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A railway culvert maintenance management approach based on risk assessment techniques

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Abstract

Culverts are essential elements of any railway infrastructure. Although there are commonly a large number of these elements in any transport infrastructure, its proper maintenance is often treated as a secondary issue when it comes to the management of ordinary maintenance investments. The aim of this work is to present a methodology intended to create strategies for prioritizing investments in culvert maintenance works. Applying risk assessment techniques, a preliminary diagnosis of the current culvert condition can be obtained, evaluating failure probabilities and quantifying socioeconomic impacts. At the same time, common pathologies and general risk factors are identified in order to determine the optimal solutions to the culvert current issues. Assessment of all culverts in a transport network allows to efficiently managing the investments in ordinary maintenance, optimizing the expenses and minimizing risks.

Keywords: culverts, infrastructure maintenance, risk assessment, investments optimization

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1. Introduction

Culverts are essential elements of any railway infrastructure, however this kind of assets tend to be ignored until a catastrophic failure occurs. Culvert failure may range from structural collapse to insufficient capacity to pass floods and it might affect not only the infrastructure itself but also it could cause serious problems on the railroad and its surroundings, such as damage to the nearest properties, floods and major traffic disruptions.

Although the design of railway culverts is currently subject to national technical regulation: (Ministerio de Fomento, 2015), (Ministerio de Fomento, 2014); maintenance management aspects and evolution of service levels through time are not considered. Experience in other countries (USA, Australia) shows that having up-to-date and detailed information about culvert conditions is crucial when it comes to maintenance management (Federal Highway Administration, 2010) and planning of preventive maintenance activities (Balkham et al., 2010). As many of these structures reach the limit of their service life, management administrations must need to schedule their replacement or repair (Najafi and Bhattachar, 2010), however, currently they do not have and adequate prioritization methodology that help them planning this operations though time, so these operations are often undertaken once the incidence in the service level has occurred (corrective actions).

Figure 1. Traffic disruption events caused by culvert failure: overtopping flows and infrastructure collapse.

The aim of this work is so to develop an objective methodology based on risk assessment techniques for railway and road culverts in order to build investments prioritization models for those infrastructures. The methodology is based on the combination of probabilistic models related to the different culvert failure mechanisms and the repercussion or consequences that the failure event on the global level of service of the infrastructure. Finally, a global assessed risk level derived from the general likelihood and consequence analysis is obtained (Roads and Traffic Authority, 2010). Failure likelihood assessment is based on the analysis of failure modes, or situations where the service levels in the infrastructure are totally cut off due to culvert malfunction, including slope instability, local scour and platform overtopping flows events. Likelihood analysis of failure mechanisms is based on overall material deterioration evolution models (Salem et al., 2012), hydrologic and hydraulic characterization and preliminary analysis of embankment stability and local scour in inlets and outlets (Galán et al., 2016). On the other hand, consequence analysis is not only based on economic costs quantification (Perrin and Jhaveri, 2003), but also in the repercussion assessment for whole society.

Since the main objective of this work is to globally apply the proposed methodology to the railway transport network, being able to massively address the preliminary risk assessment of a large set of assets is a key issue of the process. Some specific applications have been developed in order to overcome this issue. Maintenance investments prioritization will be determined by the profitability of the proposed actions in every analysed culvert based on the nature and entity of the observed pathologies. Thus, it is not only possible to prioritize the kind of proceedings required at a specific time following economic criteria, but also analyse and compare the profitability of a set of preventive actions to be carried out in a certain section of the infrastructure or in the whole transport network.

The present document presents the risk assessment methodology proposed to obtain the assets preliminary diagnosis and its suitability to perform global analysis on railway and road infrastructures.

2. Methodology

The proposed methodology is based on the quantification of the asset risk level. The circumstances that constitute failure of hydraulic structures, including culverts, can be defined differently depending on the viewpoint of the analyst and purpose for the analysis. For the purpose of this analysis, failure events are defined as those situations leading to partial or total railway traffic disruption. Failure may range from structural collapse of any of the elements constituting the culvert (culvert barrel, headwalls, wingwalls and auxiliary structures), to insufficient hydraulic capacity to pass floods. The asset risk level is determined as the combination of the probability of occurrence of each of the events leading to failure (failure mechanisms) and the impact or consequences derived from this situation.

The asset risk level assessment requires a complete characterization of the culvert and its surroundings, thus it is crucial to develop a regular inspection program based on field analysis, including a detailed evaluation of the following items:

- Culvert barrels: including geometry and general condition assessment (related to structural damage).
- Inlet and outlet structures: including general configuration, geometry and condition assessment.
- Embankments: geometry characterization, general soil characterization and current condition (presence of evident signs of slope instability caused by influx or piping) based on visual assessment.
- Waterway: characterization of the waterway downstream the culvert outlet, including shape and approximate geometry of the cross section.
- Adjacent areas: general determination of location and main characteristics of the nearest elements to the culvert inlet or outlet that could be affected by an occasional instability of the railway embankment or a structural collapse of the headwall.

The field assessment must be complemented with further desktop analysis in order to determine all the required parameters to accurately evaluate failure probabilities and potential impacts of the culvert failure. The information required in this case range from average data of railway traffic intensity to the characterization of the waterway drainage basin. The aim of this work is to provide a preliminary diagnosis of the current performance of all culverts inspected, so that it is possible to prioritize the care level of each asset according to an objective parameter: the asset risk level, quantified by the yearly average economic impact of the culvert failure.

Once the assessed risk level has been determined, the preventive actions to be carried out in each case can be prioritized according to risk reduction criteria. According to the preliminary diagnosis, the key pathologies or risk factors that affect the culvert are identified and based on this information, a series of standard actions are proposed to address the deficiencies found. Each action has a specific cost and an economic repercussion on the assessed risk level defined as the reduction of the annual risk of failure caused by such remedial works. Based on these parameters, it is possible to carry out a cost-benefit study of each of the considered actions and lastly, selecting the actions in each case according to profitability criteria in the short, medium and long term.

The repairs or remedial works selected must fit within the budget availability, so that the most cost-effective actions are carried out in the first place

2.1 Failure probability

The annual failure probability of a culvert is determined as the sum of the failure probabilities of each of the failure mechanisms operating in the influence area of the culvert, causing partial or total traffic disruption in the railway. These events are grouped into four main categories called failure modes (Roads and Traffic Authority, 2010):

1. Failure mode 1: Structural collapse. There is only one potential failure mechanism:
    - 1.1 Structural collapse of the culvert barrel.
2. Failure mode 2: Slope instability. There are four potential failure mechanisms:
    - 2.1. Slope instability caused by afflux.
    - 2.2. Slope instability caused by leakage out of barrel.
    - 2.3. Slope instability caused by headwall collapse.
    - 2.4. Slope instability caused by undermining at inlet or outlet.
3. Failure mode 3: Piping. There are three potential failure mechanisms:
    - 3.1. Piping into culvert.
    - 3.2. Piping on outside of culvert due to afflux
    - 3.3. Piping on outside of culvert due to leakage out of culvert.
4. Failure mode 4: Hydraulic flow. There are two potential failure mechanisms:
    - 4.1. Erosion by overtopping flows.
    - 4.2. Cross catchment flooding.

Thus the previous mechanisms are considered independent phenomena and therefore the annual probability of failure of the culvert (global) is assessed as the sum of the probabilities of each failure mechanism. Each mechanism is constituted by a series of events that must occur sequentially so that the failure mechanism is able to take place. These events are divided into two different categories according to its nature:

- Precedent events: these events caused the failure situation, corresponding to an initial situation linked in most cases to a rainfall event or the current condition of the culvert barrel, headwall and wingwalls (deterioration). Adverse circumstances are essentially weather-related precedent events – either exceptional rainfall or extreme groundwater levels. In such cases the probability of failure may be governed by the return period of the necessary precedent event, which would be reflected in the assessment of an annual probability of failure.

- Triggering event: on the other hand, once the precedent event has taken place, the triggering event reveals the likelihood of the infrastructure to be affected by the failure mechanisms. In this case the annual probability of failure may depend on the culvert component geometry and configuration. Depending on parameters such as the height of fill, the soil type and embankment configuration, the global failure probability may vary according to the ability of the current configuration to potentiate or mitigate the adverse effects of the triggering events.

A series of specific studies have to be carried out in order to assess the probability of certain events previously mentioned. Some of which are:

- Hydrologic characterization of the drainage basin: a complete preliminary characterization of the watershed must be undertaken. Hydrologic semi distributed models are applied in order to proceed to the upstream peak flows calculation.
- Hydraulic characterization of the culvert: according to the culvert current configuration, geometry and waterway characteristics, the hydraulic performance of the culvert in the peak flow situations can be obtained.
- Embankment slope instability caused by afflux preliminary studies: considering the hydraulic performance of the culvert previously obtained.
- Embankment slope instability caused by undermining at inlet or outlet preliminary assessment based on experimental studies (Galan et al., 2016).

The integration of these specific studies on the global assessment of the failure probability of each failure mechanism is crucial to identify pathologies linked to potential deficiencies of the hydraulic capacity of the culvert. Additionally, each failure mechanism can be easily decomposed into a series of risk factors, defined as the main pathologies that can lead to the culvert failure. According to its nature, the risk factors are divided into five main categories:

- Partial or total blockage of the culvert barrel.
- Structural deterioration of the culvert barrel.
- Structural deterioration of the culvert headwall or/and wingwalls.
- Evidences of substantial erosion at the culvert outlet or inlet (undermining).
- Deficiencies found in the hydraulic capacity of the culvert.

Figure 2. Risk factors examples: structural deterioration of the culvert barrel, partial blockage of the culvert barrel, evidences of substantial erosion at the culvert outlet.

Identification of the influence level of each risk factor is crucial in order to determine the optimal remedial works to be undertaken in each asset.

Failure consequences

The main purpose of the consequence analysis is to identify the effects of the hazards on the element at risk. The consequences of the culvert failure can be described as the socioeconomic impact produced by subsequent traffic disruption. Those consequences are divided into two main categories:

- Consequence for risk to life: qualitative analysis of the risk to life assessed as the combination of the specific vulnerability (track speed limit, height of fill, security level) and the temporal probability (linked with the average railway traffic intensity).
- Consequence for risk to property and socioeconomic impacts: consequence with respect to property damage and other consequential effects (traffic disruption) of the failure are to be assessed by a quantitative analysis of the economic repercussion caused by each specific failure mechanism. The type of damages and adverse effects are different depending on the nature of the mechanism. In general terms, these consequences can be divided into two main categories:
    - Direct economic costs: there are some consequences that directly affect the railway administration such as rehabilitation and repair costs.
    - Indirect economic costs: on the other hand, some impacts are not directly assumed by the competent administration but they affect society as a whole. These costs include:
        - Traffic disruption costs: linked with the increase in travel times derived from circulation by alternatives routes of the rail network (Perrin and Jhaveri, 2003).
        - Compensation costs derived from landslide impact on near properties due to embankment slope instability: in this case the economic impact depend on many factors such as: height of fill, type of property affected, distance from the element to the failure influence area and general nature of adjacent development.
        - Compensation costs derived from flooding upstream the culvert: in many cases the flooding is caused by the insufficient hydraulic capacity of the culvert so the compensation must be held by an insurance company or the proper administration. Upstream nearest crops and constructions may be affected as long as the flood remains.
        - Traffic disruption costs in upstream adjacent transport infrastructures (other railways or roadways) caused by floods.

Global socioeconomic impact will be assessed for each failure mechanism considering that the consequences of failure may depend on the nature of the failure itself. Where there are multiple consequences, the total should be considered, as it may increase the consequence class above that derived from the individual effects. Note that the consequence classes used for loss of life (combined vulnerability and temporal probability) are not considered equivalent in economic terms to those for the damage to property and consequential effects, reflecting the lower tolerance which exist in society for loss of life compared to pure economic losses.

Culvert failure risk analysis

Once the annual probability of failure linked to each of the ten mechanisms studied is obtained and knowing the level of economic and social impact associated with each culvert, it is possible to determine the preliminary risk level of the asset. The risk level associated with a particular culvert is the direct result of the integration of the annual failure probabilities and the eventual economic and social impact linked to each failure mechanism. The nature of these mechanisms leads to consider that these events are independent so the total risk will be the sum of all the risks evaluated for the same asset.

3. Preliminary results and potential implementation

This section shows the main conclusions drawn from the application of the risk assessment methodology to a set of 757 culverts located in different roadways the province of Ciudad Real, Spain. The set includes different types of culvert barrels, different materials and deterioration conditions. Additionally, the sample covers a considerably wide geographical area so that from the point of view of the topography and the characteristics of the watersheds it is considered sufficiently representative.

An important aspect to consider is that although the results shown below correspond roadways, it has been considered that these results show the potential of the methodology to be applied to different kind of linear infrastructures and its versatility since the changes to be made in the assessment of probabilities and consequences in order to consider the level of risk in railway culverts is minimal.

This analysis has been held in different communication routes (motorways, national highways and autonomic roads) with different traffic intensities in order to fully cover the spectrum of potential socio-economic impact. A number of peculiarities have been recognized to be taken into account during the diagnostic process listed below:

- Evaluation of the hydraulic capacity of groups of culverts connected in series
- Evaluation of the hydraulic capacity of groups of culverts connected in parallel.
- Evaluation and particular recognition of culverts in extensions of roadway, recognizing different typologies and materials in the same culvert barrel in several of them.

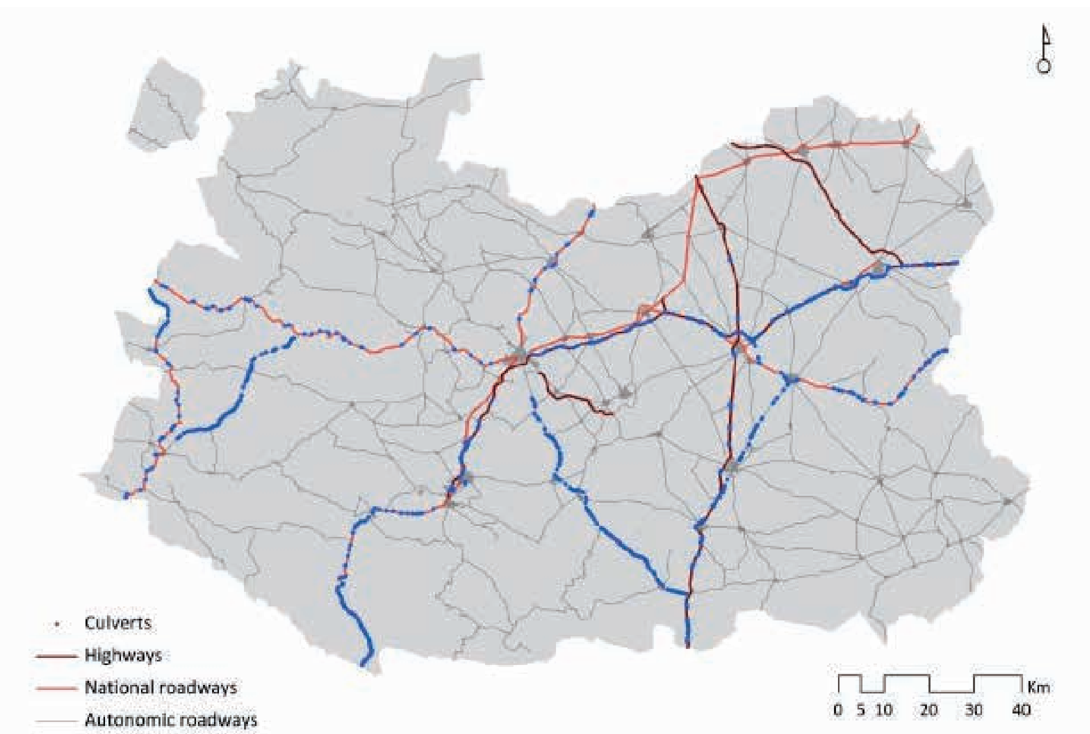

Figure 3. Location of the inspected culverts, Ciudad Real (Spain)

Failure mechanisms	Annual probability of failure	Economic impact	Economic risk	
	(-)	(€)	(€/year)	(%)
Structural collapse of the culvert barrel	0.00842	136829	1151.5	49.3
Slope instability caused by afflux	0.00138	57312	78.8	3.4
Slope instability caused by leakage out of barrel	0.00013	7841 0	10.1	0.4
Slope instability caused by headwall collapse	0.00220	57308	125.9	5.4
Slope instability caused by undermining at inlet our outlet	0.00208	56788	118.3	5.1
Piping into culvert	0.00264	117859	310.6	13.3
Piping on outside of culvert due to afflux	0.00004	112439	5.0	0.2
Piping on outside of culvert due to leakage out of culvert	0.00171	117859	201.6	8.6
Erosion by overtopping flows	0.00472	70461	332.4	14.2
Cross catchment flooding	0.00032	524	0.2	0.1

Table 1. Main results obtained: annual failure probability, economic impacts and risk.

Incidence Risks factor/pathologies	INCIDENCE
	(%)
Partial or total blockage of the culvert barrel	34.50
Structural deterioration of the culvert barrel	7.83
Structural deterioration of the culvert headwall or/and wingwalls	14.34
Evidences of substantial erosion at the culvert outlet or inlet (undermining)	29.60
Deficiencies found in the hydraulic capacity of the culvert	13.73

Table 2. Main results obtained: risk factors and pathologies observed.

Tables 1 and 2 show the statistics of the results obtained in the risk analysis performed in some roadways in the province of Ciudad Real. Table 1 shows the mean values of probability, total economic impact and annual risk of the ten failure mechanisms studied.

The total economic impact is divided into the direct economic impact associated with the repair / rehabilitation costs directly attributable to the competent administration (representing on average 69% of the total economic impact) and the associated indirect economic impact to the costs derived from the traffic disruption on the roadway and various compensation costs, which are held by society (31% of the total). On the other hand, for the purposes of the present study only the indicators of impact and economic risk are shown since the impact and personal risk on the users of the road is assessed only in qualitative terms.

Notice that probabilities and consequences values must be converted to qualitative scales so that the qualitative assessed risk level can be obtained. A scale of 5 risk categories defined by annual probability of failure and economic impact ranges (R1 to R5, where R1 is the highest level of risk) based on recommendations of other authors (Roads and Traffic Authority, 2010) has been established. Applying this rating scale, less than 1% of evaluated assets are in the R1 category, whereas in the majority of the studied cases (41%) the risk level fits in the lowest category (R5).

The failure mechanism presenting the highest risk is the structural collapse of the culvert barrel (directly related to the general deterioration condition observed inside the culvert barrel) and erosion caused by overtopping flows (due to partial or total blockage / insufficient hydraulic capacity during peak flows). Since many of culverts studied are above twenty five years age and the impact caused by the structural collapse of the culvert barrel implies the total cut of service in the roadway and the complete restitution of the culvert, the incidence level on the total risk in this failure mechanism remains high.

On the other hand, the most common pathologies affecting culverts have been identified. Each of these pathologies affects one or more failure mechanisms, depending on their nature. The need to extract these risk factors from the final diagnosis is because they represent the most reliable indicator when planning preventive repair and / or replacement actions based on the preliminary diagnosis results. As shown in Table 2, the risk factor that has the highest percentage of incidence on total risk is that related to the hydraulic capacity of the culvert. This average value includes the cases where the culvert does not present any specific pathology, so the remaining risk (100%) is due to the residual probability associated with failure mechanisms triggered by rainfall events. In order of relevance, the pathologies associated with the structural deterioration of the culvert barrels and headwalls at inlet or outlets, partial or total blockage of the culvert barrel and undermining at inlet/outlet are highlighted.

4. Conclusions and further implementation

In this section the potential of the culvert risk assessment methodology applied in the development of systems of investments prioritization in the maintenance of this type of structures has been discussed.

Once the preliminary diagnosis of the set of assets studied has been obtained, the following level of development of the methodology is presented: the analysis of investments in maintenance and its prioritization based on risk reduction criteria. The selected rehabilitation measurements or remedial works in a particular culvert will be determined in the first place for operational restrictions (the rehabilitation techniques depend, in most cases, on the cross section typology, shape and material of the culvert barrel) and in the second place for the study of the risk factor currently operating on the asset. The cost of remedial works is determined according to the characteristics of the culvert (general field measurements) while the repercussion in terms of risk reduction per year, is evaluated considering the specific impact of every rehabilitation measurement in the global risk assessment considering the current and the forecasted scenario. Since the economic repercussion of the actions to be undertaken can be considered virtual benefits, it is possible to carry out a profitability analysis of the set of potential remedial works previously determined, according to the service life of each action considered.

Once this analysis is performed, it is possible to prioritize the actions according to the profitability indicators provided in the short, medium and long term, not only to evaluate the profitability of different potential actions in the same asset, but to select the most profitable updates linked to the set of culverts studied of a particular railway network, and prioritizing its implantation during a reference period of time.

The type of remedial works to be implemented in the profitability analysis fit the most common pathologies detected in culverts:

- Restitution of the culvert barrels (increasing hydraulic capacity of the culvert during peak flows).
- Erosion protection measures at inlets/outlets.
- Restitution and repair works in headwalls and wingwalls, according to the current condition of the asset.
- Restitution and repair works inside the culvert barrels, leakage prevention measures.
- Removal of blockage elements (debris and vegetation) inside the culvert barrels.

In conclusion, this works outlines the necessity of having a methodology for identifying and prioritizing investments projects in culvert maintenance widely supported by robust applications capable of massively analysing overall culvert risk conditions in transport networks. Global analysis of the results could lead to the establishment of a common management framework including alert and support-decision systems implementation in the planning and execution of investments in preventive maintenance actions of culverts.

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