and the quality of the foam.

a) b)

c)

Fig. 3
Different methods for foam application a) Open formwork with roof to protect against rain b) Closed formwork to be placed around the penstock c) Spray-foam is applied to the pipe, two persons are required as work force

As in many development projects the progress and quality were not uniform. The foam produced at the start of the project showed greater property deviation compared to the final product. The method with direct application to the pipe provides for the best progress and predictability in the project. Besides, research by [3] indicate that spray-foam end up with better mechanical properties and density than pour-foam.

5. ANCHORING OF BENDS

The penstock at Lille Måsevann includes two 15° bends which were constructed without any concrete or rock bolt measures. Static head acting on the bends are 44 mWC. Both bends were anchored using 300 mm of spray-foam with spray application. The bends were anchored to the gravel bed by a combination of the gravity of the penstock system and the resulting ‘’locking’ interaction between the foam and the gravel.

a) b)

Fig. 4
a) Application of foam at the bend b) The bend after removal of the tent

To monitor displacement over time, four displacement transducers were installed at one of the bends, described in [5]. The type of equipment used was WA Inductive displacement transducers with a measuring range of 20 mm. The measuring Is based on the differential inductor principle with an inductive quarter bridge. The system is highly accurate to 0,2% of the measuring length, in this case 0,04 mm. The deformations can be monitored in real-time inside the pumping station. Figure 5 shows which direction the plunger is extended. The axial deformations in the direction is given as decreasing values in the graph Figure 6.

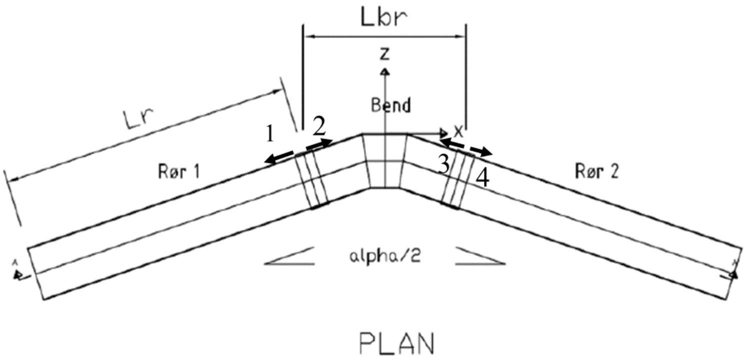


Fig. 5
Placement and measured direction of the displacement transducers

Two full seasons with pumping have been experienced at the time of this presentation. Figure 6 shows measurements conducted 28.04.17, during first filling of the penstock. The displacement transducer’s position is given on the left axis, and water pressure (black line) is given on the right axis.

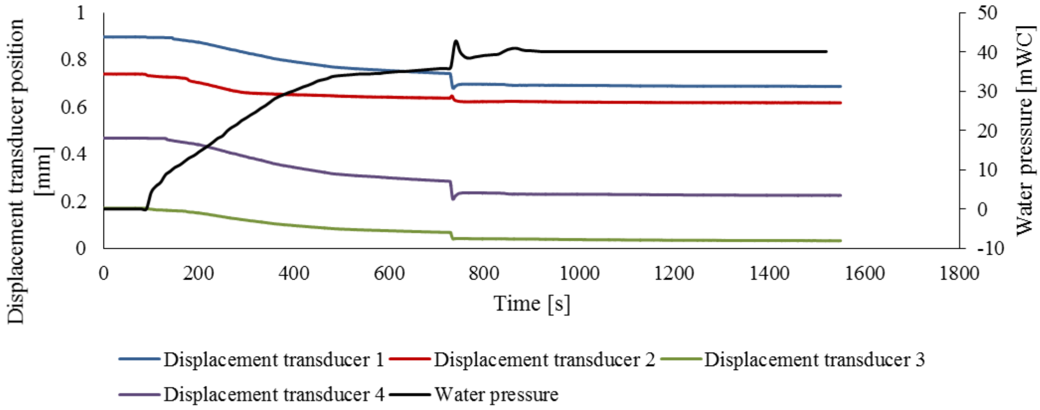
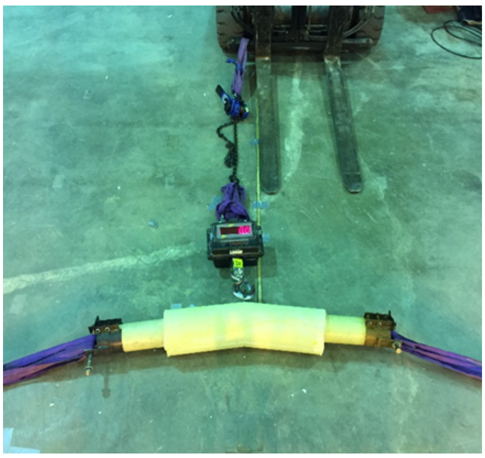


Fig. 6
Deformation measurements at Lille Måsevann, 28.04.17

The results shows that the bend has very small deformation in the pipes axial direction (~0.2 mm). The small deformation can indicate that the forces are distributed as a combination of compression and tension in the foam. The measurements confirm that the foam distributes a fraction of the hydraulic forces as tensile stress in the pipe axial direction. No measurement of foam compression deformation in force resultant direction was carried out.

In addition, deformation and angle deflection in the pipe joints had to be verified within the engineering requirements set by the regulator. Deformation calculation was carried out, stiffness of foam, backfill and in situ soil was taken into account. As a conservative approach for first time use in penstock, tensile restraining capacity was not included. Further, a scale test rig was set up at NTNU the spring of 2016, to investigate the capacity of bends anchored with PU foam. The scale test rig is shown in Figure 7a.



a)

b)

Fig. 7
a) Setup of the bend test rig b) Bend in full scale

The test rig was set up without a bend coupling to ensure that all forces acting on the bend was distributed in the foam. A concentrated load was set up directly in the bend with a metal hook inserted in the pipes to simulate forces from internal pressure in the pipe. Test results indicate that the capacity of the foam increases with larger cross-sections and increased bend angle. For instance, the test with foam thickness of 40 mm at 30° bend had an ultimate bend load of 1 kN corresponding to 19 mWC internal pressure. The idealised distribution of the forces in the foam in the test is not possible to verify exactly by the full-scale monitoring program. In the field distribution of forces in the bend will not only occur in the foam; the surrounding masses, bend coupling and interface layer between the foam and drainage layer will also absorb the forces. This is the main explanation of the large difference in displacement between laboratory and field results; the field displacements are much lower than predicted, according to the conservative calculation model, which is a result of not taking the full set of stabilizing factors into account.

6. VIBRATIONS IN THE PENSTOCK

Vibrations from the rotating runner propagate along the penstock. This was recognized even the first hour of operation in November 2016 for a long distance upstream of the pumping station. Both sound and remarkable vibrations on the frozen ground were recognized. The frequency in the vibration corresponded with the rotational speed of the runner. This could easily be proved, because the unit was operated by the frequency controller on several different rpm's. The runner is an asymmetric 'pump wheel' which introduce significant but predicted vibrations in the unit. The test program in the lab in 2015, 2016 and 2017 didn't include yield tests for the foam and it's not clear how this may will influence the long-term quality of the anchoring. The effect of the foam layer on the pipe is to attenuate the energy propagating from the runner through the water mass, by reducing amplitude and dissipating the energy as heat. The energy absorbed in this dampening effect would otherwise be transmitted from pipe surface to granular backfill in a classic system, with the attendant risk of damage of the pipe surface from sharp stones edges. Absorption of acoustic wave energy in foam is a well-understood phenomenon. The full set of mechanical interactions between pipe, pipe bend and surrounding PU-foam and soil masses are not yet fully understood or modelled, but this is an objective of further research, both in academic and operational settings.

The long term behavior of the foam in frozen soil is still based on the results from the lab tests. Samples may subsequently be extracted from the foam in the field and tested. This will verify the extent to which foam in the field is sensitive to the freeze-thaw processes. How any variations in mechanical properties due to freeze-thaw cycle affect system performance can only be established by pushing comparative samples to failure, which is not possible in the field.

7. CONCLUSIONS FROM OPERATION

At Lille Måsevann 300 m of buried penstock was enveloped in foam, including two bends. The commissioning of Lille Måsevann penstock proves that the method with PU-foam as backfill works on a full-scale project, both for construction and operation.

The PU-foam absorbs water at varying rates, but tests in the frost laboratory indicate very little influence on the strength. Long term deformations in the bends shows no development, while displacements are followed closely by the monitoring program.

PU-foam as backfill and for anchoring of bends is a promising alternative to the traditional method. However, to obtain desired quality and safety, precautions on-site needs to be met. As such a strict quality test program must be followed to verify the statement in a longer term perspective.

ACKNOWLEDGEMENTS

The authors like to acknowledge Nina Johnsen for contribution to this article and ENOVA for financial support to make this project possible.

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SUMMARY

Today the most commonly used backfill for penstocks for small hydro are gravel and rockfill, which is time consuming and costly due to transportation. Penstock BV with Guy Harris developed a method with polyurethane foam as a replacement for gravel and rockfill which may lead to lower investment costs and reduced construction time. NTNU made the required initial laboratory tests in 2015 and Statkraft AS initiated a research project to verify the method in 2016. The project involves the construction of Lille Måsevann Pump with a buried penstock connecting Lille Måsevann to Store Måsevann – the intake reservoir for Adamselv hydropower plant. Lille Måsevann Pump is the first of its kind where sections of the penstock, including two bends, are enveloped in polyurethane foam (PU foam). Previously only scale tests have been carried out.The full-scale project is located in Finnmark County, Norway, and the construction work was done the summer of 2016. By the summer 2018 this DN800/900 mm penstock have experienced two years of operation. Monitoring of elastic and non-elastic displacement of the bends proves the behavior during start/stops and other dynamic load situations. Out of the total length (1130 m) approximately 300 m were anchored by in foam.

The experiences made from both construction and two years of operation at Lille Måsevann Pump has acquired new knowledge to the subject. The behavior of the penstock is without any kind of unexpected observations and the penstock performance is as for other penstocks constructed in traditional ways.

Aujourd'hui, le remblai le plus utilisé pour les conduites forcées des petites centrales hydroélectriques est le gravier et la roche broyée, ce qui prend du temps et coûte cher en raison du transport. Penstock BV avec Guy Harris a développé une méthode qui utilise la mousse de polyuréthane en tant que remplacement du gravier et de la roche broyée, ce qui peut réduire les coûts d'investissement et réduire le temps de construction. NTNU a effectué les premiers tests de laboratoire nécessaires en 2015 et Statkraft AS a initié un projet de recherché de grande envergure pour vérifier la méthode en 2016. Le projet prévoit la construction de la ‘Pompe Lille Måsevann’, avec une conduite enterrée reliant Lille Måsevann au magasin Måsevann - le réservoir d'admission de la centrale hydroélectrique Adamselv. La Pompe Lille Måsevann est la première du genre où des sections de la conduite forcée, y compris deux coudes, sont enveloppées dans la mousse de polyuréthane (PU-foam). Auparavant, seuls les tests d'échelle avaient été réalisés. Le projet de grande envergure est situé dans le comté de Finnmark, en Norvège, et les travaux de construction ont été réalisés à l'été 2016. À l'été 2018, cette vanne DN800 / 900 mm a connu deux années d'exploitation. La surveillance du déplacement élastique et non élastique des coudes prouve le comportement pendant les démarrages / arrêts et autres situations de charge dynamique. Sur la longueur totale (1130 m), environ 300 m ont été ancrés en mousse.

Les expériences de construction et de deux années d'exploitation nous ont permis d'acquérir de nouvelles connaissances sur le sujet. Le comportement de la conduite forcée est sans aucune sorte d'observations inattendues et la

performance de la conduite forcée est comme pour d'autres conduites forcées construites de façon traditionnelle.