A new step in the risk assessment’s procedure: extension to all the hydropower waterways

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Introduction

Last year, during Hydro2019 in Porto, STUDIO FROSIO presented the results of a simplified procedure for penstock risk assessment.

The innovation of the proposed method consisted in providing a tool to preliminarily evaluate the risk of penstocks failure. That has been useful both to prioritize the plants to be subjected to more in-depth analysis and allow to focus on more critical failure processes.

The method was based on an innovative grid built on the classical definition of risk as product between damage and probability of occurrence. The concept of interceptibility, derived from the “likelihood of detection” of FMEA (Failure Mode and Effect Analysis) was furthermore added in order to better fit the risk definition to the specific subject of the analysis.

The new method proposed, at the time limited to the preliminary evaluation of the risk associated to the penstocks failure only, has been today expanded to other waterways of a hydroelectric plant, as tunnels and channels.

The approach proposed has really been successful, so much that today it is planned to be applied to more than 100 real cases in the Bolzano Province by the end of the year.

The results of the performed analysis provide not only a large statistic base for further evaluation and optimization of the method itself but also a consistent dataset to get a better knowledge of the actual state of health of the HPPs in the region.

In continuity with the Hydro2019, this year, the process that led to the extension of the method to the other civil works of the plant has been described in this paper.

Additionally, a statistic analysis and a critical evaluation of the results of the risk assessments performed is proposed. The analysis is focused on defining which type of the structure (penstock, tunnel or channel) is characterized by the highest risk level. Furthermore, within the same type of structure, the types of failure which are characterized by a higher recurrence will be detected and critically analysed.

1. The method

The evaluation of the potential risk of failure of the considered waterways has been performed by means of the computation of the Risk Priority Number (RPN) index. This index is the main concept of the Failure Mode and Effect Analysis (FMEA). It is the product of three ranked parameters: the *occurrence*, the *severity,* and the *detection*. For each element (penstocks, tunnels and channels) different failure modes have been considered and, for each of them, the possible causes are analysed.
Afterwards the RPN is computed for each cause of each failure mode (*Table 1*). Then, the global risk level of the structure has been associated to the maximum RPN computed (*Table 3*).
In the traditional FMEA, the criteria for quantifying the three parameters are mostly subjective, and they are described qualitatively in natural language based upon the experience of teams (LIANG, 2013). To overcome this problem, Studio Frosio went more in deep in the failure mechanism correlating *occurrence, detection*, and *severity* with the surrounding environment, providing relations to determine the value of these parameters in a quantitative or semi-quantitative way.
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 could be modified according to the reliability of the existing information by means of the introduction of specific correction coefficients.

Component	**Failure mode**	**Cause**
Penstock	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
Tunnel	Partial failure	Instability and/or decay of the rock mass structural conditions
		Presence of active/inactive tectonic lines and seismology
		Critical hydrogeological conditions
		Absence or damage of the lining
		Failure of the watertight doors in the manholes
		Presence of irrigation valves
		Human error
	Total failure	Slopes instability
		Critical sections
		Attacks and vandalism
Tailrace channel	Banks overflow	Flood hazard
		Unsuitable freeboard
	Partial failure	Seismology
		Structural failure of the work
		Human error
	Total failure	Slopes instability
		Attacks and vandalism

Table 1. Analysed events and relative failure modes

1.1 Parameters definition

1.1.1 Determination of the Occurrence

In the hydropower sector, a consistent lack of information regarding failures can be experimented due to the inclination of owner, constructor and manufacturer not to share information regarding failures in their plant. Additionally (fortunately), the number of failures in the hydropower sector are not so many to provide a solid sample that could justify statistical analysis.

The lack of these information affects the determination of the occurrence which is generally performed according statistical analysis based on the number of failures over the number of pieces realized. 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.

Penstocks

For each cause assumed for the type of failure considered the parameters which lead in the occurrence evaluations are reported below.

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 could influence the occurrence rating for stray current cause. According to the actual conditions the occurrence rating is set between 0 and 2.

Human error: The occurrence of penstock failure due to human errors could be correlated to the presence (or absence) of specific procedure and protection in the plant automation system aimed to prevent unintentional damages caused by the user’s actions. For this cause the occurrence value could vary between 1 and 2.

Damage or pull-out of expansion joints: The probability of pull-out or damage of the expansion joints has been related to the number of inspections and the type of maintenance operations performed to these critical components. According to those parameters the occurrence could vary between 1 and 3.

Failure of connections: The occurrence of failure of the connections is related to the type of connection (ribbed or welded) and to the outcomes of inspections. Its range is set between 1 and 3.

Failure of supports: The number of pipes supports that can fail without causing the failure of the penstock shell is the parameter considered. The higher this number, the smaller the occurrence value: the occurrence rating is set between 1 and 3.

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 evaluated by means of a visual inspection (focused on the evaluation of the state of wear) an its value can vary between 1 and 3.

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. According to that the occurrence rating is set between 1 and 3. Correction factors has been introduced in order to take into account possible lack of data concerning the structural and environmental conditions, thickness or stress testing.

Wear of pipe shell: Regardless of its stress state, the pipe shell may deteriorate due to the sediment transport. The general lack of precise information about the conditions of the shell (obtainable only with internal pipe inspection or dedicate test) has been overcome considering the type of watercourse (river or creek) and the presence (or absence) of other HPPs upstream to the intake which can give an indications about the amount of suspended sediment in the water and conveyed in the penstock. The occurrence rating is set between 1 and 3.

Boulders 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. Hydrogeological instabilities reported in literature lead to high values of occurrence, especially if there are evidence of past events. The occurrence rating is set between 1 and 2.

Attacks and vandalism: The probability of such an event is related to the social environment of the area in which the plant is located. Generally, considering the current peaceful situation, the probability is very low. Therefore, a value of occurrence to 1 has been chosen. Nevertheless, the value could be increased up to 4 in case of very critical environment.

Tunnels

For each cause assumed for the type of failure considered the parameters which lead in the occurrence evaluations are reported below.

Instability and/or decay of the rock mass structural conditions: For the determination of the occurrence of this cause of failure the type and quality of the rock mass and the outcomes of the inspection reports are considered. Concerning the inspection, differential settlements and cavities, symptomatic of the poor quality of the rock, are the main defects that should be detected. For what concern the type of rock, generally, magmatic and metamorphic rock masses have better geotechnical and mechanical properties than recent sedimentary rock masses. The occurrence of tunnel partial failure can assume a value between 1 and 4.

Presence of active/inactive tectonic lines and seismology: The presence of active or inactive tectonic lines is detected according the available information and cartography. According to the presence or absence of these “risk factors”, and according to the seismology and to the quality of the rock mass, the occurrence could vary between 1 and 4.

Critical hydrogeological conditions: Water-flows into tunnels can lead to important damages to the structure (damage or decay of the lining, decay of the rock mass). These phenomena cannot be negligible especially for superficial tunnel in morainic soils or heavily fractured rock masses.
The occurrence of tunnel partial failure due to the presence of critical hydrogeological conditions is evaluated by means of the results of the inspections and hydrogeological maps which provide information about the permeability and the flow lines of the area. Its value range is set between 1 and 2: the greater the permeability of the area, the higher the occurrence value. The occurrence value can be increased by 0.5 if we are dealing with a superficial tunnel. If no information regarding the hydrogeological conditions of the soil are available, a correction coefficient is introduced that lead to an increase of the occurrence value up to 4.
Absence or damage of the lining: The absence of the lining has been analysed in combination with the structural conditions and the quality of the rock mass: if the quality of the rock mass is good, the absence of the lining is not critical for the safety of the structure. On the other hand, in case of poor quality rock mass, the absence of tunnels lining, or the presence of damage in the existing lining, could represent an important cause of failure.
According to the evidence reported above the occurrence value range is set between 1 and 4.
Failure of the watertight doors in the manholes: Frequently, due to the important length of the tunnel structures, there are manholes along the tunnels to guarantee the access at the different tunnel progressive. The connection with the external environment is ensured and protected by watertight door. Although there is no historical evidence of defects, failures of the watertight doors can lead to water leaks which could hinder the access to the manholes during maintenance operations. According to the conditions of the watertight door an occurrence between 1 and 4 could be assigned in the model for this cause of failure.
Presence of irrigation valves: Sometimes, along the tunnel, there are derivations for irrigation purposes. These are generally regulated by valves. To ensure their functionalities, valves require regular inspections and maintenance. The probability of failure of these elements can be linked to the frequency of these activities. According to that the occurrence rating is set between 1 and 3.
Human error: As for the penstocks, the occurrence of tunnels failure due to human errors could be correlated to the presence (or absence) of specific procedure and protection in the plant automation system aimed to avoid unintentional damages caused by the user's actions. For this cause the occurrence value could vary between 1 and 2.
Slopes instability: The occurrence of tunnels total failure due to the slope instability is evaluated by means of geological maps which provide information about this complex phenomena in the area interested by the tunnel. According to the information reported the occurrence rating is set between 1 and 4. This value can be increased by 0.5 if there are evidence of past events.
Critical sections: The inlet and the outlet of a tunnel are critical sections for the tunnel structure in which all the failure mechanisms already considered may occurs with more frequency. A value of occurrence between 1 and 4 is attributed by means of a correlation with the sum of the occurrence value related to all the previous causes analysed.
Attacks and vandalism: The probability of such an event is related to the social environment of the area in which the plant is located. Generally, considering the current peaceful situation, the probability is very low. Therefore, a value of occurrence to 1 has been chosen. This value should be increased up to 4 in case of very critical social environment.

Channels

For each cause assumed for the type of failure considered the parameters which lead in the occurrence evaluations are reported below.
Flood hazard: Flood events affecting the receiving water course can lead to accumulations of transported material and obstruction of the tail race channel with the consequent overflow of the water. The probability linked to this failure cause is evaluated by means of the hydraulic risk maps. If there are evidence of flood past events, the occurrence value will be higher. Its value range is set between 1 and 2.
Unsuitable freeboard: In the channel design best practice it is necessary to consider the worst surge height in determining the height of the banks in order to ensure an adequate freeboard. If an adequate freeboard is not provided, a flood could happen. According to the safety coefficient considered in the design, occurrence vary between 1 and 4.
Seismology: The occurrence of this cause is related to the seismic classification of the area which can be easily studied by means of seismic hazard maps. Occurrence could vary between 1 (low seismicity) to 4 (very high seismicity).
Structural failure of the work: The probability linked to this failure cause is evaluated by means of the comparison between the stress acting on the structure and the strength values in the worst load conditions (generally empty channel). According to that ratio the occurrence value range is set between 1 and 4.

Human errors: As for the penstocks and tunnels, the occurrence of penstock failure due to human errors could be correlated to the presence (or absence) of specific procedure and protection in the plant automation system aimed to avoid unintentional damages caused by the user's actions. For this cause the occurrence value could vary between 1 and 2.

Slopes instability: The occurrence of channel failure due to the slope instability is evaluated by means of geological maps which provide information about the slope instability of the area crossed by the channel. According to this information, the occurrence value can vary between 1 and 4 also considering the distance between the slope and the channel axis. Finally, the occurrence value can be increased by 0.5 if there are evidence of past events.

Attacks and vandalism: The probability of such an event is related to the social environment of the area in which the plant is located. Generally, considering the current peaceful situation, the probability is very low. Therefore, a value of occurrence to 1 has been chosen. This value should be increased up to 4 in case of very critical social environment.

1.1.2 Determination of Severity

Starting from the assumption that the severity of a damage due to a component failure is not related to the component but it is related only to the damage occurred to the surroundings, the evaluation range for the severity has been set equal for each component (penstocks, tunnels and channels).

The severity evaluation is the one initially proposed for the penstock: it is assumed that the extent of the damage, i.e. how severe are the consequences of an event, depends on the following parameters:

Definitions	Value
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

Table 2. Criteria for the evaluation of the severity rating

It must be noted that the above damages are not mutually exclusive. When the most severe one happens, it often comes with the less severe ones. In the method, the higher damage is the one that is considered for the rank of the severity parameter.

The evaluation of the type of damage is strictly related to the urban environment close to the waterways 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 waterways path.

1.1.3 Determination of Detection

Detection is linked to the effectiveness of the controls aimed to prevent and/or detect the cause or failure mode before the failure cause major damage.

The detection systems are considered as the combination of:

a. A system of *measure* that allows to alert when the plant is working out of normal conditions (usually differential system, velocity measure, water level gauge etc.)
b. A system for the *interruption* of the flow in the waterways if the plant starts to work out of the normal operating conditions. Generally, this is constituted by valves or gate.

Penstocks

It exists a wide range of detection systems and their difference consist mainly in how small is the deviation from the normal working conditions that they are capable to detect. The most common detection systems installed on HPP's penstocks are paddle type flow switch (able to detect total failure and partial failure of the penstocks) and differential discharge measure systems (which are able to detect even small breach in the penstock).,

According to the capability of the installed detection system to detect even small failure, the detection parameter could assume a value ranging between 1 (differential system) and 5 (absence of any detection system).

In addition, a correction coefficient (up to + 1) is applied in order to take into account additional factors such as redundancy, frequency of the functionality tests and possibility to detect also visually the damage at the penstock.

Tunnels

Due to the nature of this type of works, no effective detection systems are available on the market. Frequent and scrupulous inspections are the only way to get a global knowledge of the state of health of the tunnel and to detect any type of failure. Accordingly, the frequency of the inspections is the first parameter considered in the rank of detection. This cover the evaluation of the *measure function* of the detection system.

The second function of the detection system is the *Interruption function*. Generally, interruption system as gate or valve are installed at the head of the tunnel and on the length of the tunnel in correspondence of the junction with secondary derivations. The time necessary for the personnel to reach the closure button (if any) in the worst conditions is taken into consideration as additional parameter in the determination of the detection rank.

Regarding any secondary intake works (common in tunnels), additional aspects are considered such as:

i) their potential contribution to the failure, in terms of flow rate;
ii) their accessibility;
iii) the time to reach them.

Multiplicative coefficients which express the aspects described above declined for the secondary derivations has been considered.

According to the parameters described above a value between 2 and 5 is assigned at the detection parameter.

Channels

The evaluation of the detection in channel is based on the presence, on the channel of a level gauge (*measure function*) and to the presence of a gate or other *interruption* device.

Detection can assume 3 values:

i) level gauge with automatic intervention of the flow interruption device D=1;
ii) level gauge without automatic intervention of the flow interruption device D=3;
iii) no detection systems D=5.

1.2 Risk definition

For each cause of failure mode considered, independently by the type of structure analyzed, the risk is evaluated by means of the RPN index, defined as the product of Occurrence, Severity and Detection:

$$\mathbf{RPN = O \cdot S \cdot D}$$

At the maximum value among the ones computed is associated the global risk level of the structure. According to the resulting risk level some corrective actions could be taken in consideration in order to lowering the global level of the risk of the structure (see table below).

Risk level	Actions
Negligible (up to12)	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

Table 3. RPN values and required action

The definition of the risk level is equal for each component, i.e. penstocks, channels and tunnels and it is related only to the RPNs resulting from the analysis. This allows to compare the results obtained for different works with each other.

2. Application to the real cases

Due to the Covid situation, there has been a delay in the application of the method. Instead of the 100 structure initially planned, to date, the pre-assessment method has been applied only to 25 different plants for a total of 58 structure: 35 penstocks, 15 tunnels and 8 channels.

Even if the number of structure analysed is well below the expectation, the amount of data obtained is sufficient to perform a critical statistical analysis on the results coming from the application of the method.

In the pictures below (*Fig.1 – Fig.6*), some real examples for each type of analysed structure are shown.

Fig. 1. Example of assessed Penstock

Fig. 2. Example of rivetted type of connection

Fig. 3. Water intake inlet sections of assessed tunnel

Fig. 4. Watertight door along the headrace tunnel

Fig. 5. Example of assessed Tailrace channel

Fig. 6. Example of assessed Tailrace channel

Statistical analysis

As a preliminary step, a pooling of all the obtained results has been done: all the global risk level computed for all the assessed works has been collected in a unique sample able to describe both how the method responds to the application at different structures and to understand the global state of health of the portfolio analyzed.
As shown in the graph *Fig. 7*, most of the assessed works is characterized by a medium risk level (48%). The cause of this results has been investigated in the analysis presented below.
Regarding the response of the method to the application to different structures it is important to underline that the method provide different results for different structure characterized by different conservation level. This proves that the method is capable to detect the different status of the structure.

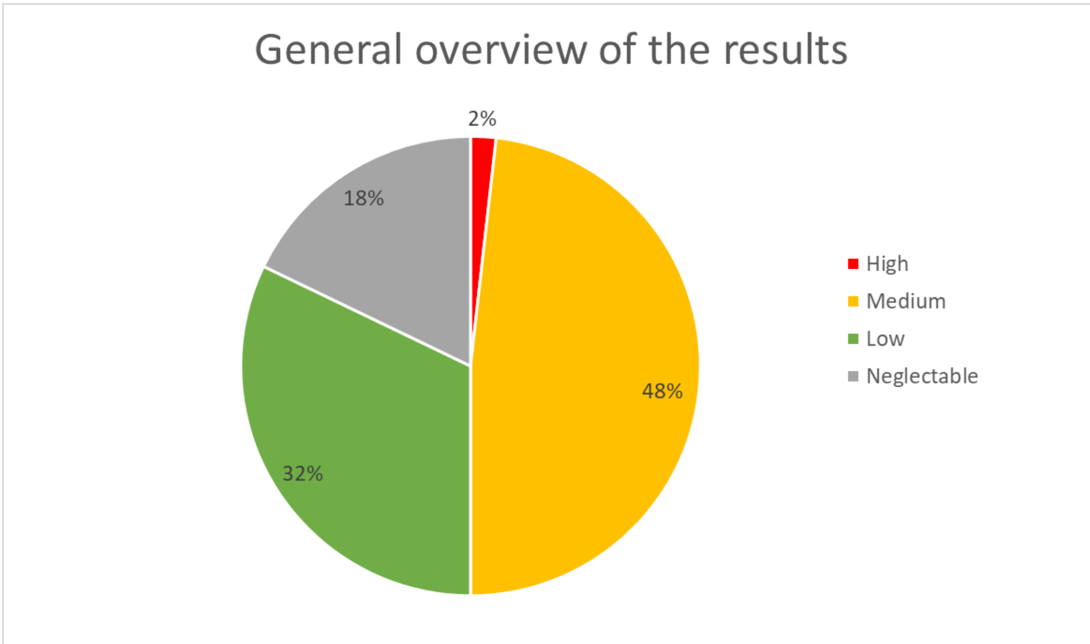

Fig. 7. General overview of the results

More detailed results concerning each type of waterways analyzed (penstocks, tunnels and channels) are presented below.
The description of the results related to the analysed structure is presented according to the subdivision by i) the risk level and ii) the cause of the highest RPN value that lead to the global risk level.
Lastly the most recurrent cause which lead to the definition of the global level of risk for the structures has been analysed.

Penstocks

Among the 35 penstocks assessed, 9 (26%) resulted with a negligible global level of risk, 6 (17%) penstocks are characterized by a low global of risk and 20 (57%) with a medium global level of risk.

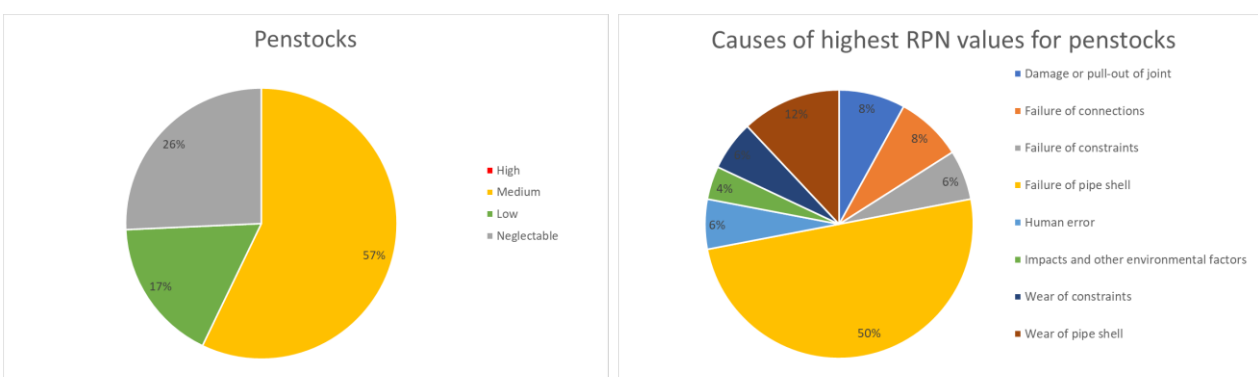

Fig. 8. Graphs showing the results for penstocks

The most common cause which lead to the definition of the global level of risk is the *failure of the shell* (Fig. 8). This cause of failure has been studied more in deep in other to understand what are the factors that lead to a such high RPN. For each parameter (occurrence detection and severity) the rank has been subdivided in sub-classes and the frequency of the assigned value has been evaluated.(*Tab.4*).

Cause: Failure of pipe shell					
Range of Occurrence	**No.**	**Range of Detection**	**No.**	**Range of Severity**	**No.**
0-1	3	0-1	4	0-1	1
1-2	4	1-2	6	1-2	33
2-3	11	2-3	1	2-3	1
3-4	17	3-4	2	3-4	0
		4-5	22	4-5	0

Table 4. Occurrence, detection and severity frequency related to the most critical cause

17 Penstocks over the 35 are characterized by an occurrence related to the failure of the shell between 3 and 4 (the highest possible). It is important to underline that high values of occurrence is related to the lack of information regarding the materials of the penstock and not from an effective structural failure risk of the penstock. Since the evaluation of the occurrence has been made according to a rigid matrix, in case of the lack of information, the value of the occurrence is strongly affected by a correction coefficient. Even if this correction factor is highly detrimental for the entire evaluation, thanks to its introduction it has been always possible to complete the analysis without additional (expensive) investigation in a quantitative and standardized way.
22 Penstocks over the 35 are characterized by a detection value between 4 and 5 (the highest possible). Such high value is correlated to the absence of a suitable detection systems is highly detrimental for the global evaluation of the RPN. By the way, the provision of sensitive detection systems (i.e. differential systems) is relatively inexpensive if compared to the total cost of the plant or to even only to the cost of the penstock. It follows that a lowering of the global risk value of the structure could be easily achieve with relative small effort by installing these types of detection system. This is particularly true in case of exposed penstocks. On the contrary, if the penstock is buried, problems in the installations of such detection systems arise and the procedure could become quite expensive and not always justified.
Severity for all the assessed penstocks is between 2 and 3, relatively low. 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.). The penstock path 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.

Tunnels

As for the penstocks, the results of the pre-assessment method applied to the tunnels are presented according to the global risk level of the structure. A more detailed analysis on the causes which determine the higher RPN in the risk evaluation is then proposed.
Among the 15 tunnels assessed, 11 (73%) resulted with a low global level of risk and 4 (27%) with a medium global level of risk none with an high global risk level.
The most common cause associated to higher RPN is related to the critical hydrogeological conditions (Fig. 9).

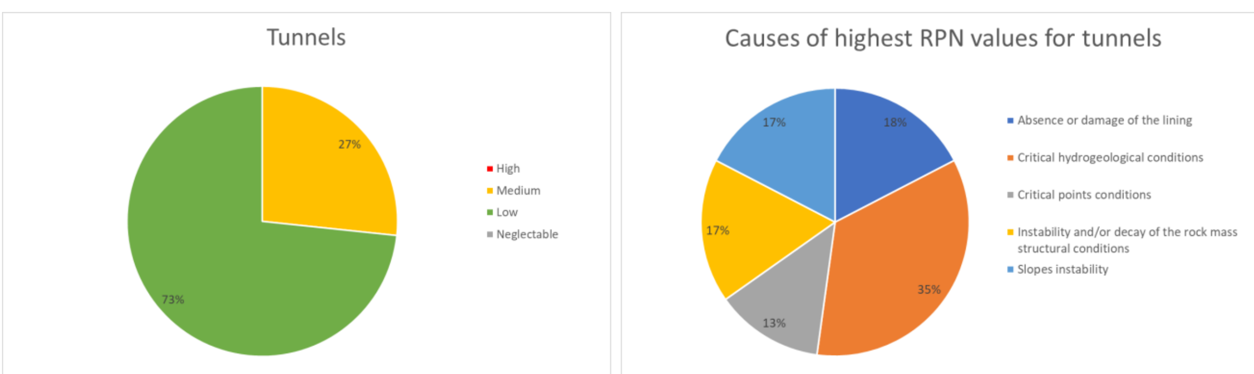

Fig. 9. Graphs showing the results for tunnels

The absence of tunnel characterized by high level of risk is mainly due to the fact that this type of structure is generally well maintained and frequently inspected by the owner of the HPPs. This could be correlated to the value of the structure. The cost of realization of tunnels is higher with respect to the cost of penstocks and channels so the owner is more inclined to perform all those activities that can extend their useful life.
From the analysis of the causes of the failure which lead to the higher RPN (*fig. 13*) it is possible to understand that there is not a recurring cause. This because in different context different factor could determine the global level of risk of the structure. This confirm once more time the site specificity of this type of structure.
Nevertheless, the results show a light predominance of the cause *critical hydrogeological conditions.*
Within this cause, the frequency assumed by values of occurrence, detection and severity has been evaluated (*Tab.5*).

Cause: Critical hydrogeological conditions					
Range of Occurrence	**No.**	**Range of Detection**	**No.**	**Range of Severity**	**No.**
0-1	0	0-1	0	0-1	0
1-2	2	1-2	4	1-2	15
2-3	2	2-3	11	2-3	0
3-4	11	3-4	0	3-4	0
		4-5	0	4-5	0

Table 5. Occurrence, detection and severity values related to the most critical cause

Among the 15 tunnel 11 has an occurrence between 3 and 4 (the highest possible). This is not related to effective hydrological conditions in the site but because, despite the availability of several maps regarding geological characterization, hydro-geological hazard maps, landslide and avalanche, no information about the soil permeability has been found. Furthermore, a detailed characterisation of the soil crossed by the tunnel is not available. Due to the completely lack of information, a maximum occurrence value equal to 4 has been set for all the assessed structure.
Most of assessed the tunnel (11 over 15) have a detection ranked between 2 and 3 (relative low value). For the tunnels, detection is assessed especially in relation to the presence of an adequate inspections plan. Since it represents a crucial requirement for the efficient operation of the structure, for all the assessed tunnels, frequent and adequate inspections are foreseen, and their resulting reports have been made available by the Client. For this reason, detection has assumed low values and not cause an increment of the RPN value.
As for penstocks, the evaluation of the severity of the different failure mode has been done considering the exposed element in the surrounding of the tunnel (houses, roads, electrical lines, railways etc.). Severity for all the assessed tunnels has a value between 2 and 3. Since most of the tunnels are characterized by several kilometers of length, sometimes their paths can affect some critical elements such as roads, cycle lanes, hiking trail or they can cross some urban areas (mainly, not densely populated). On the other hand, frequently their paths cross woods, fields, and meadow, and they have been tunneled several meters under the surface. For this reason, a potential failure of the tunnel can unlikely jeopardize the people safety and activities.

Channels

According to the 4 risk classes proposed, among the 8 channels assessed, 1 (12,5%) resulted with a negligible global risk, 3 (37,5%) channels are characterized by a low global risk, 3 (37,5%) with a medium global risk and 1 (12,5%) with a high global risk.
The most common cause associated to higher RPN is related to the *structural failure of the work* (*Fig. 10*).

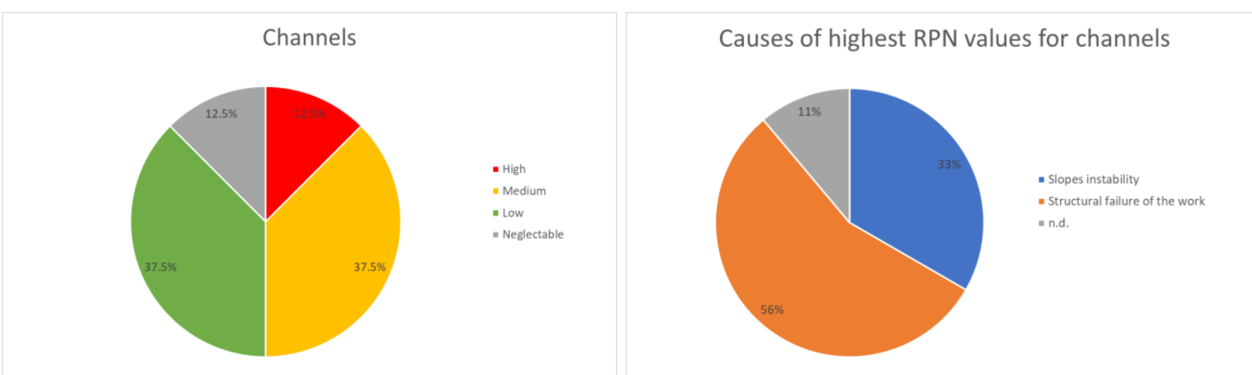

Fig. 10. Graphs showing the results for channels

Within this cause, the frequency assumed by values of occurrence, detection and severity has been evaluated (*Tab.6*).

Cause: Structural failure of the work					
Range of Occurrence	**No.**	**Range of Detection**	**No.**	**Range of Severity**	**No.**
0-1	0	0-1	0	0-1	2
1-2	0	1-2	0	1-2	5
2-3	0	2-3	1	2-3	0
3-4	7	3-4	0	3-4	0
		4-5	6	4-5	0

Table 6. Occurrence, detection and severity values related to the most critical cause

The whole channel, the occurrence of the structural failure is characterized by an occurrence between 3 and 4 (the highest possible). As for penstocks, high values of occurrence are related to the structural failure of the work come from the lack of information regarding the materials and from the lack of detailed drawings reporting the channels characteristics and not from an effective structural failure of the work.

The same consideration made for the penstock could be done also for the channels: even if the application of the correction factor could be detrimental for the resulting RPN it allows to perform this type of analysis also in case of absence of input data and without the necessity to perform expensive and time consuming additional investigations.

Detection is another critical parameter.6 over the 7 channels analysed are characterized by a detection rank between 4 and 5 (the highest possible). Most of the assessed channels are not provided by an adequate detection system. This because the need to keep under control this type of waterways is not considered crucial for the plant by the owner. As for the penstocks, the provision of an adequate detection systems (i.e. level gauge) is relatively inexpensive if compared to the total cost of the plant. It follows that a lowering in global RPN value can be easily obtained if high RPN values are caused by this parameter.

As for the other components, the evaluation of the severity of the different failure mode has been done considering the exposed element in the surrounding of the channel (houses, roads, electrical lines, railways etc.). In most cases, severity ranges between 1 and 2. Since all the analysed channels are tailrace channels and, in general, due to their limited extension in terms of length, they cross a limited area close to the powerhouse, the value of severity associated to the channels is very low. Sometimes, especially if the powerhouse is located close to an urban area, the path of the tailrace channel can involve roads or cycle lanes. In this case, the severity value can be increased up to 3.

3. Conclusions and further optimization

From the application to the real cases of the innovative risk pre-assessment method the following considerations could arise:

i) The method is easily implementable eve in absence of specific information about the structure thanks to the introductions of some corrective factors able to take into account the uncertainties derived by the lack of the information. Even these factors could highly impact the resulting RPN and it reflects on the final global level of risk of the assessed structure the advantages deriving by the use of this coefficients such as to avoid additional investigations by specialists (that are generally expansive and time consuming) are undeniable.

ii) Thanks to the implementation of the method by means of a simple spreadsheet a positive reduction of the time required by the analysis has been experimented. This permit to apply this method on large scale. The easy way in which the analysis could be performed has also other advantages such as to allow to simulate in very short time the result of correction actions which could be assumed with the aim to reduce the level of risk and to makes also simple the continuous update of the level of risk of the structure.

iii) Despite the effort to make the analysis as much objective as possible a certain degree of subjectivity is still present. In any case this small degree of subjectivity does not substantially affect the results.
The method has been revealed objective and consistent and capable to differentiate the results according the actual state of risk of the different structures.

iv) Thanks to the expression in quantitative way of the output of the method (RPN is basically a number) it is possible to prioritize the actions focusing the owner’s effort on the structures that have a higher RPN or risk index. For this reason, the method could be considered as a decision-making tool.

All these advantages, which has been already shown during the application of the method to the only penstocks, are still valid also for the application to the new assessed components.

The method is still being perfected and its modular structure allows to further optimization such as the introduction in the analysis of more specific conditions initially not considered.

This will lead to new challenges that Studio Frosio and its team are looking forward to taking on them.

References

1. **Sankar, N.; Prabhu, B.;** "Modified approach for prioritization of failures in a system failure mode and Effects Analysis", *The International Journal of Quality & Reliability Management*; v.18, n.3, 2001.
2. **Palady P.,** "FMEA Author's Edition by Paul Palady",1997.
3. **Liang X.,** "A new method for failure modes and effects analysis and its application in a hydrokinetic turbine system", *MSc Thesis*, 2013.
4. **Papetti, L.L.; Cazzago, D.; Frosio, G.; Festa, F.; Irsara, H.,** "Development of a simplified procedure for penstock risk assessment", *Hydro 2019*, Porto, 2019.

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