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Life assessment of penstock based on stress and flow analysis: A case study of Trishuli hydropower station

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Abstract

Hydropower penstocks are subjected to structural degradation due to internal pressure and wall thickness reduction over a period of time. This research presents a combined numerical and analytical assessment of a penstock located upstream of the Main Inlet Valve of an operating plant, Trishuli Hydropower Station (24 MW). The net hydraulic head is calculated considering surging head, frictional head, bend loss, and reducer loss. Based on net hydraulic head, internal pressure was analytically calculated and validated through Computational Fluid Dynamics. Structural behavior was determined analytically, calculating the Von Mises Stress and confirmed through the Finite Element Method in ANSYS. Mesh independent test was performed for numerical reliability. The critical thickness was calculated to be 5.537 mm analytically, whereas through numerical simulation it was found to be 5.3 mm, showing a deviation of 4.28 %. The Ultrasonic Testing performed on the penstock shows the reduction of wall thickness from 12 mm to 7.5 mm, indicating the corrosion rate of 0.078 mm/year. As per the projection, the penstock reaches its critical thickness by 2050, showing the estimated safe remaining service life is approximately 25 years from 2025 AD.

1. Introduction

Trishuli Hydropower Station is a 59 year old hydropower plant, located at Trishuli, Nuwakot. Initially, its installed capacity was 21 MW (7 units of Francis turbines of 3 MW) which was commissioned in 1967 AD. It was constructed with joint initiatives of the Government of Nepal and India at a cost of 140 million Indian rupees. In 1995 AD, it was rehabilitated and upgraded to power generation capacity of 24 MW (6 units each 3.5 MW & 1 unit of 3 MW). It uses the water of the Trishuli river for power generation. The hydropower type is peaking run of river, having design discharge of 45.66 m^3/s annually, annual design generation of 163 Gwh, and gross head of 51.4 m. Its cumulative generation has reached 6031.9 GWh till 2081/82. The high pressure water is conveyed through a penstock from the forebay to the turbine. It consists of a total of 4 penstocks. 3 numbers of penstock having 71.66 m length and 2.3 m internal diameter are bifurcated to 2 numbers of turbine with capacity of 3.5 MW each, and 1 penstock having 89 m length and 1.5 m internal diameter is directed towards 1 turbine with 3 MW [1].

A penstock, generally made up of mild steel, is a closed conduit for conveying high pressure water from intake or reservoirs to the turbines for power generation. It helps to convert potential energy to kinetic energy while maintaining the pressure head. Basically, Penstock is subjected to internal water pressure and water hammer effect. On a long run, penstock experiences material degradation due to corrosion, sediments and external environmental conditions, etc which can reduce the thickness of the penstock wall, changing the pressure and stress distribution.

The penstock of Trishuli Hydropower Plant is in continuous operation for nearly 6 decades. It is exposed continuously to hydraulic loading, surge pressure, environmental conditions (corrosion, sediments). These

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can cause thinning wall thickness and affect the structural integrity of the penstock. While routine inspections and maintenance was done but no comprehensive structural integrity assessment has been conducted combining hydraulic, mechanical, and material degradation analysis. Failure to address such issues could lead to unexpected breakdowns, reduced generation capacity, increased shutdown time, safety hazards to downstream communities, and huge economic loss. Despite various studies in penstock, very limited research has integrated a field based Ultrasonic Thickness (UT) testing with combined CFD and FEM analysis for the life analysis of aging penstock of hydropower in case of Nepal. Moreover, existing research neglect site specific behavior. This research addresses this gap by combination of structural, hydraulic, and field based corrosion assessment to predict remaining service life of penstock. The core objective of the research is to estimate the remaining useful life of the penstock based on structural and hydraulic analysis.

2. Literature review

Aging hydropower structures are suspected of structural damage due to exposure to pressure and harsh environmental conditions. The major cause of old hydropower failure is improper penstock integrity assessment [2]. Pressure surges when valves close or load changes suddenly. The repeated changing loads can trigger cracks, especially in welded and stress concentration regions [3]. The continuous flow of water containing sediment can gradually loss the metal from its surface. The internal pressure exceeds the allowable stress when the thickness of wall reduced below its critical value [4]. Generally, penstock fails from the longitudinal welds, girth welds, and stiffener to shell joints. The welded regions face high stress, and the crack starts from there because they represent HAZ, geometric discontinuities, and the point of stress concentration [5]. The penstock is generally supported by saddles which behave like a beam. If sliding is restricted the bending moment increases, which further increases longitudinal stress causing cracks to develop. The normal life of penstock is generally 40–60 years [6]. If penstock exceeded this period, it may fail causing massive problems. Corrosion causes the reduction in thickness of penstock causing to lose structural capacity. According to [7], the wall thickness reduction due to corrosion increases the hoop stress which ultimately reduces the factor of safety. So, corrosion allowance is taken for designing penstock. Similarly, [8] stated that, small loss in wall thickness can lead to massive increase in value of von Mises stress. The flow of water may be laminar or turbulent based on Reynold number (Re). If Re is less than 2000, the flow of water is laminar, and if greater than 4000, the flow is turbulent. Between 2000-4000, it may be either laminar or turbulent [9].

CFD can be used for visuilizing velocity distribution and pressure gradients that cannot be captured by analytical methods and validating the analytical results. Ansys FLUENT and Ansys CFX are the best tools used in modeling the fluid flow. In [10], the CFD was conducted in penstocks and resulted in those analytical values under steady state conditions. Similarly, [11] focuses on the importance of mesh independence test for ensuring numerical accuracy in CFD analysis in penstock. FEM is used extensively to evaluate stress and deformation in steel penstocks. It allows realistic approach of the material geometry, its properties, and boundary conditions. In [12], the stress analysis was conducted for penstocks at pressure loading and reported that numerical values were more promising than analytical values. The study focuses the stress concentration zones (localized) play a important role in structural failure. In [13], the Kulekhani IIIs bifurcation was optimized by the help of CFD. They redesigned the bifurcation which reduced turbulence and lowered the loss coefficient, confirming both hydraulic efficiency and structural safety. It is not economical to use unit wise penstock for turbine unless the head is low. By use of bifurcation or trifurcation, the water is conveyed to desired number of generating units.

The minimum thickness of wall is needed for safely withstand internal pressure without exceeding the limit of allowable stress. Various research has be concluded in FEM based stress which can be used to estimate critical thickness of penstock by correlating von Mises stress with wall thickness variation. The methodology that combines finite element stress and erosion rate was described in [14]. Their study found a critical thickness of 24 mm for a penstock which was 50 years old and predicted a remaining useful life of 19 years. The analysis of Sundarijal Hydropower in [4], calculated equivalent Von Mises stress and critical thickness 1.3 mm and 5.5 mm for two different sections and recommended suitable maintenance and reinforcement. Here, the factor of safety was found to be 2.6, which is considered unsafe in Indian Standard for design of penstock. In [3], a fatigue analysis was done based on crack growth to predict life of pipe that shows the crack growth, and weld regions are most vulnerable due to fabrication imperfections. In [15], CFD and Monte Carlo simulations were combined for pumped storage system model analysis. The predictive control model can reduce stresses (transient) by smoothing changes in discharge which extends fatigue life without modifications in structures [16].

Corrosion in penstock is inherently a nonlinear process that is influenced by various factors like hydraulic loading, water chemistry, variation in temperature, coating condition, and maintenance practices, etc. Over long period of time, the behavior of corrosion may increase or decrease depending on these factors [17]. The corrosion growth in pipelines is more realistically represented by using nonlinear and probabilistic model because corrosion defects such as pitting do not develop uniformly and their growth rate and depth vary with environmental conditions and time [18]. However, they also noted that linear corrosion growth models are widely used for life estimation due to limited data requirements and simplicity. [17] explains that linear corrosion models are commonly used for life assessment of steel pipelines and pressure systems where detailed historical records are not available. In many penstock life assessments, a linear corrosion model is adopted when only original thickness and current thickness are available. The linear corrosion model assumes a constant reduction in wall thickness over a period of time. [4] applies similar approach to determine remaining life of Sundarijal hydropower, where the remaining life was estimated based on current measured data, original thickness and ooperational period.

3. Research methodology

The research flow will be as shown in Figure 1.

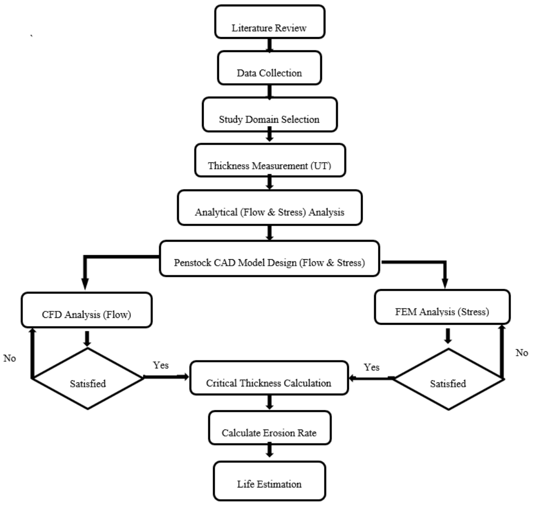

Figure 1: Methodology

3.1. Data collection

The penstock of THPS consists of four numbers of penstock. The three numbers of penstock are 71.66 m in length and 2.3 m diameter each. They are bifurcated and connected to turbine units 1,2,3,4,5, and 6 which are of capacity 3.5 MW each. One penstock is 89 m in length and 1.33 m in diameter. It is connected to turbine unit 7 having 3 MW capacity [1]. The 4th number of penstock is chosen as a topic of study due to accessibility to the site for thickness and alignment survey, and this penstock is the only one without bifurcation which helps to simplify the study. The thickness of penstock is measured using an ultrasonic thickness measuring device. For thickness measurement the surface is cleaned first and only then is the probe placed in the section by filling ultrasonic gel in it. The maximum thickness measured is 11.4 mm and minimum thickness measured is 7.5 mm. The alignment survey was done to determine the length, angle, and diameter of penstock and a tentative model and a general penstock layout is designed as shown in Figure 2.

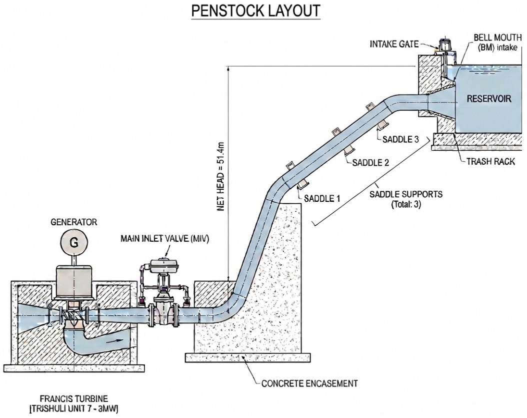

Figure 2: Penstock layout

3.2. Analysis section selection

The selected domain is at the gross head is 51.4 m and just ahead of MIV. The length of section is taken 5 m, wall thickness 7.5 mm, and internal diameter 3.135 m.

3.3. Analytical pressure collection

The internal pressure acting on the penstock is calculated analytically based on the available water head. Pressure is calculated for maximum pressure conditions, i.e. surging conditions. Assuming steady incompressible flow, the pressure inside the penstock is determined using the hydrostatic relation:

$$P = \rho g H_{\text{net}} \tag{1}$$

where,

ρ is the density of water,

g is the acceleration due to gravity, and

H_{net} is the effective head available.

The net head for surging condition of the hydropower is calculated using formula,

$$H_{\text{net}} = H_{\text{gross}} + H_{\text{surging}} - H_{\text{frictional}} - H_{\text{reducer}} - H_{\text{bend}} \tag{2}$$

where,

H_{gross} is the gross head,

H_{surging} is the head generated due to water hammer or a sudden change in the velocity of water,

$H_{\text{frictional}}$ is the frictional head loss due to friction between water and the wall of the pipe,

H_{reducer} is the head loss due to reduction of flow area by the use of a reducer, and

H_{bend} is the head loss due to a change in the direction of water flow through a bend.

$$H_{\text{surging}} = \frac{2VL}{gt_c} \tag{3}$$

where,

V is the velocity of water in the pipe,

L is the length of the pipe,

g is the acceleration due to gravity, and

t_c is the critical time, which is the time required for the generated pressure wave to travel from the point of generation.

$$t_{\text{critical}} = \frac{2L}{a_w} \tag{4}$$

where,

L is the length of the pipe, and

a_w is the velocity of the pressure wave.

$$a_w = \frac{1425}{1 + \frac{d}{100t}} \tag{5}$$

$$H_{\text{frictional}} = \frac{fLv^2}{2dg} \tag{6}$$

where,

f is the frictional coefficient,

L is the length of the penstock.

For determining the frictional coefficient, first the flow of water should be determined. If the flow is laminar, the frictional factor can be calculated directly by using formula,

$$f = \frac{64}{Re} \tag{7}$$

where,

Re is the Reynolds number.

If the flow is turbulent, the frictional factor should be determined from the Moody diagram. Reynold number is given by formula,

$$Re = \frac{\rho V d}{\mu} \tag{8}$$

$$H_{\text{bend}} = \frac{k_b v^2}{2g} \tag{9}$$

where,

k_b is bend loss coefficient.

$$H_{\text{reducer}} = \frac{k_r v^2}{2g} \tag{10}$$

$$k_r = \frac{\sin\Theta}{2}\left(1 - \frac{A_2}{A_1}\right) \tag{11}$$

where,

k_r is reducer coefficient,

Θ is the taper angle of reducer.

3.4. Analytical stress calculation

The stress developed inside pipe is generally due to hoop stress and longitudinal stress.

Hoop Stress is given by formula,

$$S_y = \frac{Pd}{2t} \tag{12}$$

Longitudinal stress due to beam action (σ_1),

$$\sigma_l = \frac{M}{Z} \tag{13}$$

where,

M is bending moment about neutral axis at section,

Z is section modulus.

$$Z = \frac{\pi \left(OD^4 - ID^4\right)}{32\,OD} \tag{14}$$

Longitudinal stress due to sliding friction (σ_s),

$$\sigma_s = -\left(\frac{\Sigma P_f}{A} + a\frac{\Sigma P_f}{Z}\right) \tag{15}$$

$$\Sigma P_f = \mu W \cos\beta \tag{16}$$

where,

β is angle of pipe with horizontal,

μ is coefficient of friction between steel and concrete,

a is eccentricity of frictional force relative to penstock, $OD/2$.

Circumferential bending stress (σ_b),

$$\sigma_b = \frac{M}{Z} \tag{17}$$

$$M = -CP_1 r \tag{18}$$

Shear Stress,

$$\Gamma = \frac{W}{2A} \tag{19}$$

So, Resultant longitudinal stress (S_x) is calculated using equation,

$$S_x = \max\left(|\sigma_l| + |\sigma_s|,\ |\sigma_l| + |\sigma_b|\right) \tag{20}$$

Here, shear stress is negligible in comparison to hoop stress. So, Equivalent stress is calculated by using Hencky Mises Theory

$$\sigma_e = \sqrt{S_x^2 + S_y^2 + S_x S_y} \tag{21}$$

This analytical stress provides a baseline for comparison with numerically obtained von Mises stress from FEM analysis.

3.5. Critical thickness and corrosion rate calculation

The critical wall thickness required to safely withstand internal pressure is estimated analytically by rearranging the hoop stress equation while considering allowable stress and factor of safety. The critical thickness is given by:

$$t_{cr} = \frac{PD}{2\sigma_y \times FOS} + t_{\text{corrosion}} \tag{22}$$

$$\text{Corrosion rate} = \frac{\text{Initial thickness} - \text{Current thickness}}{\text{Total year in operation}} \tag{23}$$

where,

σ_y is yield strength of penstock,

FOS is factor of safety,

$t_{\text{corrosion}}$ is corrosion allowance.

3.6. Modelling and simulation for pressure

The geometric model of the penstock was developed based on actual design and operational data of the hydropower project. A 3D model with uniform thickness of penstock was designed in SOLIDWORKS. The designed geometry was exported in STEP extension and then imported to ANSYS for further analysis. ANSYS Fluent is used to evaluate pressure and velocity distribution inside the penstock. The simulation setup is as shown in Table 1.

3.7. Modelling and simulation for stress

ANSYS Mechanical was used for structural analysis where deformation and von Mises stress were evaluated. The analytically calculated pressure was applied uniformly on the internal surface of the penstock. One end was constrained for preventing the body motion and another end was allowed for free movement. The simulation setup for stress analysis is as shown in Table 2.

3.8. Mesh generation and mesh independent test

A mesh independence test was conducted by refining the mesh and monitoring the maximum velocity. Mesh convergence was achieved at a point when further refinement resulted in negligible change in results which ensures numerical accuracy as shown in Figure 3.

Table 1: Simulation setup for flow analysis

Parameters	Details
Type	ANSYS Fluent
Physical Preferences	CFD
Mesh	Tetrahedral with element size 30 mm, node number 509208, element number 496157
Element order	Linear
Inlet	Velocity 5.743 m/s
Outlet	Pressure 0.53 MPa
Wall	No Slip
Turbulence	K-E Turbulence
Solution	PV coupling method
Iterations	300
Solver type	Pressure based
Time	Steady

Table 2: Simulation setup for stress analysis

Parameters	Details
Type	Static Structural
Physical Preferences	Mechanical
Mesh	Tetrahedral with element size 20 mm, node number 734092 & element number 105000
Analysis setting	Fixed support at one end face and frictionless support at other end & pressure of 0.5352 MPa at inner surface

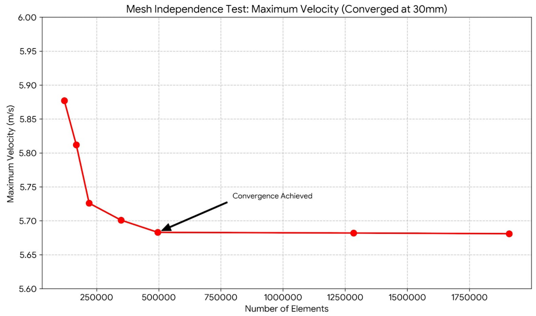

Figure 3: Mesh independence for flow analysis

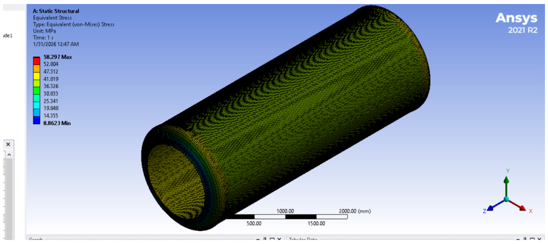

Figure 4: Equivalent (von-Mises) stress at overall section

4. Results and discussions

Based on the above-mentioned methodologies, following parameters were calculated as mentioned in Table 3.

From structural analysis of penstock, the maximum (Von - Mises) stress is found to be 58.297 MPa at outer section of pipe and 8.8623 MPa the inner surface of penstock as shown in Figure 4 and 5.

The blue color shows minimum stress development at inner surface while the red color shows maximum stress at the outer surface. Moving from inner to outer surface, the stress formation is maximizing.

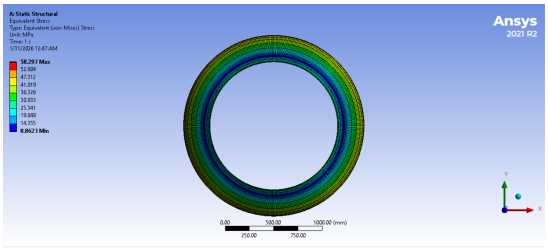

Figure 5: Equivalent (von- Mises) stress at circumferential section

The mathematical calculation results the value of von

Table 3: Calculated parameters

Flow Parameters	**Results**	**Stress Parameters**	**Results**
Discharge (Q)	7.8 m^3/s	Hoop or circumferential stress (S_y)	46.92 MPa
Outer diameter (OD)	1330 mm	Longitudinal stress due to beam action (σ_l)	25.79 MPa
Min thickness (t)	7.5 mm	Longitudinal stress due to sliding friction (σ_s)	-4.52 MPa
Area (A)	1.358 m^2	Circumferential bending stress (σ_b)	-0.18 MPa
Velocity (V)	5.743 m/s	Shear Stress	0.12 MPa
Reynolds number (Re)	7552045	Resultant longitudinal stress (S_x)	30.31 MPa
Frictional head loss ($H_{\text{frictional}}$)	0.040 m	Equivalent stress (σ_e)	60.20 MPa
Bend loss (H_{bend})	0.117 m	Critical thickness	5.537 mm
Reducer loss (H_{reducer})	0.0044 m	Corrosion rate	0.078 mm/year
Surging head (H_{surging})	3.473 m		
Net head (H_{net})	54.5626 m		
Inside pressure (P_{net})	0.53 MPa		

Mises stress of 60.20 MPa, while the simulation resulted a maximum stress of 58.297 MPa as shown in Figure 4 and 5. The percentage deviation between these two stress is only 3.16% as mentioned in Table 4.

The thickness of the penstock is reduced by 0.2 mm and equivalent stress is analyzed through Structural Analysis. The thickness is reduced till the equivalent stress reaches the working stress of penstock. The working stress of penstock is one third of the ultimate tensile strength. As the ultimate tensile strength is 382.48 MPa, the working stress is calculated as 127.49 MPa. So, upto this stress the thickness is reduced and the critical thickness is determined at that point. The graph is plotted between equivalent von mises stress and thickness as shown in Figure 6.

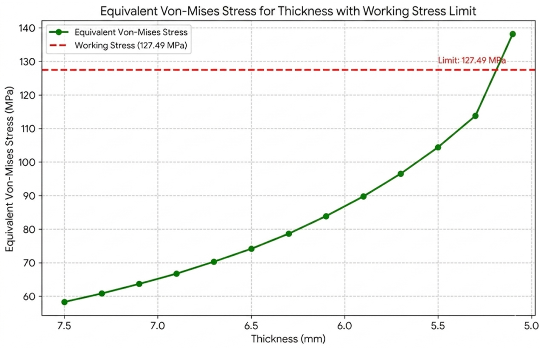

Figure 6: Equivalent (von-Mises) stress at varying thickness

The critical thickness obtained from numerical simulation was found to be 5.3 mm. A comparison between analytically and numerically calculated critical thickness values is presented in Table 5. The analytical method yielded a critical thickness of 5.537 mm, while the simulation result showed a deviation of 4.28 % from the analytical value as shown in Table 5. Since the analytical method resulted a higher values, the analytical critical thickness value of 5.537 mm is adopted for further analysis to ensure factor of saftey.

The initial wall thickness of the penstock at the time of installation in 1967 AD was 12 mm, which has reduced to 7.5 mm over a service period of 58 years, indicating a total thickness loss of 4.5 mm. Based on this reduction, the corrosion rate of the penstock is calculated as 0.078 mm per year. Assuming that corrosion continues at the same rate as mentioned by [4][17][18], the penstock wall thickness is expected to reach its critical thickness by the year 2050 AD as shown in Figure 7. Therefore, the remaining safe operating life of the penstock is estimated to be approximately 25 years.

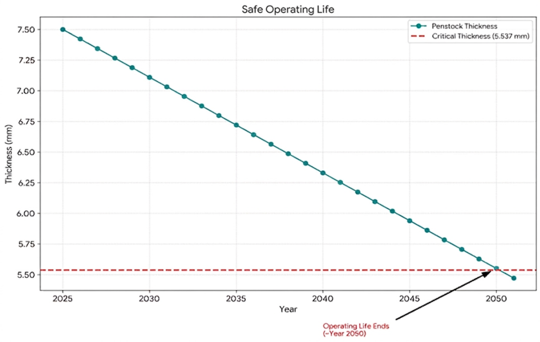

Figure 7: Life estimation

A comparison with past research shows a similar trend in thickness reduction induced by corrosion. In [3], the original thickness of the Sundarijal HPS penstock was 12 mm in 1934 AD, which reduced to 7.2 mm after operating 85 years in 2019 AD, corresponding to a corrosion rate of 0.0564 mm per year. Based on this rate, the penstock was estimated to reach its critical thickness by 2048 AD. In comparison, this study of Trishuli HPS considers a penstock with an initial thickness of 12 mm in 1967 AD, which reduced to 7.5 mm after operating 59 years in 2025 AD, resulting in a higher corrosion

Table 4: Comparison table of stress from analytical and simulation method

Analytical result	Simulation result	Percentage deviation	Remarks
60.20 MPa	58.297 MPa	3.16%	Acceptable

Table 5: Comparison table of critical thickness from analytical and simulation method

Analytical result	Simulation result	Percentage deviation	Remarks
5.537 mm	5.3 mm	4.28%	Acceptable

rate of 0.078 mm/year. Accordingly, the penstock is assumed to reach its critical thickness by 2050 AD. The results of the present study are influenced by uncertainities in input parameters such as UT measurements, variables, material properties, boundary conditions etc. These parameters may infleunce the results of pressure estimation, stress calculation, corrosion rate prediction, numerical analysis, and life estimation by certain margin. Ten percent variation in corrosion rate results in three years variation in predicted life [19].

5. Conclusion

This research presented an integrated analysis (analytical and numerical) of an aging penstock section located upstream of the Main Inlet Valve (MIV). The analytically determined critical thickness was 5.537 mm, while numerical simulation predicted 5.3 mm, with a deviation of 4.28 %, indicating satisfactory correlation between the two methods. Field data revealed a reduction in wall thickness from 12 mm to 7.5 mm over 58 years, corresponding to a corrosion rate of 0.078 mm/year. Based on a linear corrosion model, the penstock is projected to reach its critical thickness by 2050 AD, providing an estimated remaining safe service life of approximately 25 years from 2025 AD.

This research can further be used for economic analysis of the penstock performing cost benefit analysis of maintenance or replacement to the Government Owned Entity, NEA. Also, other sections of the penstock can be used for better analysis. Regular monitoring should be done to track the corrosion progression. Preventing maintenance techniques like coating can be done to extend service life. The real time data of various parameters can be used for accurate results. Furthermore, FSI simulation incorporating transient pressure pulsation can be done in future, to get more accurate results.

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