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AN INVESTIGATION OF REASONS AND CONSEQUENCES OF DETERIORATED HYDRAULIC CAPACITIES OF CULVERTS CONCERNING RAILWAY TRACK STABILITY

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Abstract

The establishment of railway routes requires earthworks and the construction of tunnels, culverts, bridges, and viaducts. Railway routes can pass through highly variable regions in terms of geography, climate, hydrology, and land use, which require careful consideration of the possible effects of each aspect on the safety and serviceability of the railway service along a route. Culverts are very important civil engineering structures designed to allow passage across the railway route. Culverts are part of the railway substructure and most culverts are designed for hydraulic purposes. Hydraulic culverts can allow the passage of small streams and surface flows that arise after heavy rains and floods across the railway route. They must provide a sufficient cross-sectional area for the passage of current and future estimates of flow rates expected to occur across the railway route. The flow rate that the culvert can accommodate is the hydraulic capacity culvert, which is determined by the unobstructed cross-sectional area of a culvert. The hydraulic capacity of a culvert can deteriorate by sedimentation and can become insufficient due to climate changes that are unaccounted for and changing land use patterns. Therefore, the railway authority must monitor the states and functionalities of its culverts along its railway network and update their service lives with the ongoing changes that occur along the railway route that can influence the service lives of the culverts. This study elaborates on the conditions that can reduce the functionality of culverts and provides two case studies where reduced culvert functionality has resulted in the collapse of railway track structures and consequential train derailments.

Keywords: Railway, culvert, hydraulic capacity, flood, embankment

1 Introduction

Land transportation routes for roadways and railways frequently traverse through varying topographies, geologies, climates, and different land use patterns. Design of transportation routes not only requires the mechanical design for the serviceability and safety needs of the respective transportation modes but also the protective design that protects the route from the detrimental elements of nature such as floods, landslides, and rock falls. Since the conditions mentioned above along a route are not constant, their variability must be accounted for in the design of transportation routes and included in the route maintenance plan. The particular conditions and the change of these conditions along the length of the transportation route must be accounted for.

This paper addresses the functionality of culverts underneath railways. The design of culverts is frequently governed by their hydraulic needs represented by their hydraulic capacity. These needs are based on hydrological data based on accumulated rainfall measurements and data

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concerning topography, geology, and land use. Based on the design life of the transportation route, projections are made into the future to estimate the expected hydrological conditions in the future and maintain the functionality of the structure throughout its design life.

A hydraulic culvert must allow the passage of flow underneath the transportation route without any adverse interaction of the flow with the substructure and the superstructure of the transportation mode serving along the particular route. If the flow exceeds the capacity of the culvert, the consequences can range from mere superstructure overflowing to structural collapse. This paper investigates two case studies where culvert failures have occurred that resulted in partial or full collapse of the railway track structures, which led to a wide spectrum of distress ranging from serviceability losses to derailments. Probabilistic assessment for seasonal and extreme flow conditions is discussed and the dangers of extending the functional lives of culverts beyond a certain statistical point of confidence are portrayed.

2 An insight into the differences in condition monitoring and braking response characteristics in roadways and railways

Roadway and railway transport greatly differ in terms of the action and reaction times of their operators and the braking times needed to stop their respective moving vehicles. Braking action is a reaction to a necessity to stop or a perceived threat. There is a great difference between the braking distances for the vehicles that travel along roadways and railways [1, 2]. Geometric designs of one-way roadways rely on stopping sight distances, which is the distance needed for the driver to see and perceive the threat that requires the vehicle to stop, react to this perception, and engage the brakes to bring the vehicle to a full stop.

However, the situation is much different for railways. The distance needed for contemporary passenger trains to stop is much longer than the perceivable visual distance that the machinist can see and react to. Not only the reaction times to engage brakes to stop or reduce speed are higher than on roadways but also the engagement of the braking system at full capacity along the length of the trains can take more time than roadway vehicles [3, 4]. When the machinist sees and perceives a threat to stop the train, there usually is not a sufficient distance and time to stop unless the speeds are very low and the machinist is on extreme alert and the braking efficiency and brake response times are optimal under emergency braking conditions. Therefore, he/she must be warned before the first sight of an obstacle or a track failure to stop the train. In other words, the information concerning the need to stop must be conveyed to the machinist through an intricate array of signalization and information-conveying infrastructure and not rely on the perceivable sight distance of the machinist [3, 4]. These particularities for railways are in strict contrast to the means of information conveyance to the driver of a car to initiate braking to a full stop. Unless proper signalization and information-conveying infrastructure are in place to constantly inform and alert the train machinist, traveling along a railway occurs “blind” compared to traveling along a roadway.

Route characteristics along roadways are also much different than railways in terms of the facilities along the route that can provide passive and indirect observation and control. Each of these locations provides an indirect means to collect and convey information along a roadway if an adverse event happens. Trains on the other hand stop only at dedicated stations and sometimes at select junctions along an intercity route. Stretches of track between the stations are mainly rural. Typically, there are 1 or 2 crew members at the most that are constantly present at the locomotive of the train observing the track ahead. Therefore, the indirect means to observe the conditions along a railway track is quite limited when compared to a roadway. The occurrence of an adverse event along a roadway that results in the partial or full destruction of the roadway has more chances to be seen and reacted to as opposed to the same adverse conditions occurring along a railway track such as the failure of a culvert and the damages that can result thereof.

Railway track routes are composed of a variety of civil engineering structures that support and protect the track. Culverts are fundamental civil engineering structures that are numerous and quite variable in size and structure. Functionality and safety of culverts are essential to the functionality and safety of railway tracks and in addition to their management and maintenance, their condition assessment through structural health monitoring is becoming a necessity. The following section elaborates on the functions of hydraulic culverts and their criticality in the structural stability of railway tracks.

3 An insight into design event probabilities

Improperly designed and improperly supported railway track structures can fail due to earthwork failures that can be triggered by undrained or unconveyed water. Hydraulic culverts are meant to provide transfer of water flows that would normally cut through the railway route by a properly designed and dimensioned gap underneath the railway track. Culverts are shorter in span compared to bridges. Culverts can support the loads above them through the arching action under compression or bending moments along their spans depending on how they are designed. Their spans are typically limited to about 10 meters beyond which they need to be considered as bridges in terms of how they resist the loads they support [5]. There are special curved designs to increase the culvert span to 15 m with proper cover depths and compaction within the track embankment. Prefabricated concrete and corrugated metal provide many design options for contemporary culverts. Depending on the needed hydraulic capacity, the varying depth and span requirements are met with tailored solutions for the hydraulic needs.

The service life of a structure is the period during which the designed structure is functional under the peak demand. The service life of a culvert is the time interval during which the culvert meets the demand for extreme flows considered for a certain design period that can be foreseen. The National Institute of Standards and Technology (NIST) advises using a categorical approach that includes routine, design, and extreme event design [6]. The routine level design is for hazards that have a 50% or greater probability of occurring over the next 50 years. The design level specifies the event with a 10% chance of happening over 50 years while extreme event levels have a 1% to 3% probability of occurrence over 50 years [7, 8]. The probability of occurrence of an extreme event increases with time. If the annual (n_1 = 1 year) probability of occurrence of an extreme event is p_1 = 0.75%, then the probability of occurrence of this event in n_2 = 50 years is p_2 = 31% based on Equation (1) [9].

$$p_2 = 1-\left(1-p_1\right)^{\frac{n_2}{n_1}} = 1-\left(1-0.0075\right)^{\frac{50}{1}} = 1-0.69 = 0.31 = 31\% \tag{1}$$

Looking at the above discussion from a different perspective, one may also ask the question that if the annual (n_1 = 1 year) probability of occurrence of an extreme event is p_1 = 0.75% = 0.0075, what is the time interval (n_2) that this event would definitely (p_2 = 100% = 1) occur? Equation (2) shows the mathematical form of this question where n_2 is the value sought and which is about 720 years for an event with an annual probability of occurrence of 0.75%.

$$p_2 = 1-\left(1-p_1\right)^{\frac{n_2}{n_1}} \rightarrow p_2 = 1 = 1-\left(1-0.0075\right)^{\frac{n_2}{1}} \rightarrow n_2 \sim 720 \text{ years} \tag{2}$$

Figure 1 shows the variations of the probabilities of occurrences of adverse events in time with varying annual probabilities that remain constant (P_{a1}, P_{a2}, P_{a3}, P_{a4} and P_{a5}) and change in time every 20 years. With increased annual probabilities, the time interval needed for the certainty of occurrence decreases, being respectively 130 years, 180 years, 270 years, 540 years and 720 years with P_a values 4%, 3%, 2%, 1%, and 0.75%.

However, the annual probability of occurrences does not remain constant in time but may increase with the increased changes in climate and land use patterns. Changes in land use patterns are becoming an important factor in hydrological assessments with increasing urban areas, especially in developing countries. A rural area that has later been transformed into a paved urban area will have different permeability values and hence different overflow conditions in the event of a flood. Therefore, the final plot in Figure 1, assumes an increase in annual probabilities every 20 years and forecasts the cumulative probability of occurrence of an adverse event in time (P_a variable). Figure 2, details the variation of probabilities within the 100-year service life span of a transportation structure. In this figure, the effect of an increase in the annual probability of occurrence on the overall accumulated probability of occurrence in time is better portrayed. This figure portrays the increased probability of occurrence within a certain service life span of a structure if the chances of annual occurrences are increasing. This fact in return highlights the prospects of reduced service life for a structure since the projections for service in time, typically base on fixed estimates for probabilities of occurrences.

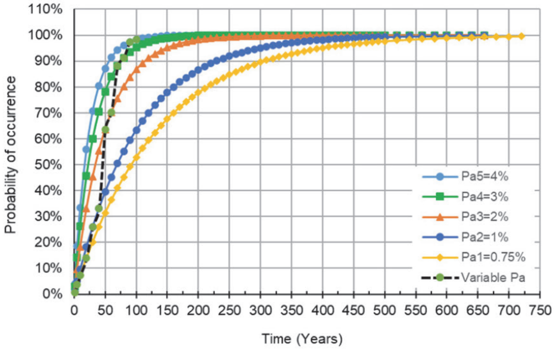

Figure 1 Occurrence probabilities in time with variable annual probabilities

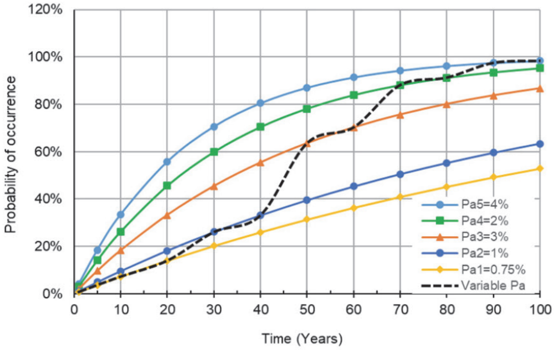

Figure 2 Occurrence probabilities in a century with variable annual probabilities

If the service life of the culverts of a railway was estimated based on an annual probability of occurrence of 0.75% and the projected probability of failure in 50 years was estimated at 35%, this value can have increased to more than 60% if the annual probability of occurrence has increased every 20 years up to an annual probability of 3%. Such increased chances of failures can result in disruptions or total functionality losses depending on the design of the systems.

Figure 3 shows a generic representation of the functionality recovery curve of a structural system. Throughout the life of a structure, the goal is to keep the structural functionality to its full capacity. Whereas the expected deteriorations along the structure reduce the functionality to expected levels, scheduled and well-planned maintenance can counter this decrease and uphold the system functionality to its maximum. However, when a disruptive event occurs, system functionality reduces at a rate and down to a level based on the magnitude of this impact and the resilience of the system.

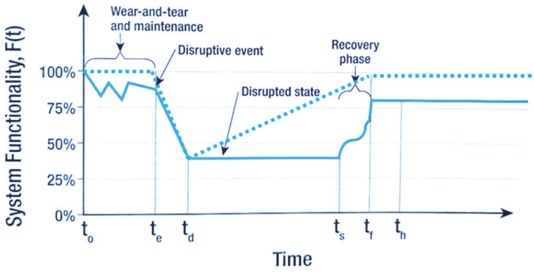

Figure 3 Resilience recovery curve of a system [9]

The reduction can be gradual and low, can be abrupt and high, or can eliminate system functionality. The disrupted state continues until the engagement of actions to eliminate the effects of this disruption and elevate the system functionality back to the possible highest level that may or may not equal its maximum level before the event. The recovery can occur in stages leading to a fully recovered phase. The dotted lines represent an ideal summary for the functionality variation where wear and tear does not occur and system recovery begins as soon as the disruptive event terminates (t_d), which is rarely the case, and the system is gradually fixed to reach its full functionality. The trough in the functionality curve between t_e and t_f is typically referred to as the "resilience triangle" as an indicator of how quickly a system responds to and recovers from a disruption. However, due to a typical difference between t_d and t_s as well as the phases of recovery up to t_h, this is hardly a triangle in reality.
Figure 3 is a good representation of an understanding that can apply to every structural system. If the system in question is a culvert underneath a railway the hydraulic capacity of which has depleted, the occurrences that follow concerning the functionality of the railway route can be represented in this manner. The following section presents two cases, where culvert failures resulted in total loss in railway track functionalities as well as loss of human lives.

4 Case studies for critical culvert failures

This section provides insight into two accidents along railway tracks that occurred due to culvert failures that resulted in the structural failures of railway tracks. The capacities of the culverts reduced drastically due to their reduced capacities. The two culverts are different in configuration and size but the reasons that led to culvert failures have to do with hydraulic malfunctioning of culverts that led to substructure and superstructure failure of the respective railways. In both cases, the accumulating causes leading to culvert failures were unnoticed by the respective railway authorities. Abrupt variations in climate and changing land use patterns severely reduced the functionalities of the culverts in time. The implemented inspection routines failed to evaluate the conditions of the culverts. When the culverts failed, the failures were not observable to the train crew to react to and stop the trains before engaging with the damaged track areas. The culvert failures led to the full failure of the railway track embankments causing train derailments.

4.1 Case study #1

On 28 April 2013, train No. P69341-28 encountered a roadbed slump at Mile 83.55 of the Canadian National Railway Togo Subdivision, near Togo, Saskatchewan as it was traveling at 60 km/h. The two locomotives and the two leading cars derailed [10]. During the 4 days before the accident, a rapid rise in temperatures rapidly melted the approximately 50 cm thick snow that covered the area of the accident. Table 1 shows the variations in temperature before the day of the accident.

Table 1 Recorded highest temperatures before the day of the accident

Date	Temperature
24 April 2013	0.1 °C
25 April 2013	2.3 °C
26 April 2013	7.9 °C
27 April 2013	13.1 °C
28 April 2013	6.1 °C

A culvert within a roughly 18 m wide embankment that spanned a ravine failed. The toe of the failure was near the roughly 122 cm diameter culvert shown in Figure 4a. A rapid melt of the snowpack beginning approximately one week before the derailment resulted in a rapid increase in groundwater levels, saturating the embankment. The water within the culvert buried deep within the embankment was relatively insulated from the warming weather and remained frozen. The ice plug at the downstream outlet of the culvert prevented drainage resulting in ponding in the upslope ditch. Figure 4b shows the ice-clogged culvert and the collapsed embankment. Due to the malfunctioning culvert, the accumulating waters along the upstream face of the embankment forced the embankment to work as a dam, which was a function that it was not designed for. The increased hydraulic head in the culvert barrel and the vertical shaft structure seeped the water due to accumulating pressures into the embankment. The north face of the embankment was also covered with phreatophyte vegetation, which thrives in areas where the soil is saturated or in groundwater discharge areas.

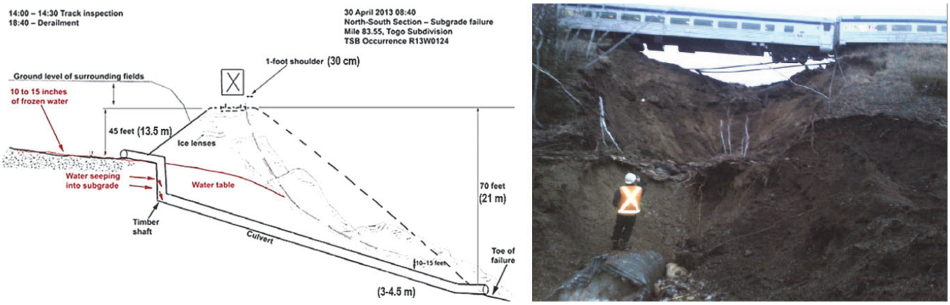

Figure 4 a) Embankment profile showing the clogged and seeping culvert, b) View of the collapsed embankment from the toe of the culvert [10]

The embankment was evaluated and was found to have high shear strength and was not prone to failure if adequate drainage was maintained. The routine track inspections also failed to identify the blocked drainage system due to the inaccessibility of the culvert to routine track inspections. The crew observed a 3 m portion of ballast missing under the track, just ahead of the train, and placed the train into emergency braking.

Although immediate action was initiated, the range of vision available to the crew did not allow sufficient time to stop the train before reaching the affected area. As the train traversed the unsupported portion of track, the embankment collapsed further beneath the weight of the train, leading to the derailment shown in Figure 4b.

4.2 Case study #2

On July 8, 2018, a passenger train that was carrying 362 passengers along the Uzunköprü-Halkali Regional line between the cities of Edirne and Istanbul, derailed, killing 24 passengers and heavily injuring 42. The cause of the derailment was the failure of a clogged culvert under the overflows and the scour of the embankment surrounding the culvert [11].
The estimated 150-year-old masonry culvert could not provide drainage for the approaching upstream flow rate that was multiple times the flow rate the culvert could have supported and provided passage underneath the railway track. The excessive flows flooded the culvert and overran the railway line. However, the real damage began as the flood waters began to scour the embankment soil around and above the culvert. The washout of the soil above the culvert undermined the railway track which led to the loss of the track superstructure above the culvert. In an instant, a part of the ballasted railway track was completely washed away with roughly 12 m [35 ft] of track panel suspended about 45 cm (1.5 ft) above the culvert. Figure 5a and 5b shows the undermined track and the collapsed embankment. The fill surrounding the culvert was weakened by random wild plant growths, the large roots of which created planes of weakness within the embankment slopes. Unlike, special species of grass-type vegetation, wild vegetation with deep and large roots is detrimental to the stability of the embankment soils [12, 13].

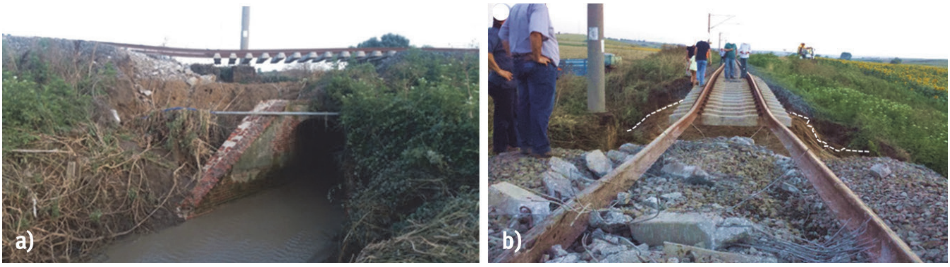

Figure 5 a) Undermined railway track and the (b) collapsed embankment [11]

One particular problem with this railway route was the insufficiency of the embankment width. Outer layers of saturated embankment, slipped along these planes, dragging along the upper ballast layers for the railway track. Figure 6 depicts the developed failure on the embankment that can be correlated to image on Figure 5b. The accumulated water pressure on the southern side of the culvert pushed the weakened remaining ballast layers towards the north thereby undermining the railway track panel composed of ties and rails. The passenger train approached the undermined region towards Istanbul at about 110 km/h. The machinist could not have seen the damaged track ahead and responded to stop the train. The locomotive passed over the undermined region with an intensive impact followed by the derailment of 5 of the 6 trailing wagons

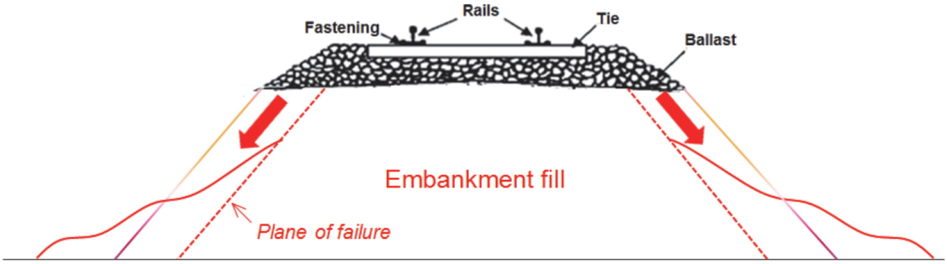

Figure 6 Embankment failure that led to superstructure failure

3 Discussion

This study began by introducing an insight into differences in roadway and railway operations in terms of response times to adverse conditions along respective routes and differences in route management. The study provided a discussion concerning the probabilistic estimation for adverse events concerning the design of transportation structures and railway culverts in particular. The study elaborated on how effective a failed culvert can become in a railway operation if not continuously inspected and managed. Finally, two case studies were introduced that included culvert failures, which led to structural collapses and train derailments. The two case studies showed that information concerning the developing conditions along the culverts was not available to the transportation authorities and the train crew. The conditions of the culverts were not known despite track inspections and the likely indicators of drainage failure such as vegetation growth were unnoticed. The first case study involved culvert capacity degradation due to ice formation within the culvert and the buildup of pore water pressure. The second case study involved the degradation of the culvert capacity of a historic culvert that was 150 years old. The intactness of the culvert misled the railway authority in terms of its functionality as a hydraulic element. Not only the conditions of agriculture surrounding the culvert area greatly changed in more than a century but also the climate conditions changed drastically as well. The culvert design was not assessed against these changing conditions. The limited width of the embankment resulted in the loss of the ballast layer as the side slopes collapsed due to detrimental vegetation within the embankment, dragging along the ballast layer above.

4 Conclusions

Transportation engineering is not based on exact sciences. The conditions for design in terms of user demand and structural response cannot be exactly defined but are represented by statistical levels of confidence that can deteriorate over time. Therefore, not only the represented conditions required for their design but also their changes in time must be well studied, understood, and represented. This is especially important in our generation when climate, population, social demands, and land use patterns are changing. Transportation engineering structures are not constantly habited but are temporarily occupied by their users. This results in reduced observational opportunities for their functional and structural assessments. Transportation structures are not isolated structures with a single condition occurring but incorporated structures with many conditions occurring along their lengths that can mutually interfere with and disrupt the service conditions. Therefore, transportation structures must have dedicated structural health/condition monitoring and transportation management systems.

Roadways and railways may traverse through many unique and distinctively different geographies and climate zones, the topographies and land use patterns of which can differ. The transportation authority must have a system to collect data for these differences that can occur in time. For instance, the conditions of land use along the route of a railway, whether it's agricultural or industrial, must be known and up to date by the transportation authority so that any changes in surface flow conditions and the content of this flow can be addressed and the hydraulic structures of the railway infrastructure can be checked for sufficiency. The culvert system along agricultural and rural lands must be supported by trap structures that can reduce the debris content of the water headed towards culverts and also provide a visual for the accumulating debris conditions towards the culverts. The abrupt changes in the climate conditions leading to unprecedented rainfalls must be known by the transportation authority to slow or halt the railway services along the affected routes.

However, this wide spectrum of parameters that concern the transportation authority cannot be managed and monitored by only the transportation authority. Protocols must be established between the transportation authority and the departments of meteorology, agriculture, zoning, and land use agencies. These protocols must include the type and the frequency of data that must be supplied to the transportation authority. Depending on the rate of changes that take place, the frequency of updated data should be adjusted accordingly, such that a high rate of change in climate conditions would require a higher frequency of meteorological update.

In close relation with the hydraulic health of a transportation structure, is the need to prevent the growth of weeds and wildering plants within the structures, especially the earth embankments of the roadways and railways. Contrary to specially selected and planted plantations to control erosion, the random growth of wildering plants, weakens the slopes of the earth embankments. Therefore, roadways and especially railway authorities have special plantation removal procedures that are mechanical and chemical. This maintenance item is sometimes overlooked but has a strong potential to affect the structural integrity of a transportation route through its effect on the stability of embankments.

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