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APPLICABILITY OF RISK-BASED MAINTENANCE STRATEGY TO A PENSTOCK

STRATEGIJA ODRŽAVANJA ZASNOVANA NA RIZIKU – PRIMENLJIVOST NA CEVOVOD

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- welded joint
- penstock
- prototype model
- risk based maintenance

Ključne reči
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- zavareni spoj
- cevovod
- model prototipa
- održavanje zasnovano na riziku

Abstract

The risk of brittle fracture of the penstock of the reversible pump turbine is recognized in an early stage of design. To reduce the cost of penstock construction one tunnel is accepted. The HSLA steel of 700 MPa yield stress, 47 mm thick, is selected for the most stressed penstock section. It was necessary to assure structural integrity of welded joints and the penstock structure by involving an appropriate maintenance and repair approach. Maintenance procedures are in continuous development, and the most promising probably is the risk-based approach, developed recently. Basic requirements of this approach are considered in the paper, and the possibility and convenience to apply them for the penstock is evaluated.

Izvod

Rizik od krtog loma cevovoda reverzibilne turbine je ocenjen u ranoj fazi projektovanja. Da bi se smanjili troškovi izgradnje cevovoda prihvaćen je jedan tunel. Zbog toga je za najopterećeniji segment cevovoda izabran HSLA čelik, 700 MPa napona tečenja, debljine 47 mm. Bilo je potrebno i da se osigura integritet zavarenih spojeva i konstrukcije cevovoda uvođenjem odgovarajućeg pristupa za održavanje i opravke. Postupci održavanja se neprekidno razvijaju, a možda su najperspektivniji postupci zasnovani na riziku, razvijeni poslednjih godina. U radu su razmotreni osnovni zahtevi novih pristupa, i ocenjena je mogućnost i pogodnost njihove primene na cevovod.

INTRODUCTION

Hydroelectric power plant (HEPP) systems might require large amounts of water in the reservoir lake and high fluid flow rates for operation. For such a system, the consequences of unexpected failure can be catastrophic, representing a great risk in service. In order to avoid failure, preventive measures need to be applied, /1/.

One of the very important components in HEPP is the penstock which can be exposed to high stresses, and eventually be susceptible to failure. To reduce the risk level, operational safety of individual components in the HEPP system, including penstocks, must be at very high level. This requirement comprises the assurance of high quality of produced components.

Failures of penstocks and pipelines are not very frequent. Mechanical damages observed before and during service, the fatigue, corrosion defects, welding imperfections and environment effects are referred to as the most important causes. Plastic collapse and brittle fracture are not cited often as a failure cause, because applied steels for pipelines are ductile, and pipelines are used in the region above nil-ductility transition temperature.

However, cracks, brittle fracture and leakage were experienced in penstocks produced of weldable high strength low alloy (HSLA) steels, developed and applied to reduce manufacturing costs by a lowered wall thickness, /2/. The proof pressure test is required before acceptance for service, in some cases testing of the model is also necessary.

EXAMPLES OF BRITTLE FRACTURE AND LEAKAGE

Two selected examples of failures /2/ can illustrate the significance of risk analysis. They also have shown the role of welding procedure specification (WPS) for penstock maintenance and in-service risk.

A typical example of fast brittle fracture is catastrophic failure of the penstock (length 2640 m, hydrostatic water pressure 864 m), that occurred in 1973, during the pressure proof test of one knee close to the machine hall of HEPP "Santa Isabel" in Bolivia. Failure occurred at 735 m pressure, e.g. at 84% of the design pressure. The water jet passed through a hole, 1 m long and 0.7 m wide, and destroyed tropical vegetation along 130 m and 10 m in width. About 6000 m^3 of water leaked for one hour, before closing the valve in the surge tank. The penstock was repaired with new knee segments. The tubes were produced of quenched and tempered steel Aldur 50/65D. This steel is designed for penstocks. The pipe diameter of the damaged knee was 1.15 m, plate thickness 22 mm. Mechanical properties of the material, tested after failure, had corresponded to the specification. Metallographic examination revealed that the cause of failure was brittle fracture, that initiated in the heat-affected-zone (HAZ) of a longitudinal welded joint, performed by submerged arc welding (SAW) procedure. The crack developed from the initiation point on both sides in the directions parallel to weld, and arrested at the transversal manual arc welded joint, where it continued to grow in the direction normal to the weldment. It is evaluated that the possible cause of failure is the weld repair, since the preheating had not been applied, although required by welding procedure specification (WPS). The applied steel is ductile, tough and crack resistant, but the presence of a high level residual welding stress due to improper welding technology reduced the penstock strength. After repair, in a repeated test, the penstock passed a pressure 30% above the design pressure, corresponding to 1170 m.

Another example of penstock failure is at HEPP "Perućica", caused by partial leakage, and it showed the significance of quality assurance in welding. Neither brittle fracture nor complete leakage had occurred, but the occurrence of cracks in welded joints required measures to prevent the breakdown of power plant operation. Cracks occurred in the welded joint of a ring, (pos. 104, Fig. 1), 100 mm wide, consisted of 6 circumferential segments.

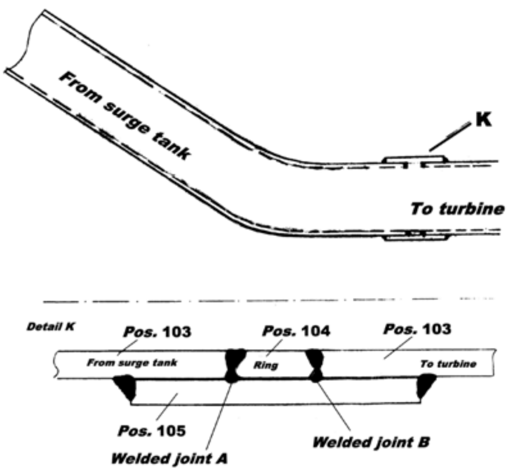

Figure 1. Design of collar (pos. 105) and ring (pos. 104).
Slika 1. Izvedba spojnice (poz. 105) i prstena (poz. 104)

The penstock diameter (pos. 103 left) is reduced from 4000 mm to 3400 mm in the turbine inlet line (pos. 103 right). Two pipelines were produced by two manufacturers, and significant misalignment and end distance occurred, what was solved by the collar (pos. 105), welded before the ring and accepting the loading by fillet welds. The ring served to fill the gap. After the welding, the tunnel was filled with concrete outside the penstock, and the penstock was protected inside by lacquer. Steel of 450 MPa yield stress, microalloyed by vanadium, was selected for collar and ring. After 10 years of service numerous cracks were revealed, several hundreds millimetres long, in both ring welded joints "A" and "B" (Fig. 1), some of them passing through the weld and reaching the fillet weld of pos. 105, i.e. the space between the collar and ring. During the inspection of the emptied penstock, water was found in cracks, indicating that crack depth had reached the tube thickness. Monitoring of cracks showed that they did not grow, or grew slowly.

Examination had shown that cold cracks are in question, that occurred due to improper preheating and the rigidity of the penstock at the ring weld. Once initiated, they developed due to corrosion. Significant for their occurrence was an overloading of the penstock in the early stage of service, followed by vibrations. Cracks did not endanger directly the integrity of the structure, but affected the contact of inner welded joints of collar with water, what, in addition to acting stress concentration, could initiate cracks also in the loaded welded joint of the collar. For this reason the repair is performed by changing all segments of the ring (pos. 104).

DEVELOPMENT OF MAINTENANCE SYSTEMS

The presented two cases clearly show the importance of maintenance for continuous penstock operation and for the prevention of failure. The penstock configuration is not convenient for monitoring. Thus, only during long term breakdowns the inspection is possible. The selection of the proper inspection and maintenance system is in this situation important.

Maintenance of technical systems has developed and is improved during the years. Corrective maintenance, which implies to eliminate the effects of experienced failures, is the first generation of maintenance strategies, yet simple, but is not attractive any more. The second generation was scheduled maintenance that considers higher plant availability, longer equipment life and lower costs. In the last thirty years many complex strategies have been developed as a third and a fourth generation. Those include TPM (total productive maintenance), LCC (life-cycle costing), RCM (reliability centred maintenance), RBI (risk-based inspection), RBM (risk-based maintenance), /3/. Nowadays most attractive are the risk based inspection and maintenance, because they can assure the best practical results.

Risk is defined as the combination of the probability of an event and its consequences. Risk analysis can provide information for different types of consequences that may arise from equipment failures, as are environmental, health, safety and business consequences. This is very important for large and complex industrial systems, like oil refineries, petrochemical and chemical plants, steel production and power plants.

However, the current practice of inspection and maintenance planning in power plants is still mostly time oriented and based on prescriptive empirical rules and experiences rather than being an optimized process where risk measures for safety and economy are integrated, /4/.

The major challenge for a maintenance engineer is to implement a maintenance strategy, which maximizes availability and efficiency of the equipment, controls the rate of equipment deterioration, ensures a safe and environmentally friendly operation, and minimizes the total cost of the operation. This can be achieved only by adopting a structured approach to the study of equipment failure and the design of an optimal strategy for inspection and maintenance /5/.

For the selection of a maintenance strategy using a risk-based approach it is essential to develop cost effective maintenance polices for mechanised and automated systems because in this approach the technical features (such as reliability and maintainability) are analysed, considering economic and safety consequences, according to Kumar /5/.

Furthermore, the use of risk-based methods in inspection and maintenance of piping systems in power plants gives transparency to the decision making process and gives an optimized maintenance policy based on the current state of the components.

Lack of a unique standard for RBM results in various methods and techniques for analysing the risk and making inspection decisions based on those analyses. According to /6/ there is no unique way to perform risk analysis and involve RBM. Different approaches are reported, ranging from only qualitative to completely quantitative /5/.

The only available applicable risk-based standard is American Petroleum Institute standard (API 581, Risk Based Inspection-Base Resource Document). However, this is standard for the American industry and applicable only for process plants. The Extensive European project RIMAP /7/, begun in 2001 and ended in 2004, was induced to offer a European standard for RBM. It produced four industry specific workbooks for the petrochemical, chemical, steel and power generation industries, aimed to provide more specific guidance on how to apply the RIMAP approach in these sectors. However, this approach is to complex, and will not be considered here.

In this paper it is accepted that the level of failure consequences is very high /1, 2/, thus the probability of failure should be very low. Relevant parameters for failure occurrence are required, and they can be established by theoretical and experimental analysis, and when possible, supported by a numerical analysis /8/.

Risk based maintenance optimization

A qualitative risk assessment ranks system and components relative to each other. When a qualitative risk assessment should be performed, relative failure probability and consequence severity can be classified into broad groups, assigned as ‘high’, ‘medium’ and ‘low’. Although any number of groups could be applied, probably a maximum of five failure probability and five consequence severity groups may be accepted with sufficient confidence. Qualitative analysis uses words to describe the magnitude of potential consequences and the likelihood that those consequences shall occur. These scales can be adapted or adjusted to suit the circumstances, and different descriptions may be used for different risks /9/.

Quantitative analysis includes data acquisition and their elaboration, related to the equipment history and failure modes and consequences. It is necessary to quantify the probability of failure occurrence and consequences, whose product represents the risk value. It is of importance for this analysis to select proper parameters that can describe the phenomenon and be convenient to quantify necessary margins, theoretically, experimentally, numerically, and also empirically based on the experience.

According to API, as well as to RIMAP, this can be performed at three different levels, depending on the detail of analysis. In the API approach, the levels are categorized as qualitative, semi-quantitative and quantitative analysis, the corresponding categories in RIMAP are at screening, intermediate and detail levels.

It is well known that there are also other different scales for consequences and likelihood, and the corresponding risk matrix. Scales and matrices can be defined in respect to a specific analysed problem, with no strict rules. Hence, it is difficult to select a proper matrix.

First, i.e. qualitative level is based on one general matrix, Table 1. In this matrix, consequences are categorized, based on several parameters (health, safety, environment, business, security) as A to E; A indicates low, almost negligible consequences, and E refers to fatal and serious consequences. Probability categories are graduated 1 to 5, category 1 representing a very unlikely detrimental event, once in over a 100 years (1×10^{-4}), and category 5 representing a very probable event occurring at least once in a year (1×10^{-1}).

Table 1. Scheme for risk-based qualitative evaluation of maintenance.
Tabela 1. Shema kvalitativne procene održavanja na bazi rizika

		Consequence category				
		A	B	C	D	E
Probability category	5					Very high
	4				High	risk
	3			Medium	risk	
	2		Low risk	risk		
	1	(Very low, negligible risk)				

As it has been mentioned, the consequences of penstock failure can be extremely serious /2/, indicating category E. For safe and reliable use of penstock it is of utmost importance to assure an extremely low frequency of detrimental events, measured as 1×10^{-4}, or once in more than 100 years. This can be achieved by special measures in all steps of design, construction and operation. On the other hand, very strict requirements have to be posed for such a structure, complex regarding design and manufacture, so to prove that detrimental events are unlikely to occur. This might be possible only with sufficient and confident data, experimentally verified.

Peculiarities for a risk-based approach to a penstock

Dominant failures of pressure equipment are fast fracture, leakage and corrosion. Fast fracture could be brittle fracture under plane strain condition or ductile fracture due to overloading in the plane stress condition. Leakage is a consequence of a through-wall crack, produced as a time dependent stable crack growth. Corrosion can develop in a specific environmental condition, and stress corrosion is supported by applied stress. A common feature of these three failure modes is the existence of crack. Welded joints are prone to cracking, and they are most critical regions of the welded structure. Hence the quality level of the performed welded joint needs to be assured following strict requirements during the manufacture, according to ISO 9000 series standards.

Structural integrity depends on crack behaviour. For the control of a crack, two aspects are important. It is necessary first to detect the crack and identify its location and size by different non-destructive test (NDT) methods. Then crack significance needs to be assessed by applying a convenient parameter and method based on fracture mechanics. In order to assure safe operation according to European directives for pressure equipment (PED), these two aspects should be considered before equipment is accepted for the European market, since welding quality cannot be verified on the final product but has to be induced during manufacture, /10/. In-service welded joint quality needs also to be controlled by inspections in the maintenance system.

However, the penstock is not available in-service for inspection at short time intervals or by continuous monitoring, but only when it is emptied. An accepted inspection interval for HEPP is ten years, and NDT of the penstock should be performed then on selected critical welded joints. Thus, from a risk point of view it is necessary to assess the risk level for all welded joints before inspection, and perform the inspection only on joints of the highest risk. Therefore, the next step should be analysis of stress concentration.

PROTOTYPE MODEL OF A PENSTOCK

The reversible turbine pump storage HEPP “Bajina Bašta”, in the design period, about 40 years ago, has been the solution of the world’s highest head and water speed. The failure in HEPP “Santa Isabel” in Bolivia, /2/, was a clear warning to the investor regarding the risk of brittle fracture when the penstock is produced of HSLA steel. Accordingly, it was decided to perform experimental testing of two full scale prototype models of the most stressed segment of the penstock, with the design knee of 5° (Fig. 2). Prototypes had been produced of quenched and tempered HSLA steel SUMITEN 80P (SM 80P), 47 mm thick, by “Sumitomo”, Japan, (yield strength of 700 MPa; ultimate tensile strength above 800 MPa), selected for the penstock manufacture.

Manufacture of penstock prototype

Cylindrical mantle of full-scale model, consisting of 3 segments, 973 mm, 970 mm and 1943 mm in length, designed with a 5° knee corresponding to the penstock transition segment, was covered with two shaped lids (Fig. 2). The steel plates, two for each segment, were rolled and welded.

Welded joints designed for penstock longitudinal (L) and circular (C) welds with preparation given in Fig. 2, are MAW and SAW welded, using basic low hydrogen electrode LB118 for MAW and core wire U8013+M38F flux for SAW welding, produced by “Cobe Steel”, Japan. To minimize the influence of lids on the stress state in the mantle, two ring stiffeners are welded near circular weldments. Certified welders welded the prototype models and later the penstock. Specified and qualified manual arc welding (MAW) and submerged arc welding (SAW) procedures were used, also applied in the subsequent penstock fabrication.

Hydro-pressure test – resistance to stable crack growth

The hydro-pressure test of the second model with no crack has enabled post-yield analysis of weldments. Trial samples for additional tests were welded simultaneously with the model, see /11/.

The hydro-pressure test was performed at ambient temperature (between +6°C and –3°C). Strains were monitored by strain gauges, and controlled by moiré grids. Acoustic emission sensors in critical regions enabled the control of large plastic strains or crack initiation, to prevent a catastrophic fracture during pressurizing. In the first test step the pressure reached 90.2 bar (σ_t = 399 MPa), corresponding to operating pressure. In the second step the pressure was 120.6 bar (σ_t = 533 MPa), that is close to the total operating and water hammer load. Measured strain values for selected location and strain gauges (SG) (2; 34; 53; 59) enabled to quantify residual plastic strains, ε_{pl}, (Fig. 3). The level *b* corresponds to maximum strain in the first step, level *a* indicates residual strain; level *d* is maximum strain in the second step, and level *c* is total residual strain. Strain developed uniformly in PM (53) and circular SAW WM SC (59). Total plastic strain of 0.1% after pressurizing is found on circular CS WM (59). Plastic strain 0.24% was found in WM LS1 (2, 34). The loop in Fig. 3 is attributed to the effect of undermatching, WM strain hardening and strain redistribution in unloading and reloading due to the release of stored elastic energy in the PM.

An important conclusion from the performed test is the non-uniform behaviour and different local plastic deformations (Fig. 3), indicating the most critical welded joint, at the cross-section of CM and LS1 weldments, close to the stress concentrator, 5^0 knee, Fig. 2.

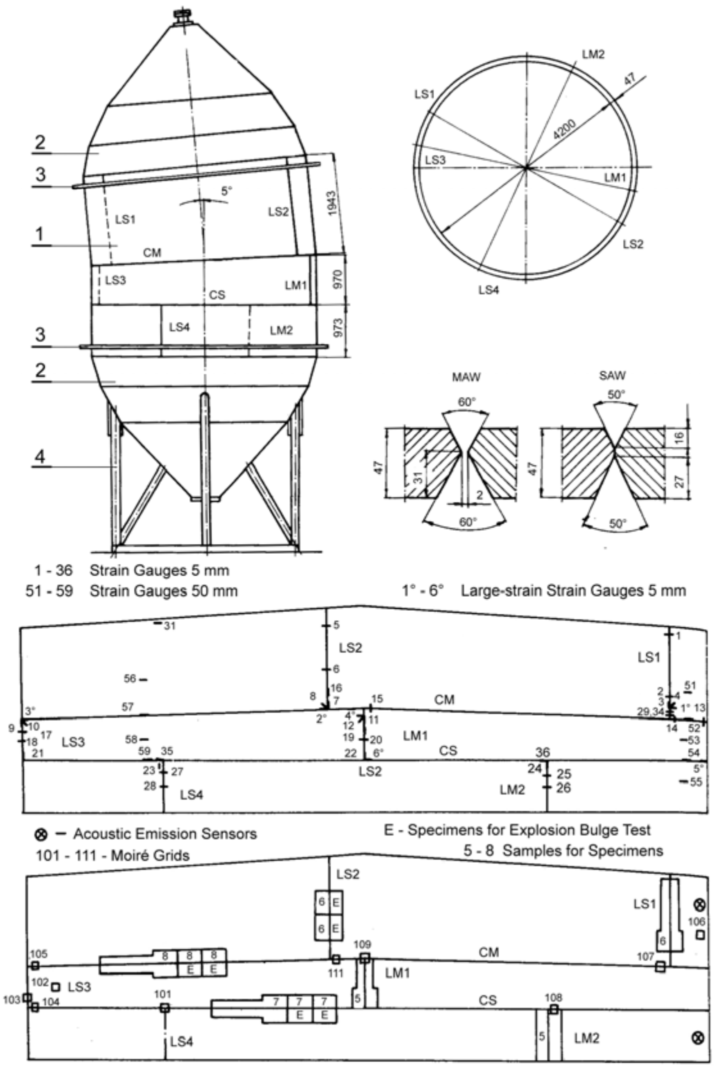

Figure 2. Full-scale model of penstock most-stressed segment: 1-mantle; 2-lid; 3-stiffener; 4-supports of leg L-longitudinal, C-circular; MAW - manual arc welding (M); SAW-submerged arc welding (S).
Slika 2. Realni model najopterećenijeg dela cevovoda: 1-oplata; 2-poklopac; 3-ukrućenje; 4-oslonci L-podužni, C-kružni; MAW-elektrolučno zavarivanje u zaštiti CO_2 (M); SAW-elektrolučno zavarivanje pod praškom (S)

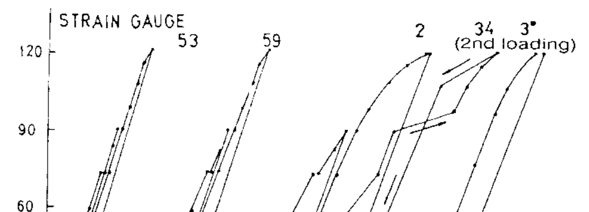

Figure 3. Typical relationships between pressure and strain.
Slika 3. Tipične veze između pritiska i deformacije

DISCUSSION

The risk of failure by brittle fracture or leakage of pressure equipment, which might endanger in-service safety, had been well recognized in the case of HEPP "Bajina Bašta" penstock in the late 70-ties. Followed experimental investigation /11, 12/ enabled to obtain a global picture regarding crack significance for service safety and reliability of constructed penstock and an indirect proof of penstock welded structure quality, sufficient to accept that there is no risk for the penstock in operation. However, it was only a qualitative evaluation, with no specified values of parameters accepted as relevant (resistance to brittle fracture, resistance to stable crack growth). The subsequent research in the scope of the joint Yugoslav–US project "Fracture mechanics of weldments" /8/ delivered more useful results to support safety assessment of the penstock. The motivation for experimental investigation of two full scale prototypes according to the specified programme was to gain sufficient data for risk level evaluation, based on experience and available knowledge at that time, about thirty years ago. Most important results, presented here, allowed us to make a qualitative assessment regarding the brittle fracture, strain distribution in the loaded penstock (Fig. 3). Obtained results have shown that by applying proper measures in the design and manufacture it is possible to assure safe operation of the penstock, based on qualitative assessment of risk. However, meanwhile developed approaches for inspection and maintenance /7, 9,/ are interesting to develop a reliable system for penstock and to use gained valuable information still interesting for additional consideration on how to quantify risk levels of probability and consequence. In that sense this paper, aimed to analyse applicability of new developed principle based on risk, can be considered as a continuation of performed investigation.

From the risk aspect point of view, the following four steps can cover activities in inspection and maintenance:

1. Non-destructive testing (NDT) for crack detection, if present in a structure, including their location and size.
2. Assessment of crack significance using specified parameters and their determined measurable values.
3. Decision on the repair actions for detected cracks.
4. Repair performance.

Let us shortly consider the actual situation. The penstock is accepted for use thirty years ago, after strict testing according to standards and an executed proof pressure test. So this is sufficient to assume that the penstock was defect free initially. Having in mind the penstock construction and operating data it is accepted that regular inspection should take place when the HEPP operation is stopped for general inspection of the system, about after every ten years in service. According to the available data this was performed twice till now. Only the first step, NDT, of the four cited activities was performed. It is to mention that, according to valid rules, educated and skilled personnel, certified for applied NDT methods, need to be engaged by an independent testing institution. The results have shown that there is no need for a next step.

Meanwhile an intensive development in inspection methods and devices took place, followed by extension of modelling and numerical programming. As a result, continuous monitoring could be applied for different objects, like those presented in /13, 14/. It might be expected that continuous monitoring will be developed also for the penstock. This will be beneficial for the risk-based inspection (RBI).

CONCLUSION

Risk significance regarding brittle fracture and stable crack advancement preceding the leakage has been evaluated thirty years ago, after experimental analysis at a level sufficient to accept the penstock of HEEP “Bajina Bašta”. Development of new systems for inspection and maintenance that took place since that time opened the possibility to assess the risk consequence and probability at a more accurate level. Considering this new development and performed experimental analysis it is found that new principles are applicable to the penstock. This can help to improve the actual system of penstock inspection and maintenance. The experimentally obtained results also contain many valuable data that may be additionally used for the risk evaluation. Hence, further investigation in this field is necessary and is welcomed.

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