Simplified Fragility Evaluation Method for RC Piers

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For the analysis of the seismic risk, the structural fragility analysis method helps quantifying the effect of the uncertainty associated with the variability of structural materials and foundation soil parameters. Fragility analysis for a typical RC bridge pier structure is performed by FEM nonlinear analysis including the effect of the foundation soil flexibility. Typical fragility analysis involves analysis of the structural response with a large number of parameters combinations generated through Monte Carlo Simulation (MCS). The effect of parameter variability on structural response and structural safety is being assessed.

A faster fragility evaluation method named Simplified Fragility Evaluation Method is proposed herein for the simplification and the speed-up of the structural fragility evaluation, by computing the effect of the structural parameters variability on the structural response at one loading level and extrapolating the response at other loading levels by using as reference the load-displacement structural response computed for the characteristic values of parameters. Proposed fragility evaluation method's computational efficiency is compared with that of equivalent fragility determined by the Monte-Carlo method.

Keywords: Fragility Evaluation Method, Monte-Carlo Simulation, Material Variability, RC Pier

1. Introduction

The highway and railway RC bridge piers are structural elements built in large numbers, in standardized shapes. Seismic action producing damage to any pier element could potentially sever the route causing interruption of the traffic and delays until restoration works are being completed REF.[1]. For the analysis of the seismic risk the probabilistic analysis methods based on the fragility analysis are being applied, as such methods could account for the variability of various parameters considered in numerical analysis, including the variability of the structural materials and of the foundation conditions. Simplifications and implicit speed-up of the fragility computation have been typically associated with the reduction of the number of computational cases and parameter distribution optimization, see REF. [2],[3]. Alternatively, the computation speed-up of the fragility curve could be achieved by applying the proposed Simplified Fragility Evaluation Method, as shown in REF.[4], the method is being presented in detail in the following paragraphs.

2. Simplified Fragility Evaluation Method

The determination of fragility curves by the classic MCS method is requiring a large number of simulations at each loading level to account for the variability of the structural material and soil material variability, computed at various increasing levels of loadings until the preset threshold is exceeded.

In order to speed-up the evaluation of the characteristic fragility curves, the Simplified Fragility Evaluation Method is being proposed and described herein.

Simplified Fragility Evaluation Method requires only a single complete set of MC simulations computed at a given accelerations loading level, set at the point where the load-response curve determined with the characteristic values of the parameters is crossing the threshold level, as shown in Fig.2.

The behavior of the RC pier load-response is nonlinear and is assumed to be represented by the response computed using characteristic values of the parameters.

Further, the method uses the mean reference load-response curve to determine extra points on each analysis set load-response curve by extrapolation, without

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requiring the computing of the entire set of MC simulations at each loading level.

The proposed method consists of the following computational steps:

1) Determine the characteristic reference curve for modeling the non-linear demand-capacity response of the structure using the generally available mean value of the parameters and with increasing peak acceleration level of the scaled accelerogram.
2) Determine the acceleration ACC_{crit} corresponding to the point where characteristic load-response curve is crossing the safety threshold level.
3) Conduct a full set of simulations with the MCS generated structural parameters for determining the demand-response ratio at the ACC_{crit} loading level.
4) Determine the accelerations corresponding to safety threshold crossing level (blue filled circles in Fig.2, by shifting demand/response curves parallel to the characteristic reference curve for each simulation in the set.

The characteristic fragility curve is further obtained by plotting the cumulated number of failed cases ratio versus the corresponding loading level.

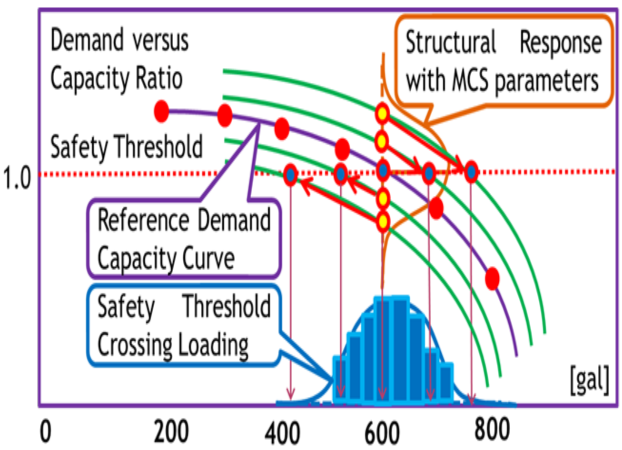


Fig.2 Overview of calculation flow for the Simplified Fragility Evaluation Method

Proposed method determines directly the earthquake input level for which response is exceeding a certain safety threshold using a single complete set of MC simulations and the mean characteristic load-response curve, significantly reducing the number of the numerical analysis cases needed to determine simplified mean fragility curves, and correspondingly resulting into speed-up of the fragility evaluation.

The ratios of safety threshold exceeded cases versus the loading level as determined by Simplified Fragility Evaluation Method are further integrated into the mean fragility curve as shown in Fig.3. The proposed method could give a faster, direct and simplified evaluation of structural fragility.

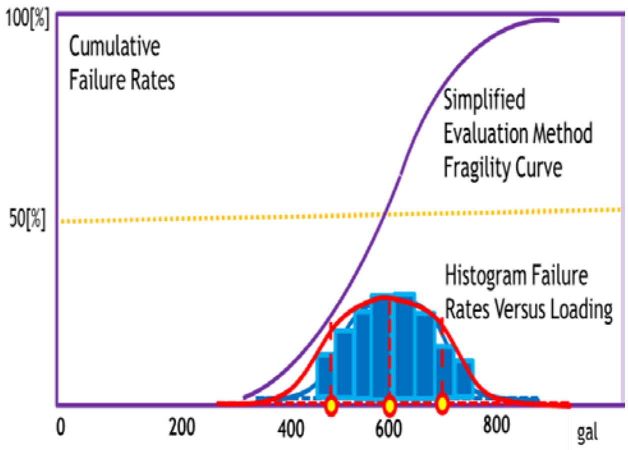


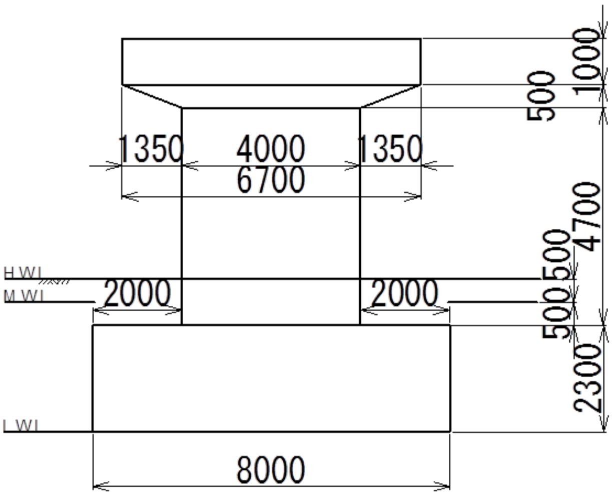
Fig.3 Fragility curve by Simplified Fragility Evaluation Method

3. Application of Simplified Fragility Evaluation Method to RC Pier Fragility

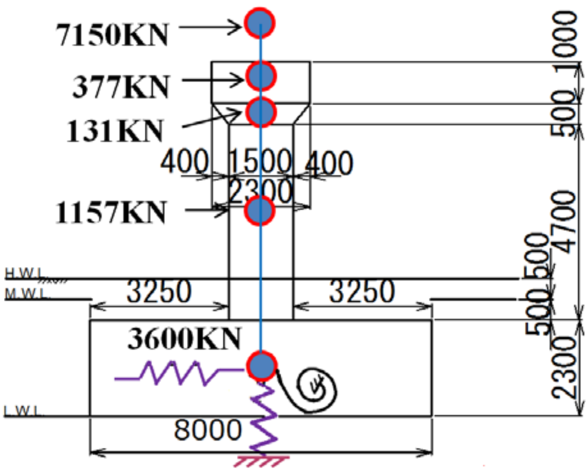
The application of the proposed Simplified Fragility Evaluation Method to the evaluation of the fragility curve for a typical RC pier with a spread foundation is presented. RC piers are essential structural elements; damage incurred by the pier could determine the interruption of service and potentially could lead to the failure of the structure. A typical RC pier with a spread foundation and with dimensional characteristics set similarly to REF.[6] is being modeled. The 3D RC pier model dimensions are presented in Fig.4.

The non-linear analysis is conducted by TDAP-3 FEM software considering variability of concrete material and foundation soil. For effective numerical analysis, the discretization of the structure using lumped mass and nonlinear beam elements, with the ground springs modeling the foundation soil flexibility is applied.

The Monte-Carlo Simulation (MCS) is applied for generation of structural parameters and quantification of the uncertainty associated with the RC pier materials and soil conditions is listed in Table 1.



(a) RC pier side view (XZ plane)



(b) RC pier side view (YZ plane) with model lumped mass discretization

Fig.4 RC pier structural dimensions and analysis model with lumped mass locations

Table 1. Structural and Soil Material Characteristics

Structural Material	Material Parameter	Average Value μ	Standard Deviation σ
Concrete	f'_{ck} [N/mm^2]	32.0[N/mm^2]	1.215 (actual)
	f_t [N/mm^2]	f_t =0.23* f'c $^{2/3}$	
	E_c [KN/mm^2]	E_c = 8.39* f'c $^{1/3}$	
Steel	fs [N/mm^2]	γs *370.0[N/mm2] (γs =1.0)	17.78 (actual)
	Es[KN/mm^2]	195.0[KN/mm2]	
Soil	Vs[m/s]	300m/s	31.06 (actual)
	ρ [KN/m^3]	20	

The failure state limit criterion is flexural failure (ultimate displacement and ultimate rotation angle of pier column due to flexural moment combined with axial loading exceeding the safety threshold), with the verification of the shear failure condition, assuming no torsional failure occurs. The corresponding demand versus capacity ratio including the variability of soil and concrete material and modeling of the ground flexibility effect are being plotted in Fig. 7, with safety limit ratio C_{SSI} as defined in Eq.(1), considering the translation term.

The swinging of the pier on foundations could further increase the displacement of the top of the pier and of the deck. The safety limit ratio C_{SSI} defined in Eq. (1) has been proposed to quantify the ratio of the column deformation, considering the top-bottom column displacement D_f, height H and rotation θ_f versus the maximum allowable member rotation θ_y, computed as specified in REF[6].

$$C_{SSI} = (D_f / H + \theta_f) / \theta_y \qquad (1)$$

MC type analysis is time consuming. The developed software implemented the automation of the FEM input parameter files generation process, the batch running for FEM analysis process and automated processing of the result files allowing for the effective analysis of a large number of cases with minimal operator intervention. The data processing flow for the developed software is shown in Fig.5.

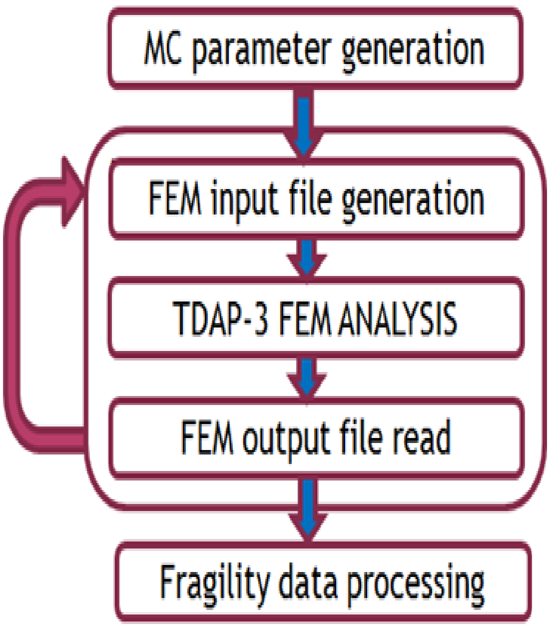


Fig.5 Fragility automated computation method

4. Evaluation of Effect of Material Parameter Variability

Most physical characteristics of the materials have various levels of variability and the measured values include uncertainty and therefore probabilistic models are being used. Selection of the relevant parameters whose variability has a significant effect on the structural response is essential to limit the number of parameter cases generated by MC simulation.

To assess the effect on structural behavior of each parameters' variability, simulations have been conducted with relevant parameter being varied while the other parameters are set to deterministic values. The results of the analysis by the Simplified Fragility Evaluation Method are being presented in the Fig.8 for combined concrete and soil parameters variability; vertical axis shows the failure probability of analyzed cases for which the rotation exceeds the safety failure threshold due to horizontal displacement as described in Eq. (1), while the horizontal axis shows the corresponding value of peak acceleration loading.

For the analyzed case, the concrete material variability and soil variability is shown to have a significant effect on the response variability. Accounting only for the variability of these parameters could model significant RC pier parameters uncertainty effects, while reducing the number of parameters to be accounted by the MC simulation.

5. Comparison with MCS Method

For the comparison, the equivalent MCS analysis have been performed for loading by a L2 accelerogram scaled at loading levels between 200 gal and 1000 gal and for up to 1000 analysis cases at each loading level to account for parameters variability of the RC pier materials and the soil materials. The input Level 2 inland earthquake accelerogram with the maximum value of acceleration 749.6 gal is shown in Fig.6.

MCS Method computed RC piers' mean displacement versus threshold ratio considering soil and concrete material variability are plotted into Fig.7 as determined with the L2 accelerogram with peak acceleration value scaled between 200 gal and 1000 gal.

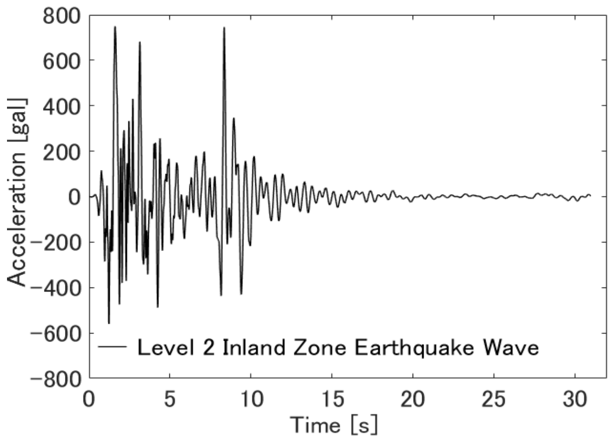


Fig.6 Level 2 inland earthquake accelerogram

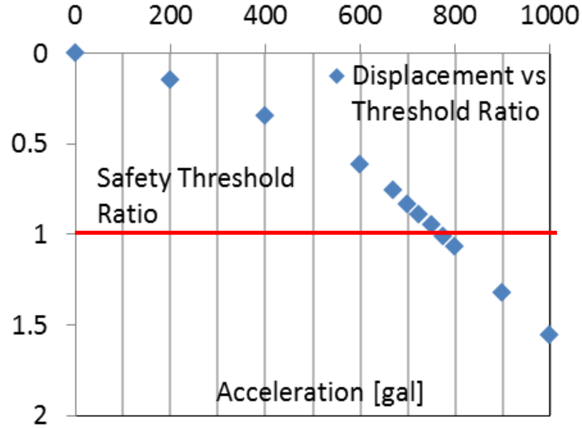


Fig.7 MCS Method computed RC piers' mean displacement versus threshold ratio considering soil and concrete material variability

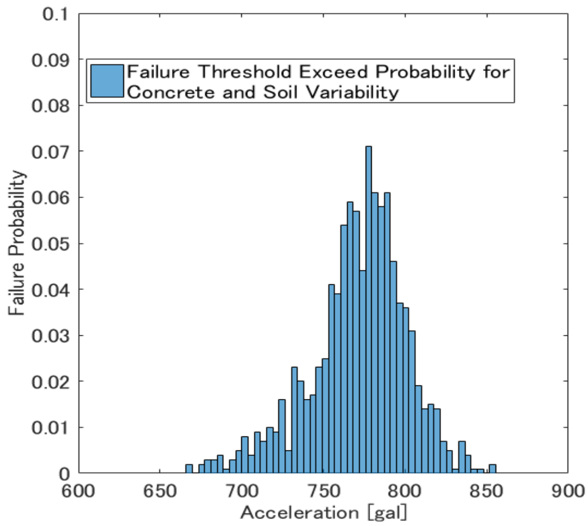


Fig.8 Simplified Fragility Evaluation Method determined failure threshold exceedance probability distribution for concrete and soil variability

The resulting characteristic fragility curve determined by Simplified Fragility Evaluation Method for 1000 analysis data sets is compared to the MCS Method mean fragility considering soil and concrete material variability, as shown in Fig.9.

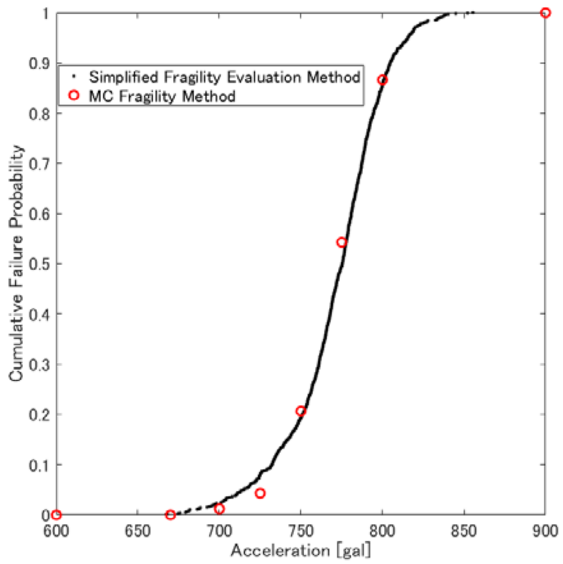


Fig.9 Simplified Fragility Evaluation Method determined fragility curves using 1000 analysis data sets versus MCS Method mean fragility

The Simplified Fragility Evaluation Method is significantly faster than an equivalent MC analysis as the computation of all the MC simulated material parameter cases is required at only one loading level for the entire set of MC simulated parameters. For determination of the reference curve simulations are conducted with one set of acceleration loading points and with the characteristic values of the parameters. The speed gain could be determined by the Eq.(2) formula:

$$SpG = MC_{set} * M_{load} / (MC_{set} * 1 + C_{ref} * M_{load}) \quad (2)$$

Where:

[*] MC_{set} is the number of cases to evaluate variability of the material parameter, determined by MCS (1000 in our case).

[*] M_{load} is the number of loading levels for which the threshold values is evaluated (M_{load}=11 in our case)

[*] C_{ref} is the number of reference curves, (one reference curve in our case).

The speed gain due to the reduction of the number of computational cases is about M_{load} times compared to classic MCS Method when an equivalent number of analyses are performed at each loading level.

It is suggested here that, varying the assumed C_{ref} used in the method could be used to adjust convergence (precision) on the expense of the speed gain, achieving desired degree of precision. A detailed description is being given in REF.[8].

The convergence of the fragility estimation by the proposed method versus the MC fragility analysis is evaluated for an increasing number of analysis cases. The convergence of the analysis for increasing number of numerical simulation cases is being herein compared in Fig.10 for 100 and 1000 analysis sets. The increase in the number of analysis cases corresponds to a linear increase in the computation time.

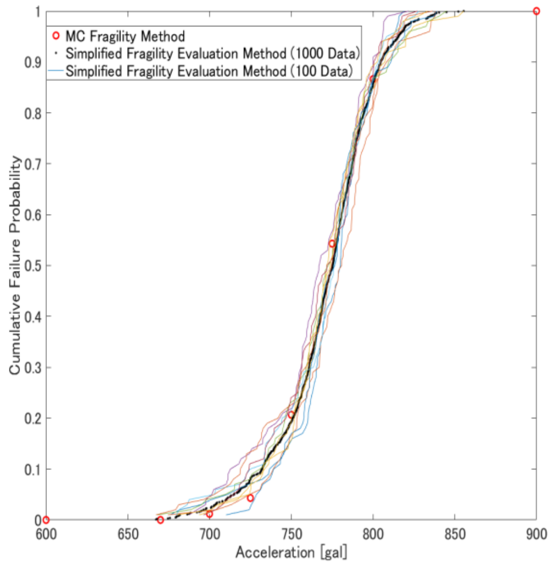


Fig.10 Simplified Fragility Evaluation Method determined fragility curves with 100 and 1000 analysis data sets versus the MCS Method mean fragility

6. Conclusions

1) For highway and viaduct RC bridge piers variability of the structural materials and soil parameters is significant and could potentially increase the detrimental earthquake effects. Fragility analysis is a suitable seismic risk assessment method. The fragility analysis of the bridge pier with spread foundations including the soil flexibility effect was performed, with focus on modeling of the RC and soil parameters variability.

2) Estimation of the effect of variability of the structural materials and soil characteristics is being performed by Monte Carlo multi-parametric simulation and FEM analysis. Modeling of the nonlinear

concrete behavior, soil-structure interaction and soil parameters variability are significant for more accurate modeling of structural response but increases modeling complexity and computational cost.

3) Proposed Simplified Fragility Evaluation Method could provide a faster way to determine the earthquake level where response exceeds a certain safety threshold, helping reduce the number of FEM cases required for the mean fragility evaluation and therefore the overall computational time. The detailed analysis flow is being presented and a programmatic procedure is implemented. The advantages of the proposed method have been presented herein in comparison with the classic MCS.

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RC橋脚の損傷度簡易評価方法

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通常のモンテカルロシミュレーション（MCS）を用いたＲＣ構造物の損傷確率評価では，コンクリートや地盤等の物性値のばらつきを考慮した1000ケース程度の計算を，多数の加速度レベルに対して実施するため，膨大な計算時間と労力が必要となる。

本論文で提案した損傷度簡易評価方法は，平均物性値を用いた計算による安全率と加速度の関係（裕度曲線）と１つの加速度レベル（裕度曲線で安全率1となる加速度）におけるMCSを用いた計算による安全率の分布から，他の加速度レベルでの安全率の分布を推定するため，大幅な計算の高速化と簡略化が期待できる。

標準的なＲＣ橋脚を対象として，通常のMCSによる方法から算定したフラジリティ曲線と簡易評価方法から算定したフラジリティ曲線の比較を行い，提案した簡易評価方法の妥当性を確認した。

キーワード：損傷度評価方法，モンテカルロシミュレーション（MCS），物性値のばらつき，RC橋脚