Scour and potential earthquake damage on bridges

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Abstract. The vast majority of total and partial bridge collapses in México are due to scour damage. Bridges are not repaired promptly after a hurricane so the bridge is exposed to both, scour and earthquake hazard. This paper presents the results of a research project oriented to study the vulnerability-based hazard risk assessment of highway bridges subjected to extreme rainfalls due to hurricane events and its effect on bridge lateral strength. Scour hazard is computed using robust statistical procedures to minimise the intrinsic uncertainty of the extreme rainfalls. Earthquake hazard is computed accordingly to Mexican codes and well-known methodologies. A case study is used to present the methodology used in the research project, which was funded by the National Center for Disaster Prevention CENAPRED through the Institute of Engineering of the National Autonomous University of Mexico.

Keywords: Scour, bridge, earthquake, damage

1. Introduction
Scour damage is the most frequent cause of bridge collapses in México, an average of 2.5 bridges per year [1], in the last 20 years a total of 36 bridges suffered total or partial collapse during extreme rainfalls, and 99 more were damaged [2].

In the Mexican Pacific Coast, a survey of the most damaged bridges due to scour has shown that these structures are located in seismic prone regions [3]. In this paper, simplified methods are used to assess the bridge vulnerability under scour and seismic hazards.

When an extreme scour develops in a bridge, several failure stages must be addressed, such as local failure due to inelastic buckling of piles [4], failure due to high overturning moments, and formation of plastic hinges.

Because data analysis played a key role in the estimation of the design flow [5], the first part of this paper focuses on uncertainty analyses and the characterization of the extreme rainfall hazard. The second part is dedicated to present well-known simplified calculations of scour depth, using Yaroslavtziev [6] and HEC 18 [7] methods, for an idealized hydraulic section of a specific bridge.

The potential earthquake damage on a case study bridge foundation is addressed using Song and Chun [8] methodology, and is presented in the third part of this paper. Finally, conclusions are described, and recommendations are given.

2. Uncertainty Analysis
2.1 Data analysis
In order to derive mathematical models for the prediction of return periods for different intensities of extreme rainfall events, meteorological and hydrological information was collected including up to
fifty years of maximum water flow in river crossings. This was performed using data bases of BANDAS system [9].

Frequently, when dealing with data bases the problem of missing data needs to be addressed. A data augmentation toolbox for MATLAB [5], was used to estimate a complete data set and minimise the possible errors. After dealing with the missing data, different probability distributions were fitted to the estimated complete data set and tested for goodness of fit using Kite’s test and probability plots, and a best fit distribution was selected.

2.2 Frequency analysis

Once the best fitted distribution was chosen, a frequency analysis was carried out considering the following premises:

1. Extreme events arise from serially independent time series with a known underlying probability distribution, whose parameters can be calculated and are stationary.

2. Data fits to a Bernoulli series, which is a simplification of the analysis, however, more powerful analysis can be performed by using Markov models [10].

If these premises are true, then the T year event that occurs at least once in a N year period is:

\[
F(x)^{-1} = 1 - \left( 1 - \frac{1}{T} \right)^N
\]  

(1)

where \( F(x) \) is the cumulative probability function, \( T \) is the return period and \( N \) is the planning year period. In most of the cases reviewed in this project, the underlying probability function in the data set was that of the General Extreme Value (GEV) type [11]. The design stream flow for a given return period for this distribution is:

\[
x_n = \mu + \frac{\sigma}{\xi} \left[ -\ln(1 - T^{-1})^{-\xi} - 1 \right]
\]

(2)

where \( x_n \) is the flow for a given return period \( T \), \( \mu, \sigma, \xi \) are the unknown location, scale and shape parameters of the distribution, respectively. These parameters of the distribution are computed using Maximum Likelihood Estimation (MLE). Figure 1 shows a comparison of the design stream flow obtained using a GEV distribution for the processed and original data. The maximum return period shown is a hundred years since this is the assumed service life of bridges in México.

![Figure 1. Design flow for different return periods.](image-url)
3. Scour Analysis

Figure 2 shows the idealized section of the bridge crossing that will be used in the scour model for the case study. For this section, the hydraulic area ($A_h$), wetted perimeter ($P_m$), and hydraulic radius ($R_h$) were obtained and used to calculate the speed and water depth [12] as follows:

$$V_s = \frac{1}{n} R_h^{2} S_h^{1/2}$$

where $n = 0.05$, is the Gauckler-Manning coefficient and $S_h = 0.06862$, is the slope of the hydraulic grade line.

![Figure 2. Idealized hydraulic section. Dimensions in m.](image)

The local scour depth evolution for this section is estimated using Yaroslavtziev [6] and HEC 18 methods for normal and complex piers [7], and the stream design flow computed in section 2.2. Furthermore, using the value of $V_s$ obtained with eq.(3), the design stream flow is obtained for different return periods (0-100 years) as shown in figure 3. Figures 4 show the annual probability of exceedance for different scour depths and methods.

![Figure 3. Scour depth/flow plot for Yaroslavtziev, HEC18 method, and HEC 18 complex pier method.](image)
Figure 4. Annual probability of exceedance for different scour depths and methods.

4. Case study
The case study bridge is located in the state of Oaxaca in the highest seismic prone zone in México. This is a four span, simply supported bridge, each span has a length of 56 m. Bridge piers made of reinforced concrete in a multi-column bent type, with circular columns of diameter $D_p = 1.2$ m; foundation piles have the same diameter. Soil mechanics information as well as mechanical properties of the bridge columns and piles were available and are used in the mathematical model.

4.1. Potential Earthquake Damage Assessment

The approach presented in the following paragraphs is based on the premises defined by Priestley on bridge seismic modelling [13] and the methodology of Shin-Tai [14]. Accordingly, the pier is idealized as two-degree freedom system as shown in the following figure 5:

Figure 5. Pier and correspondent two degree of freedom mathematical model.

The lateral stiffness of the foundation piles and the tributary masses of piles, columns and superstructure are used to calculate the first and second natural periods of the model, which are then used with a constant acceleration spectrum and equivalent damping in order to derive the seismic forces acting on the pile group [14] [15].

4.2. Shear demand
Song and Chun [8] demonstrated that the elastic seismic shear on the pile cap connection is given by:
where \( S_{a1} \) and \( S_{a2} \) are the acceleration magnitudes derived from first and second natural periods and the acceleration spectrum; \( m_s \) is the seismic tributary mass of the superstructure; \( \beta_m \) is the ratio of the generalized mass at the centroid of the pile-cap and at the center of the superstructure; \( \beta_k \) is the ratio of the lateral stiffness of the bridge column and the lateral stiffness of the soil; and:

\[
\begin{align*}
\lambda_b & \equiv \beta_k - \beta_m + 1; \\
\lambda_c & \equiv \sqrt{\beta_k^2 - 2\beta_k(\beta_m - 1) + (\beta_m + 1)^2}
\end{align*}
\]

Figure 6 shows the change of natural period because of the scour depth modification.
Figure 7. Shear demand/capacity for a series of normalized scour depths.

5. Conclusions
In this paper the proposed approach takes special consideration in characterizing and evaluating an extreme rainfall hazard as the fundamental variable in the multi-hazard evaluation of bridges. Scour depth is computed using approximated semi-empirical methods that are commonly used in engineering practice.

The proposed methodology considers the degradation of the lateral strength of the bridge piles as the scour depth increases. The approach is robust and easily accessible can be easily used by engineers to estimate the critical scour depth that demands corrective maintenance of the bridge.

It can be seen that nonlinear behaviour is expected for a single extreme rainfall event with a return period near 50 years, which is half the service life of the bridges in México.

In México, minimum budget is devoted to the preventive maintenance of civil infrastructure, a situation which leads inevitably to the damage accumulation, which in turn is associated to the vast majority of bridge collapses.

Since the scour damage accumulation has a stochastic behaviour that depends heavily on the scour – sedimentation process, this paper should be taken as a first approximation to a more complex problem.

More research is needed to develop procedures that take in to account the damage accumulation and its effects.

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