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QUALITY INSURANCE OF WELDING WORK FOR HYDRO-POWER STEEL PENSTOCKS

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ABSTRACT
Penstocks for hydro-power plants are mostly fabricated as pressure water steel pipelines. In addition, there are a several approaches for mechanical design and further installation practice, as well for quality insurance activities. While American standards fully cover all related activities (ASCE M79, AWWA M11, AWWA C206), there is luck of specific and consolidated support in European regulation. It seems that major welding quality insurance activities are covered by EN 12732 (which is a standard for gas supply systems) and by EN 10224 for base material (for steel water tubes). In addition, it seems that some major European companies, involved in penstock design and manufacture have been developed their own practices and regulations.
Particularly, for designers it is of special concern, how to define appropriate methods and amount of non-destructive testing, especially while considering long (over 5km) and large diameter penstocks (over 2,5m), as well as relatively high working pressures (over 10barg). For such design condition, and in accordance to EN 12732, it is a quite reasonable to widen and straighten non-destructive testing, but consequently fabricators are facing significant fabrication costs.
Therefore, this paper should outline some basic approaches and comparison of welding quality insurance, related to design and manufacture of welded steel penstocks, as well as suggestion for methods and amount of non-destructive testing related to design inputs.
Keywords: hydro-power plant, penstock, welding, quality insurance

1. PREFACE
A penstock, as a part of hydro-power plant, is the pressure conduit between the turbine and the first open water upstream from the turbine. Therefore, a penstock should be as hydraulically efficient as practical to conserve available head, and structurally safe to prevent failure which would result in loss of life and property. From available materials for penstock construction, a most desirable one is steel, due to the fact that steel pipe possesses many desirable qualities (or requirements) of any good conduit: strength and toughness, durability and long service life, economy of installation and maintenance, permanent high-carrying capacity, ductility and adaptability, reliability and resilience, watertight joints [1,4].
Over the years, rigid specifications have been developed covering the chemical and mechanical requirements of the steel from which the pipe is made. Great strides have been made in the fabrication, inspection, testing, joining, and coating of steel pipe. Welded steel pipe of high quality is available in the widest range of sizes (up to 240” or 6,0m), grades (over 690 MPa yield stress), wall thicknesses and lengths [1].
There are varieties of penstock implementation, as underground, aboveground, mounted within dams, etc. Each kind of implementation has its characteristics design approaches, while considering all respective loads. One of the most detailed European approaches to consider loads for pipeline design

is provided in Eurocode EN 1993 4-3, while respective code for welds design is EN 1993 1-8. However, there is no particular European standard which cover requirements for penstocks welding fabrication and its associated quality insurance. It seems that standard for gas supply systems (e.g. pipelines), EN 12732, is mostly associated with welding work on penstocks, while EN 10224 is associated with quality requirements of pipeline materials [2].

Figure 1. Installation of underground mortar coated steel penstock (by Welded Steel Pipe)

Likewise, American codes for penstock design are more consolidated. The most general are ASCE Steel Penstocks Manual No.79, and AWWA M11 (Steel Water Pipe - A Guide for Design and Installation), while particularly field welding work for steel water pipe is specified in AWWA C206.

Whichever code is applied for penstock design and fabrication, it will be shown (in Par.2. Codes Considerations) that achievement of desirable qualities of steel penstocks, as durability, integrity and optimized fabrication costs, are most significant designer's issues.

It should be noted that this paper does not have any intention to underestimate all required aspects of pipeline, or penstock, design, which can not be elaborated further due to such paper size. Only basic relation between required penstock pipe thickness, allowable hoop stress, and required amount of NDT testing are presented in this paper.

2. PENSTOCK FABRICATION TESTING AND INSPECTION

To provide required quality assurance of any kind of fabricated welded steel pipeline, as well as of penstocks, it is a common practice to perform sufficient type and amount of NDT testing of welds, as well as to perform hydro-test. However, complete quality insurance shall include all other activities related to welding work preparation, qualification, performance, and provision of adjacent technical documentation. In addition, European standards (EN ISO 3834) recognize as well as companies qualifications for welding fabrication of appropriate level. Likewise, American regulations recognize company qualification in accordance to ASME Code.

For NDT testing, a radiographic testing (RT) is most reliable. RT is normally applied only to butt welds. For welds that cannot be satisfactorily inspected by RT, as for example some of the welds on branch outlets and wyes, or fillet welds, other NDT methods of inspection can be used. Methods available are: magnetic particle testing (MT), ultrasonic testing (UT), and various methods using dye penetrants (PT). Of these, MT will only disclose defects close to or extending to the surface. The UT method requires considerable experience on the part of the inspector but it is suitable for detecting internal defects. PT is suitable only for locating surface discontinuities [4].

The purpose of the hydrostatic field test is primarily to determine if the field joints are watertight. A proof hydrostatic test on the penstock after installation is most desirable. If the entire penstock cannot be tested hydrostatically, individual sections may be tested in the shop after they have been RT-tested. Such partial pre-installation testing is also required, if feasible, to pipe segments. Hydrostatic tests should be performed at a pressure sufficient to prove the adequacy of all pipes and welds with the required margin of safety. Specification of hydro-test pressure is of particular demand. Generally, hydro-test pressure should be between 1,1 to 1,5 of maximum allowable working pressure (*MAWP*), but never such high to produce hoop stress more than 90% of penstock material yield stress ($R_{p0,2}$). Here, it should be mentioned, that *MAWP* should be based on static head (pressure for normal fluid flow) and dynamic pressure caused by water hammer or surge effects. While considering this important relation between *MAWP* and hydro-test pressure, one design approach, with significant safety consideration, may be to select allowable hoop stress in range of $0,5*R_{p0,2}$ (based on *MAWP*), while hydrostatic test pressure should never produce hoop stress higher than $0,75*R_{p0,2}$.

3. CODES CONSIDERATIONS

3.1 An American approach

An American penstock design and construction practice, before development of actual penstock specific codes as AWWA M11, was in accordance to ASME Boiler and Pressure Vessel Code, Sec. VIII, Unfired Pressure Vessels. Regardless of pressure, a minimum plate thickness is recommended for all large steel pipes to provide the rigidity required during fabrication and handling. Nevertheless, allowable hoop stress due to internal pressure and well known penstock (pipe) thickness, *t*, calculation is based on [4]:

$$\sigma_{hs} = \frac{DP}{2te} < \sigma_{all} \quad \rightarrow \quad t_{\min} > \frac{DP}{2e\sigma_{all}} \qquad (1)$$

where are:
D - Diameter of pipe,
P - Maximum allowable working pressure (*MAWP*),
e - Weld joint efficiency,
σ_{hs} - Hoop tension stress, and σ_{all} - Allowable stress based on steel pipe material yield stress ($R_{p0,2}$).

Joint efficiencies, *e*, for arc-welded pipe depend on the type of joint and the degree of examination of the longitudinal and circumferential joints. The ASME code stipulates a maximum allowable joint efficiency of *e=1* percent for double-welded butt joints completely RT-tested, and of *e=0,7* if RT examination is omitted. Corresponding joint efficiencies for single-welded butt joints without or with backing strips are *e=0,9* and *e=0,65*, respectively. If RT spot examination is used, allowable joint efficiencies are 15% (or 1,15 times) higher than for non-radiographed joints. Of course, joint efficiencies and RT inspection procedures conform to the requirements of the ASME code [4].
In addition, it is common practices that amount of NDT testing depend on level of hoop stress due to *MAWP*. The higher is hoop stress, the extensive is NDT testing. It is obvious that type and amount of NDT testing of penstock field welds is strongly dependable on working condition and penstock design approach.
Therefore, someone may conclude that design approach must be optimized between penstock thickness over-dimensioning (lower hoop stresses, e.g. less than $0,25*R_{p0,2}$), consequent lesser NDT, but higher welding fabrication costs on one side, and dimensioning as minimum as required (higher hoop stresses, e.g. up to $0,75* R_{p0,2}$), considerable NDT, but lesser welding fabrication cost on other side. The corresponding reduction in plate thickness and weight is often sufficient to defray the cost of NDT inspection. Here, for complete reduction of fabrication costs, including NDT costs, it is of special importance application of high-strength steels, even higher than 690 MPa yield stress.

3.2 An European approach

A basic approach of EN 12732 (gas supply standard) for penstock's welding works is in selection of quality requirement category (*CR-category*). There are four (4) categories, from *A* to *D*, depending on operating pressure and pipe material. For example, most strict *CR-category* is *D*, for pipelines with operating pressure higher than 16 bar, and for low alloyed C, C-Mn, microalloyed and quenched and tempered steels. Further, in accordance to *CR-category*, a quality category of fabricator (following table) is defined as well as inspection of welded joints and acceptance criteria. Therefore, for example, for *D CR-category*, the following is minimum extent of NDT testing: all welds 100%VT, while other methods extent is, for circumferential welds 20%RT, longitudinal seams 100%RT/UT, weld joints not included in the pressure test 100%RT/UT, if pipelines/units are laid or installed in built-up areas or pipelines on

Table 1. Recommended quality requirements according to EN 12732

Quality requirement	Quality category			
	A	B	C	D
Quality system according to EN ISO 3834				
- EN ISO 3834 – 2 (Comprehensive)	OPT.	OPT.	REC.	REC.
- EN ISO 3834 – 3 (Standard)	OPT.	OPT.	REC.	REC.
- EN ISO 3834 (elementary)	REC.	REC.	-	-
Welding co-ordination personnel				
- Welding engineer	OPT.	OPT.	OPT.	REC.
- Welding technologist	OPT.	OPT.	REC.	-
- Welding Specialist	OPT.	REC.	REC.	-
- Foreman with several years of experience	REC.	REC.	-	-
Qualification of welders				
According to EN 287-1 in on-site conditions	REC.	REC.	REC.	REC.
Welding procedures qualification				
According to EN 288-2*	REC.	REC.	REC.	REC.
Applicable method of qualification of welding procedure:				
- Welding procedure test	OPT.	OPT.	REC.	REC.
- Use of approved welding consumables	REC.	REC.	-	-
- Previous experience	REC.	-	-	-
- Standard welding procedures	OPT.	OPT.	REC.	REC.
- pre-production welding tests	OPT.	REC.	REC.	-
- welding procedure test for site welding	OPT.	OPT.	OPT.	REC.

Key:
REC. Recommended
OPT. Optional
\- not required
Notes:
* This standard refers to the old Qualification standards; EN 288-2 has been replaced by EN 15609

bridges, pipeline sections crossing railways, major roads and motorways 100%RT/UT. The definition of acceptance criteria is under the responsibility of the Manufacturer, depending on the design, the quality requirement category and the inspection level [7].
In addition, EN 10224, standard for water pipeline materials, requires for all pipes an fittings to be leak tight, which should be demonstrated by hydrostatic or electromagnetic test, while NDT requirements for seams are 100%UT or 100%RT [8].
Another important aspect of penstock design optimization, in relation of maximum stress state, acceptable level of imperfection, and fracture mechanics parameters, may be considered by use of novel SINTAP/FITNET procedures (European Structural Integrity procedures). Therefore, for known penstock material stress level (by mean of known operating condition, selected thickness), and known fracture toughness of material, it is possible to determine acceptable level of imperfection. Otherwise, for known stress level, and definition of acceptable imperfection level to a level of NDT equipment minimum sensitivity, a penstock material of required strength and fracture toughness may be selected.

4. COMMENTS AND SUGESTIONS

It is clear that there are "enough" standard and even some novel tools to perform successful penstock design to provide required durability, long service life, to minimize fabrication cost to satisfactory level, and finally to achieve reliable and quality welded steel structure. There is no doubt that selection of NDT method and quantity is related to main design phase, which take into account penstock operating pressure (and equivalent hoop stress level) and penstock material quality.
Extent of NDT testing provided in European gas supply systems regulation, e.g. EN 12732 and EN 10224, is reasonably applicable to welded steel penstock. Therefore, all critical welds must be 100% UT and/or RT tested, while less critical welds may NDT tested in reduced quantity, or tested by combination of NDT methods depending on working condition. However, some European company's experiences show that even 300%UT (3 times 100%UT) on critical welds was found as satisfactory to guaranty specified acceptance level.
Further optimisation may be achieved by use of fracture mechanics "tools" as novel SINTAP/FITNET procedure. In addition, for someone who is familiar with fracture mechanics, it is well known that hydrostatic test pressure should be reasonably selected (even satisfactory as *MAWP+1bar*, when surge pressure is included in *MAWP*), due to the fact that unnecessary crack growth may occur for higher test pressures (up to *1,5*MAWP*), and left undetected if most sensitive penstock areas are not NDT tested afterwards.
Finally, as it is a case in similar construction, in more demanding industries (as petroleum, or nuclear), it is recommended to perform a detailed Hazard Study of structural integrity and possible impacts to environment and humans. Outputs and results of such study, as normal or emergency ("if failure…") scenarios and recognition of critical parts of penstock welded steel construction should be incorporated in design phase. This, of course, may be beneficial for further definition of type and extent of NDT testing.

5. REFERENCES

[1] Welded Steel Pipe, Merits, Design Standards, Design Manual, Technical Data and References, AISI and STI, 2007 Ed, 2007.
[2] Pipelaying instructions for welded steel pipes, Saltziger Mannesmann LinePipe, 2008.
[3] Buried Steel Penstocks, Steel Plate Engineering Data, Vol.4, AISI, 2nd Ed., 1998.
[4] Welded Steel Penstock, Engineering Monograph No.3, A Water Resources Technical Publication, US Department of the Interior, 1986.
[5] American Water Works Association - AWWA M11 - Manual of water supply practices - Steel pipe - A Guide for Design and Installation, 3rd Ed. 1989.
[6] American Water Works Association - AWWA C206 - Standard for Field Welding Steel Water Pipe, 1997.
[7] EN 12732 - Gas supply systems - Welding steel pipework - Functional requirements, 2004.
[8] EN 10224 - Non-alloy steel tubes and fittings for the conveyance of aqueous liquids including water for human consumption - Technical delivery conditions, 2004.