

Development of a simplified procedure for penstock risk assessment

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1 Introduction

Due to the specific and favourable environmental conditions, hydropower plants in Italy started to be developed since the turn of the century.

Nowadays, the age of the plants, the necessity to guarantee adequate working conditions and, last but not least, the necessity to ensure the safety of people and goods in the surrounding area dictate the necessity to take concrete action to guarantee the safety of the various plant components.

This is also the way taken by local administrations. Some of them have already approved a resolution asking for each hydropower plant a complete risk analysis specially focused on the penstocks; in the next years, a similar approach will be probably adopted in Italy at national level.

Due to the complexity of the subject, this kind of analysis involves a large number of professional roles and disciplines.

The study of past events, the topographic, geologic and geotechnical, metallurgical analysis and the investigation on the conditions of the concrete structures are some of the preliminary steps required in order to perform a complete assessment of the failure risk of the penstock.

Building on successes with system engineering and occupational safety, and considering the multidisciplinary of the subject, it is essential to perform a preliminary analysis with the aim to identify, and to mitigate, the aspect at which the higher risks correspond.

There is, therefore, a need to analyse the potential risks of penstock failure in an easier and more efficient way. The paper describes the process that led to the definition of an evaluation grid aimed at defining the risk of the single plant assessed and defining the priority of action.

2 Materials and methods

The resulting innovative grid used to analyse the potential risks of penstock failure was based on the classical definition of risk as the product between damage and probability of occurrence. The concept of detection, derived from the “likelihood of detection” of FMEA (Failure Mode and Effect Analysis) widely used in the automotive sector, was furthermore added in order to better fit the risk definition to the specific subject of the analysis.

2.1 Overview of failure modes and effects analysis (FMEA)

Failure Mode and Effect Analysis (FMEA) was first developed as a formal design methodology in the 1960s by the aerospace industry with their obvious reliability and safety requirements (SANKAR and PRABHU, 2001). Later its use spread to other industries, such as the automotive and oil & gas (PALADY, 1997).

Basically, FMEA uses the Risk Priority Number (RPN) to prioritize failure modes.

RPN is the product of three ranked ratings, occurrence, severity and detection. It is calculated as $RPN = O \times S \times D$. Occurrence (O) rating is assigned to the cause of the failure mode to reflect the probability of the cause and the immediate failure mode, severity (S) rating is assigned to the end effect of the failure mode to reflect the seriousness

of the end effect, and detection rating (D) is assigned to the cause of the failure mode to reflect the difficulty of detecting the cause or failure mode. These ratings are quantified by integer numbers between 1 and 10. RPNs are compared with each other, and failure modes with higher RPNs are considered to have higher risk, and corrective actions are taken to reduce their RPNs. In this way the system reliability is improved.

Despite the wide implementation of FMEA in industry, controversies have always been around. The most consistent objection is about the criteria for quantifying the three ratings that are mostly subjective, and they are described qualitatively in natural language based upon the experience of teams (LIANG, 2013).

2.2 Application of FMEA to the case study purpose

The FMEA concept and its evaluation of risk based on RPN were maintained in its principles even if it was modified in order to obtain higher objectivity and replicability in the assignment of the ranked ratings.

- To ensure higher consistency in the assignment of the rating, the ranking was compressed from 1-10 to 1-5 for Severity and Detection parameters and to 1-4 for the Occurrence one.
- To overcome the fact that the three ratings are mostly subjective (in the traditional FMEA they are described qualitatively in natural language) we went more in deep in the failure mechanism correlating its Occurrence, Detection, and Severity with the environment, providing so quantitative relations to determine the final value of the parameters.
- To overcome the necessity of further specialistic analysis (time-consuming and expensive) but at the same time considering the uncertainties deriving from the utilization of not updated or assumed data, the computed rating was modified according to the reliability of the existing information.

The first step in the definition of the assessment method was to better identify the object of the analysis, “the penstock”. It has been identified in the ensemble of its part such as pipe, anchor blocks, saddle, head valve (if present), etc.

Then it has been necessary to formalize the function of the penstock to convey pressurized water to produce electric energy.

Furthermore, according to the FMEA procedure, it has been analysed all the possible ways in which the penstock can fail to fulfil its design intent and the related causes.

Three different failure mode was identified:

- Pipe breach
- Partial failure
- Total failure

Failure mode	Cause
Pipe breach	Stray current
Partial failure	Human error
	Damage or pull-out of joint
	Failure of connections
	Failure of constraints
	Wear of constraints
	Failure of pipe shell
	Wear of pipe shell
Total failure	Impacts and other environmental factors
	Attacks and vandalism

Determination of the Occurrence

In hydropower sector a consistent lack of information regarding failure can be experimented due to the propensity of owner, constructor and manufacturer not to share information regarding failure in their plant. Actually, this lack affects the determination of the occurrence of the event causing failure of the penstock and makes much more qualitative and subjective the determination of the occurrence parameter in the FMEA method. To overcome this problem for each of the causes identified above, the occurrence has been computed according to quantitative or semi-quantitative procedures taking into account the triggering conditions rather than the probability of occurrence of the direct cause of the failure.

Stray current

Stray current mainly affects not insulated steel pipes, especially when placed in swampy areas or when direct current is present (typically next to train lines). Those are the factors that influence the occurrence rating for stray current causes. Actual rating is reported in the table below.

Stray current	<i>Not insulated steel penstock</i>	<i>Insulated steel penstock</i>
Presence of train lines or swampy areas along the penstock path	2	1
Absence of train lines or swampy areas along the penstock path	1	0

Human error

During normal operation, HPPs are generally remotely controlled. Nowadays these kinds of systems are usually provided together with specific protection aimed to avoid unintentional damage by the user's actions. The human errors thus are related to the presence of specific measures, controls, and procedure for the correct execution of the actions:

Human error	<i>Absence of specific procedures</i>	<i>Presence of specific procedures</i>
Presence of automatic measures and controls	2	1.5
Absence of automatic measures and controls	1.5	1

Damage or pull-out of expansion joint

The expansion joints are elements that require regular inspections and maintenance; therefore, the probability of pull-out or damage is linked to the frequency of those activities:

Frequency of inspections and maintenance	Occurrence
Less than once every 10 years	3
At least once in 10 years	2
Yearly	1

Failure of connections

The occurrence of failure of the connections can be firstly related to the type of connection. Secondly, the operator knowledge about the components (i.e. presence of inspections reports, etc.) can be considered:

Failure of connections	<i>Riveted penstock</i>	<i>Welded penstock</i>
No inspections	2	3

Failure of connections	<i>Recent inspection with positive feedback</i>	<i>Not recent inspection with positive feedback</i>	<i>Partially positive feedback</i>
Presence of inspections	1	2	3

Failure of supports

The number of pipe supports that can fail without causing the failure of the penstock shell is the parameter considered in this risk analysis. The computation of this parameters has been performed with the same procedure used for the computation of the failure occurrence in the pipe shell (see below) neglecting water hammer.

According to the number of pipe supports that can fail, the occurrence of the partial failure of the penstock has been evaluated as follows:

Number of supports that can fail	Occurrence
0	3
1	2
2	1.5
>3	1

Wear of structural constraints

Independently of the tensional state, saddle and anchor blocks can fail due to wear caused by external conditions (chemical parameters of water and terrain, weathering, etc.). The occurrence of penstock partial failure due to the wear of constraints is so evaluated by means of a visual inspection of the saddle and anchor blocks (focused on the evaluation of the state of wear):

Results of the visual inspections	Occurrence
Extensive wear	3
Limited wear	2
No visible wear	1

Correction factors for the above occurrence value has been introduced to take into account possible lack of data. Correction coefficient is applied as follows:

Results of the visual inspections	Correction factors
Extensive information about environmental conditions available	+0
Some information about the structure or about environmental conditions available	+0.25
Information about the structure and environmental conditions not available	+0.5

Failure of pipe shell

The occurrence of penstock partial failure due to the failure of the pipe shell has been related to the safety factor (FS) computed as the ratio between the actual equivalent stress and the yield strength of the pipe.

Safety factor has been computed, according the type of material considering Tresca and/or Mohr-Coulomb methods:

FS	Occurrence
$0 < FS \leq 1$	4
$1 < FS \leq 2$	3
$2 < FS \leq 3$	2
$FS > 3$	1

Correction factors for the above occurrence value has been introduced to take into account possible lack of data. Correction coefficient is applied as follows:

Existing tests	Correction factor
Thickness measures and stress testing made less than 20 years ago	+0
Thickness measures or stress testing made less than 20 years ago	+0.5
Information about the structure and environmental conditions not available	+1

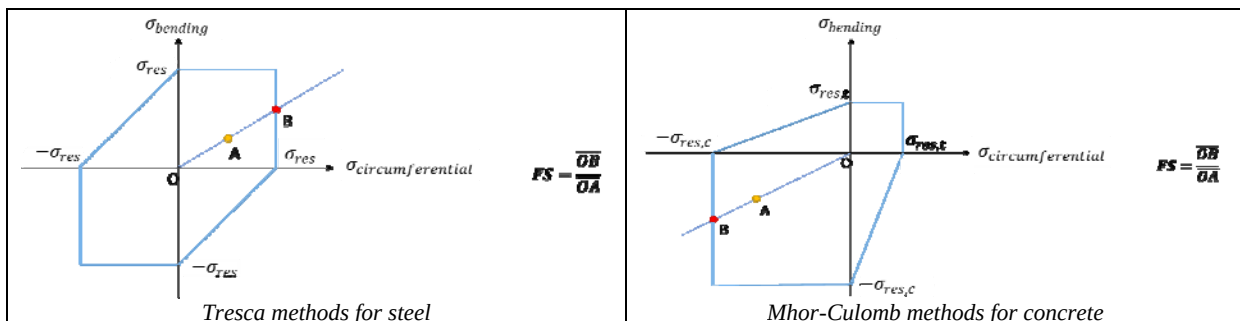


Fig. 1. Graphical determination of FS for according Tresca and Mhor-Culomb methods

Wear of pipe shell

Regardless of its stress state, the pipe shell may deteriorate due to the sediment transport.

Lacking more precise information on the state of the shell, consequent, for example, to an internal inspection of the penstock, the probability of this phenomenon is assessed according to the table below:

<i>Wear of pipe shell</i>	<i>Type of watercourse: river</i>	<i>Type of watercourse: creek</i>
Presence of other HPPs upstream to the intake	1	2
Direct withdrawal from the river	2	3

Boulder impact and other environmental factors

These phenomena are related to hydrogeological instability (such as landslides and rockfalls) that can affect the pipeline and cause its shearing.

<i>Impacts and other environmental factors</i>	<i>Proven phenomena (evidence of past events)</i>	<i>No evidence of past events.</i>
Hydrogeological instabilities remarked in literature	2	1.5
No evidence of hydrogeological instabilities in literature	1.5	1

Attacks and vandalism

Considering the current peaceful situation, the probability of such an event is very low. Therefore, a value of occurrence to 1 has been chosen for all the plant analysed.

Determination of Severity

It is assumed that the extent of the damage, i.e. how severe are the consequences of an event, depends on the following parameters:

- direct damage, i.e. the economic damage that derives from the cost of repairs
- undirect damage, i.e. the economic damage related to the plant outage and the deriving lost revenue. The owner detects the extent of the damages as the “unusable released water”, which means the water that is released because of the plant outage.
- damages to third parties, i.e. the compensation required in case of damages to properties or factories;
- damages to public infrastructures, such as railways, roads, electrical grids, telephone lines, data transmission lines, and deriving interruption of the services;
- damages to people, i.e. injuries or death.

It must be noted that the above damages are not mutually exclusive; on the contrary, when the most severe one happens, it often comes with the less severe ones.

The evaluation of the type of damage is strictly related to the urban environment next to the penstock path i.e. roads, railways, houses etc. The evaluation of this environment can be done using GIS software, orthophoto and maps of land use. Together with a focused survey, those elements ensure an in-depth knowledge of the environment in the surrounding of the penstock path.

Detection systems	Detection
Injuries or death	5
Relevant economic loss (at least equal to 50% of the value of the considered element) or plant outage up to one year, or damages to properties of the concessionaire or of third parties or to public infrastructures	4
Relevant economic loss (at least equal to 25% of the value of the considered element) or plant outage up to three months, or damages to properties of the concessionaire or of third parties or to public infrastructures	3
Significant economic loss (at least equal to 10% of the value of the considered element) or plant outage up to one month, or damages to properties of the concessionaire or of third parties or to public infrastructures	2
Economic loss smaller than 10% of the value of the considered element, plant outage up to one week	1

Determination of Detection

The detection systems (if any) have been considered as the combination of:

- Measure function: a system of measure that allows to understand that the plant is working out of normal conditions (usually differential system or velocity measure)
- Interruption function: generally, a valve (or gate) able to interrupt the flow in the penstock if the plant starts to work out the normal operating conditions.

It exists a wide range of detection systems, starting from the ones that ensure only the interruption function (valve and gate) to the ones that are able to detect also a very small breach in the pipe (differential systems) passing through the most common paddle type flow switch.

According to the capability of the system to detect even small failure, it is possible to rank the detection.

This risk analysis is performed under the assumption that, if present, the system will act correctly, i.e. the chance of simultaneous water leakage and interception system breakdown is neglected.

Detection systems	Detection
Differential system	1
Paddle type flow switch	2
Pressure measure	3
Interruption of the flow by remote control	4
No detection	5

In this case, a correction coefficient to the Detection value determined by the detection system type installed on the penstock has been applied.

The correction coefficient takes into account different factors (redundancy, frequency of the functionality tests and possibility to detect also visually the damage at the penstock).

Results of the visual inspections	YES	NO
Execution of functionality tests	+0	+1
Redundant	-0.5	+0
It exists the possibility to visually detect water leakage	+0	+0.5

Risk definition

For each event, the risk is evaluated by means of the RPN, defined as the product of probability, detection and damage, i.e. $R = P \cdot I \cdot D$

So, the risk level corresponding to the maximum value among the ones computed for the considered event is given to the pipe, according to the following table:

RPN	Actions
Neglectable (up to 12)	None
Low (from 13 to 25)	To be considered on a case by case basis
Medium (from 26 to 50)	Action aimed to reduce the risk
High (over 50)	Urgent action aimed to reduce the risk

3 Case study

The resulting innovative grid has been applied to 17 different plants, ranging from 0.85 to 120 MW, located in the Province of Bolzano.

The plants have different pipe types varying from steel pipe to concrete one and furthermore, different types of lie-down ranging from buried to exposed penstock placed on saddle and fixed to anchor blocks.

This results in a significative set of case studies which make possible to test the proposed grid under different working conditions.

All the plants were surveyed before starting the assessment procedure in order to have a better knowledge not only of the plant but also of the surrounding environment.

A quite time-consuming activity was then the retrieval of information about the penstock. Many of these plants have been built in the first half of the century and many of the detailed drawings reporting the penstock characteristics were not available. Some updated information were obtained by the monitoring activities involving thickness measurement and metallurgical properties of the pipe shell which were generally performed by the owner every 10-

15 years. Some inconsistency between the existing drawings and the results of the tests performed has been found and should be remedied.

The worst situation in that sense was experienced with reinforced concrete pipe where, generally, characteristics (and in some cases also number and type) of re-bars was not reported in the existing drawings and test on the pipe was not performed during the years.

Evaluation of the occurrences of the cause of the different failure mode has then made according to the rigid matrix presented before. Where available data regarding the state of shell, connections and joints has been taken from the most recent tests. Where no tests were available data from detailed/construction design has been used. In some cases, where both tests and construction design were not available some estimation regarding, at least, metallurgical characteristics (i.e. yielding point) has been assumed considering the constructive customs of the period of the realization of the penstock.

Information regarding geological and hydrogeological conditions has been obtained by using GIS tools; maps regarding geological characterization, hydro-geological hazard maps, landslide, avalanche are free downloadable from the GIS system of the Province of Bolzano. Geological works defence mapping (rock fall barriers, landslides and debris flow protections etc.) has been also considered in order to investigate existing critical situations.

Other information regarding the surrounding environmental conditions was deduced by the survey, which remains a crucial source of information in the method.

Evaluation of the severity of the different failure mode has been done considering the exposed element in the surrounding of the penstock (houses, roads, electrical lines, railways etc.), even if a first idea of the existing exposed infrastructure can be done during the survey, a useful tools for the exact evaluation of the presence or not and type of exposed elements can be done by using GIS tools. Satellite images can be useful to recognize houses, hotels and other possible exposed elements. Bolzano province delivers also a map showing the major infrastructure in the area and several land use map. All those have been used to evaluate possible exposed elements.

Information regarding the existing detection system has been obtained during the survey.

During the entire assessment process dialogue with the owner and person on the plant was intense and fundamental to collect all information necessary to complete the risk evaluation of the penstock.

To standardize the work and make it more consistent, a simple spreadsheet has been prepared to guide our technicians in the assignment of the rating at the different parameters.

The results for the assessed penstock are reported in the *Tab.1*.

The most common cause associated at higher RPN is related to the failure of the shell.

According to the 4 risk classes proposed, among the 17 plants assessed, 8 resulted with a neglectable RPN (below 12), 3 plants are characterized by a low RPN and 6 with a medium RPN value (between 26 to 50).

A study of the plant outages can be useful to understand the causes of the RPN resulted value.

Severity ranges for all the plants between 2 and 3, relatively low. This can be explained, in most of the cases, considering the orography. The penstock path, actually, represents a preferential way (at least for the exposed penstocks) for the water that is conveyed directly to the powerhouse which is, usually, the more affected building.

Furthermore, the penstock path in urbanized area, or vice versa, the constructions of building and infrastructures close to an existing penstock is well studied during the design phase.

Detection is one of the critical parameters in most of the cases. Generally, the lack of an suitable detection systems is highly punitive in terms of global RPN results. It is also true that the provision of sensitive detection systems (i.e. differential ones) is relatively unexpensive, if compared to the total cost of the plant. It follows that a lowering in total RPN value can be easily obtained when an high RPN value are caused by this parameter. This is particularly true in case of buried or exposed steel penstocks. If the penstock is rock embedded problems in the installations of such detection systems arise.

High value of occurrence are generally related to a lack of information regarding the materials. Absence of tests or inconsistency of existing information are quite common in the analysis and they result in higher correction coefficients for the occurrence parameter.

Considering that all the penstocks are working without any problems since their constructions, as a result of the assessments no mandatory actions have been taken. However, additional investigation was recommended in case of lack of information affecting the final RPN value and installation of differential detection system was suggested to cover the absence of detection ability.

#	Plant	P MW	Type of penstock	Joint	Lie-down	Critical cause	O	D	S	RPN
1	Bolzano EGA	4.2	Steel pipe	Welded	Saddle and anchor blocks	Failure of pipe shell	2.25	4	2	18
2	Ponte Gardena	15	Steel pipe	Welded	Buried	Failure of pipe shell	3.5	1.5	2	10.5
3	Pontives	0.9	Steel pipe	Welded	Buried	Wear of the shell	2	1.5	2	6
						Damage or pull- out of joint	2	1.5	2	6
						Human error	2	1.5	2	6
4	Selva Gardena	1.7	Steel pipe	Welded	Buried	Wear of the shell	2	1.5	2	6
						Damage or pull- out of joint	2	1.5	2	6
						Human error	2	1.5	2	6
5	Molini di tures	16.5	Steel pipe	Welded	Saddle and anchor blocks	Wear of constraints	3.5	1	2	7
6	Lappago	30	Steel pipe	Welded	Saddle and anchor blocks	Wear of constraints	3.5	1	2	7
7	Lana	132	Steel pipe	Welded	Saddle and anchor blocks	Failure of pipe shell	3.5	1.5	2	10.5
8	Bressanone	124	Reinforced concrete pipe	-	Buried	Failure of pipe shell	5	4.5	2	45
9	Castelbello	87	Reinforced concrete pipe		Buried in rock	Failure of pipe shell	5	1.5	2	15
10	Senales	3.68	Steel pipe + plastic pipe	Riveted	Buried	Failure of pipe shell	4	4.5	2	36
11	Tel		Hole in rock, concrete finish	-	-	Human error	2	4.5	2	18
						Damage or pull- out of joint	2	4.5	2	18
12	Sarentino	24.5	Steel pipe	Welded	Saddle and anchor blocks	Failure of constraints	3	1	3	9
13	Pracomune	42	Steel pipe	Welded	Buried in rock with concrete	Failure of pipe shell	3	4.5	2	27
						Damage or pull- out of joint	3	4.5	2	27
14	Premesa	8.2	Steel pipe	Welded +riveted	Saddle and anchor blocks	Failure of pipe shell	2.5	1	2	5
15	Barbiano PGA	55	Reinforced concrete pipe	-	In rock	Failure of pipe shell	3	2	4.5	27
16	Brunico	42	Hole in a rock	-	-	Failure of pipe shell	3	4.5	2	27
						Wear of pipe shell	3	4.5	2	27
17	Versciaco	3.7	Steel + Concrete pipe	-	Buried	Failure of pipe shell	4	4	2	32

Tab. 1. Assessment results overview



Sarentino HPP – shell conditions



Premesa HPP – type of connections



Selva Gardena HPP – differential detection system (D=1)



Ponte Gardena HPP – Paddle-Type Flow Switch (D=2)



Lana HPP – Private houses close to the penstock



Bolzano EGA HPP – Concrete saddle conditions

Fig. 2. Some pics taken during HPPs surveys showing some common conditions for the plants

4 Results and further optimization

The application of the innovative grid proves how the proposed method is easy to implement. With the introduction of the spreadsheet another positive effect experimented was the reduction of the time of the analysis. Actually, the entire pre-assessment procedure took only one day for the site survey, plus some days for the elaboration of the data depending by the existing documentation. This make the assessment cost effective and replicable over many plants . The methods it has been revealed objective and consistent. The easy implementation methods make also simple the continuous update including more and more specific conditions initially not taken into account (i.e. different pipe materials).

One of the most innovative approach in the method is to take into account in the definition of the ratings of the parameter the presence or absence of information. This allow to avoid the necessity of involve in the assessment procedure activities of specialists that are generally expensive and time consuming.

Last but not least, thanks to the availability of a quantitative output, it is possible to prioritize the actions focusing the owner effort on the penstock, among the ones in the portfolio, that has a higher RPN or risk index.

On the other hand, as the system is matrix-based, its flexibility is still limited. Besides, as it relies on the decision-making of the operator (even though the decisions are guided), a certain degree of subjectivity is unavoidable.

In the light of the successful application of the method to the 17 case studies the current method will be applied to other penstocks around Italy. This will make possible to study other different penstock configuration making the proposed evaluation even more general.

Furthermore, the proposed scheme will be modified in order to allow the assessment of other HPP parts like waterways and tunnels.

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