Seismic risk assessment of conventional steel constructions to the hazard of three earthquake types in Southwestern British Columbia

F.E. Pina
Department of Civil Engineering, Universidad de Santiago de Chile
C.E. Ventura
Department of Civil Engineering, The University of British Columbia

ABSTRACT: The Southwestern British Columbia, Canada, where most populated cities are located, is prone to the occurrence of three types of earthquakes: shallow crustal in the continental plate, deep subcrustal in the oceanic plate, and subduction in the interface. A methodology that measures the seismic risk of conventional construction systems in British Columbia have been developed, which integrates the occurrence of these three earthquake types with the seismic behaviour of structural systems. The list of structural systems include three steel construction systems: eccentrically braced frames, concentrically braced frames and moderately ductile moment frames. Significant differences have been observed in the seismic behaviour of these structural systems under these three earthquake types. The inherent differences of the records can be explicitly captured by the seismic risk methodology. This methodology has been used to assess schools in BC and to define steel construction systems as retrofit solutions to limit risk for life-safety standards.

1 INTRODUCTION

The Ministry of Education of British Columbia is in the third phase of a seismic retrofit program for all at-risk public schools in the province. In this phase a probabilistic risk assessment approach has been developed and implemented for measuring the risk to earthquake damage of most structural systems of school buildings. The probabilistic approach was mainly preferred due to the uncertainties of the earthquake occurrence and mechanism. The seismicity of BC is comprised by three earthquake types: crustal, subcrustal and subduction, which have distinct rate of occurrences and potentially affect schools differently (Fig. 1).

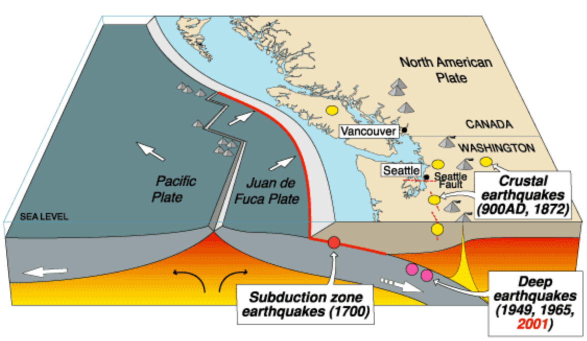

Figure 1. Cascadia Subduction Zone showing crustal earthquakes in North America plate; subcrustal earthquakes in Juan de Fuca plate and subduction earthquakes. (Cascadia_earthquake.jpeg is a courtesy of the U.S. Geological Survey. The USGS home page is http://www.usgs.gov).

Also in the third phase of the BC school retrofit program, more structural systems have been included in the library of systems for assessment and retrofit. Conventional steel systems are part of this library and considered as feasible, and preferred in many cases, alternatives for seismic retrofit. The steel structural systems available for assessment/retrofit of BC schools are described with emphasis on their performances to the three earthquake types expected in the province.

2 RISK ASSESSMENT METHODOLOGY

Details of the seismic risk assessment, SRA, methodology have been widely described and published elsewhere (Pina et al. 2010a, b, Taylor et al. 2009, Hanson et al. 2009). Main steps and ideas of this seismic risk assessment methodology are summarized here (Fig. 2).

The SRA procedure uses incremental dynamic analyses, IDA (Vamvatsikos and Cornell 2004), to estimate the incremental inter-storey deformation drifts (Step 4) of all types of school building systems (Step 1) under 3 sets of 10 motions each recorded from crustal, subcrustal and subduction earthquakes on Site Class C sites (Step 3). The intensities of the input motions range from 10% to 250% the design motion intensity given by the NBCC 2005 (Canadian Commission on Building and Fire Codes 2005). This level of shaking is called the 100% intensity level. Conditional probabilities of drift exceedance were calculated for each intensity increment of the 100% motion level (Step 5). The conditional probabilities were convoluted with the annual frequency of the intensity increment (calculated from a seismic hazard analysis in Step 2) to give the total probability of drift limit being exceeded, PDE, for all earthquake types (Step 6). The PDE can be calculated in this way for any damage level specific for the appropriate drift ratio.

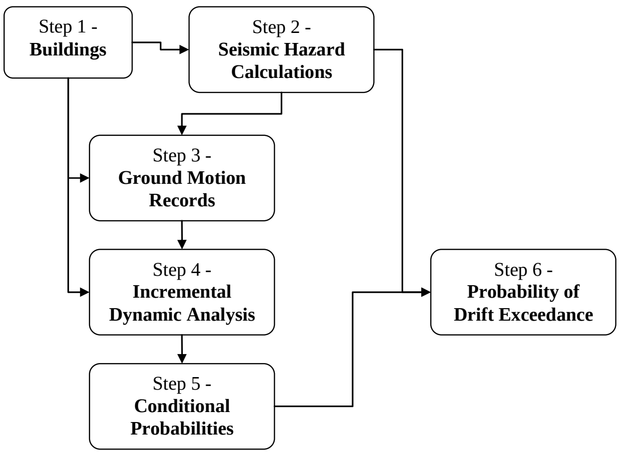

Figure 2. Calculation procedure of risk or the probability of drift exceedance, PDE, for BC school structural systems.

3 SCHOOL STRUCTURAL SYSTEMS

Most schools in British Columbia are one to three-storey buildings with lateral deformation resistance systems (in the facade and/or classroom partitions) connected by horizontal diaphragms. Most commonly found materials/systems are plywood shear-walls, unreinforced masonry walls or reinforced concrete shear-walls. Steel systems are sometimes found in gyms or covering extensive areas within the school buildings. Due to their good performance under earthquake loading, many conventional steel structural systems have been included in the next edition of the Technical Guidelines (APEGBC 2011), herein refer as TG, to be adopted as feasible seismic retrofit options.

Table 1 lists the different conventionally constructed steel structural systems that are now available in the TG. There are four main systems: Concentrically Braced Frames with Tension Only bracing, CBF-TO, Concentrically Braced Frames with Tension-Compression bracing, CBF-TC, Eccentrically Braced Frames, EBF, and Moment Frames, MF. CBF-TO and CBF-TC have been subdivided into three categories, S-1 to S-3 and S-4 to S-6, respectively, to account for the different levels of ductility expected on the existing/retrofit systems. Table 1 also shows the design drift limit, DDL, in % that indicates the maximum inter-storey deformation of each system for a life-safety performance objective. The definition of this DDL varies for each system. The procedure to determine DDL numbers are beyond the scope of this paper, but the reader is referred to detailed explanations and examples included in the TG and elsewhere (Pina et al. 2009). The last column of Table 1 indicates the hysteretic model adopted for the nonlinear dynamic analyses.

Table 1. Margin settings for A4 size paper and letter size paper.

Prototype	Prototype Number	Description	DDL %	Hysteretic Behaviour
CBF - TO	S-1	Moderately ductile concentrically braced steel frame with **tension only** bracing	2.5	Tri-linear slip model
	S-2	Limited ductility concentrically braced steel frame with **tension only** bracing	1.5	Tri-linear slip model
	S-3	Conventional construction concentrically braced steel frame with **tension only** bracing	1.0	Tri-linear slip model
CBF - TC	S-4	Moderately ductile concentrically braced steel frame with **tension and compression** bracing	2.5	Tri-linear slip model
	S-5	Limited ductility concentrically braced steel frame with **tension compression** bracing	1.5	Tri-linear slip model
	S-6	Conventional construction concentrically braced steel frames with **tension compression** braces	1.0	Tri-linear slip model
EBF	S-7	Eccentrically braced steel frame	2.25	Degrading bi-linear model
MF	S-8	Moderately ductile steel moment resisting frame	2.5	Degrading bi-linear model

4 GROUND MOTION RECORDS

Three suites of 10 ground motion records each were defined to account for the different earthquake types occurring in BC. Records for crustal, subcrustal and subduction earthquakes were selected from public databases and then modified to represent the seismic hazard of BC (further details of this work can be found in Pina et al. 2010a). The velocity spectra of these suites of records are shown in Figure 3 for the city of Vancouver in firm ground, Site Class C. In this figure, clear differences between and patterns in these three earthquake types can be observed. Crustal earthquake records tend to have large spectral demands up to periods of 2 seconds decaying smoothly for longer periods, while subcrustal earthquake records dominate at shorter periods (less than 1 second) with a sharp decay at periods longer than 2 seconds. Subduction earthquake records are much longer in duration (not shown in Figure 3) than the other two types, and they have large spectral demands at almost the entire range of periods.

5 DYNAMIC ANALYSIS OF STEEL SYSTEMS

The following is a discussion of the variation in response due to ground motion characteristics of four steel prototypes: S-1, S-4, S-7 and S-8. Nonlinear dynamic analyses of these models were performed in CANNY (Li 2009). The models were assumed to have a resistance of 10% the total seismic weight, *W*, of the building (10%*W*). The structural responses correspond to the displacement histories for the first floor and the hysteretic behaviour for three records at 100% of the Vancouver hazard level.

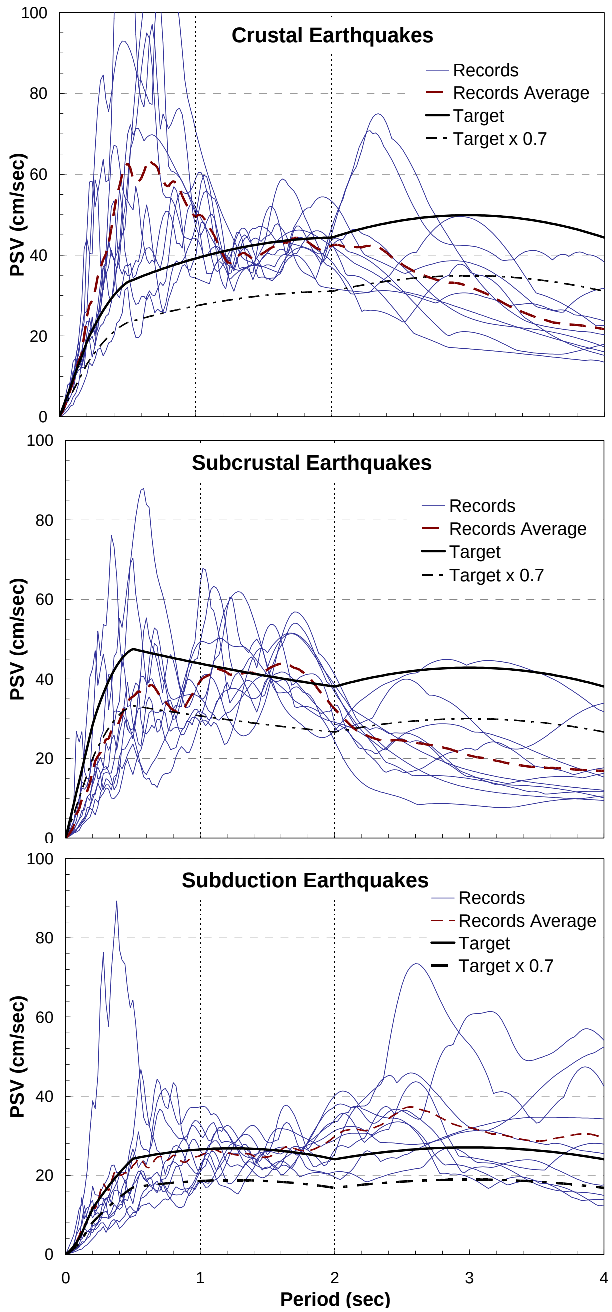

Figure 3. Spectral 5%-damping pseudo-velocities of selected/modified records and target hazard spectra for crustal, subcrustal and subduction earthquakes for the city of Vancouver, BC, in Site Class C (firm ground).

Figure 4 shows the displacement histories and the hysteretic behaviour for three records at 100% of the Vancouver hazard level of a S-1 system with 10%*W* resistance. The response in crustal earthquake is very large and skewed and the story drift exceeds the drift where onset of degradation in equivalent backbone happens. Subcrustal and subduction earthquakes exhibit more stable response and have lower responses.

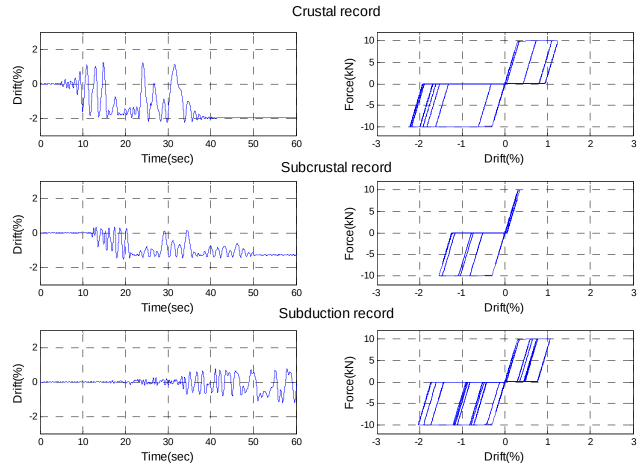

Figure 4. Displacement histories and hysteresis curves of the S-1 model for the crustal (top), subcrustal (middle) and subduction (bottom) records

Figure 5 shows the displacement histories and the hysteretic behaviour for three records at 100% of the Vancouver hazard level of a S-7 system with 10%*W* resistance. The response in crustal earthquake is very large and skewed. The response to subcrustal earthquake is also skewed but not large compared to crustal earthquake. Subduction earthquake exhibits more stable response and has lower responses.

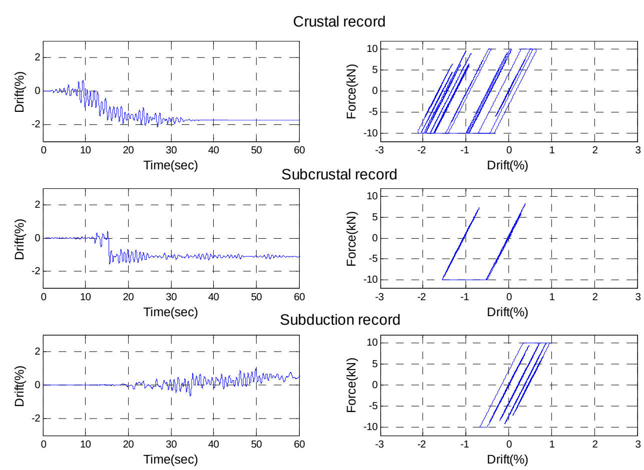

Figure 5. Displacement histories and hysteresis curves of the S-7 model for the crustal (top), subcrustal (middle) and subduction (bottom) records.

Figure 6 shows the displacement histories and the hysteretic behaviour for three records at 100% of the Vancouver hazard level of a S-8 system with 10%*W* resistance. The response in crustal earthquake is very large and skewed. Subcrustal earthquake has skewed response. Subduction earthquakes exhibit more stable response and have lower responses.

6 RISK CONTRIBUTION

Figure 8 shows the analysis results for Site Class C in Vancouver for steel prototypes S-1, S-7 and S-8 at drift limit value of 4% (value for demonstration purposes only). Figure 7 shows the annual frequencies of 4% drift exceedence for crustal, subcrustal and subduction earthquakes. It is illustrated that for a 4×10^{-4} frequency (a Poisson-based probability of 2% in 50 years) of 4% drift exceedance, the resistance values are 12%W, 11.2%W and 9.4%W for the S-1, S-7 and S-8 models, respectively.

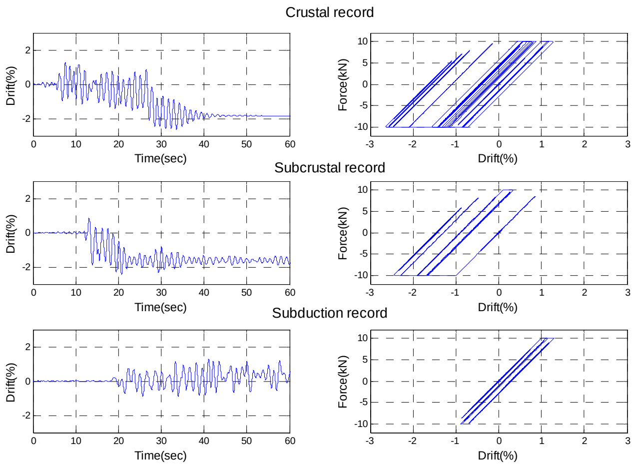

Figure 6. Displacement histories and hysteresis curves of the S-8 model for the crustal (top), subcrustal (middle) and subduction (bottom) records.

Figure 7 also allows for the observation of the individual contribution to seismic risk of each earthquake type. Crustal earthquakes dominate the total risk in the three steel models. We can deduce also from Figure 7 that crustal earthquakes dominates almost entirely for structures with much larger lateral resistances, say in these cases larger than 15%*W*.

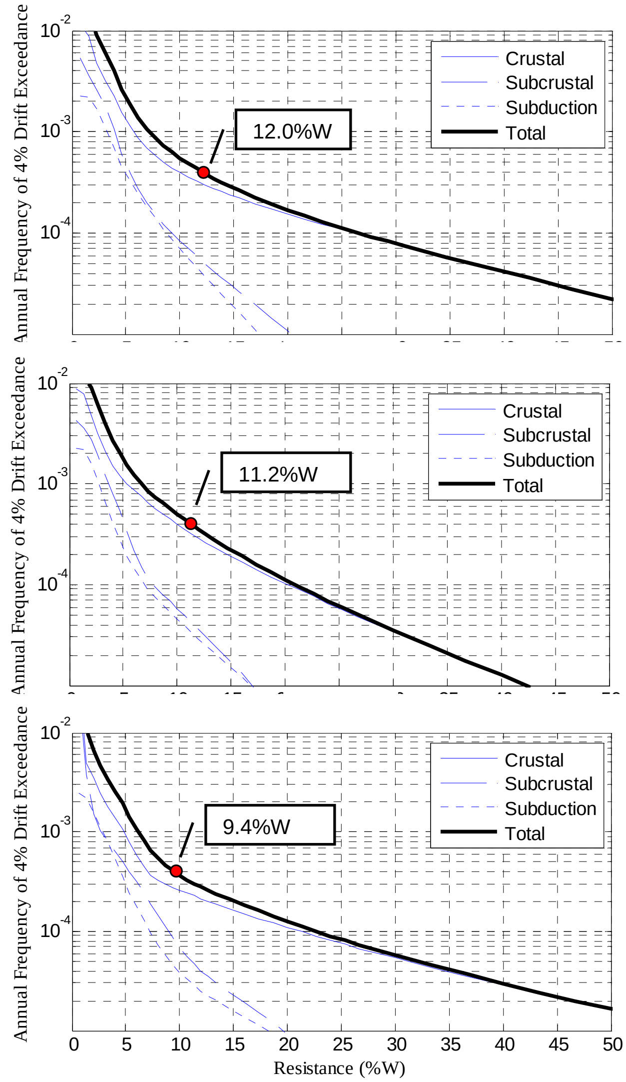

Figure 7. Annual frequency of drift exceedence at 4% drift limit for prototypes S-1, S-7 and S-8 for site class C in Vancouver

7 PDE ANALYSIS RESULTS

Risk values have been also computed for the DDL values shown in Table 1 for the S-1, S-7 and S-8 models. Figure 8 shows the resulting PDEs of the DDL values for a wide range of lateral resistances. Boxed values correspond here to the required resistance, *Rm*, to limit the risk or PDE to a 2% in 50 years. This required resistance is useful for, and familiar to, engineers to strengthen the existing structural system in the building (another system can be also used as an alternative retrofit solution by providing its respective drift limit). In these cases, the engineer should provide at least a lateral force capacity (base shear) for these systems of 16.9%W, 14.4%W, and 14.4%W to ensure a life-safety performance for the S-1, S-7 and S-8 systems of this school.

8 USER INTERFACE

A user-friendly interface program, called the Seismic Performance Calculator (SPC), has being developed for this project to provide instant access to required data for assessing the need of retrofit and for running retrofit options. The SPC is seen as the final analytical tool of the proposed methodology that provides the engineer access to a highly advanced, peer-reviewed analytical database without requiring him/her to be experienced in the use of nonlinear dynamic analysis techniques. This final analytical program permits the engineer to quickly analyze principal building elements that have analytically complex behaviour.

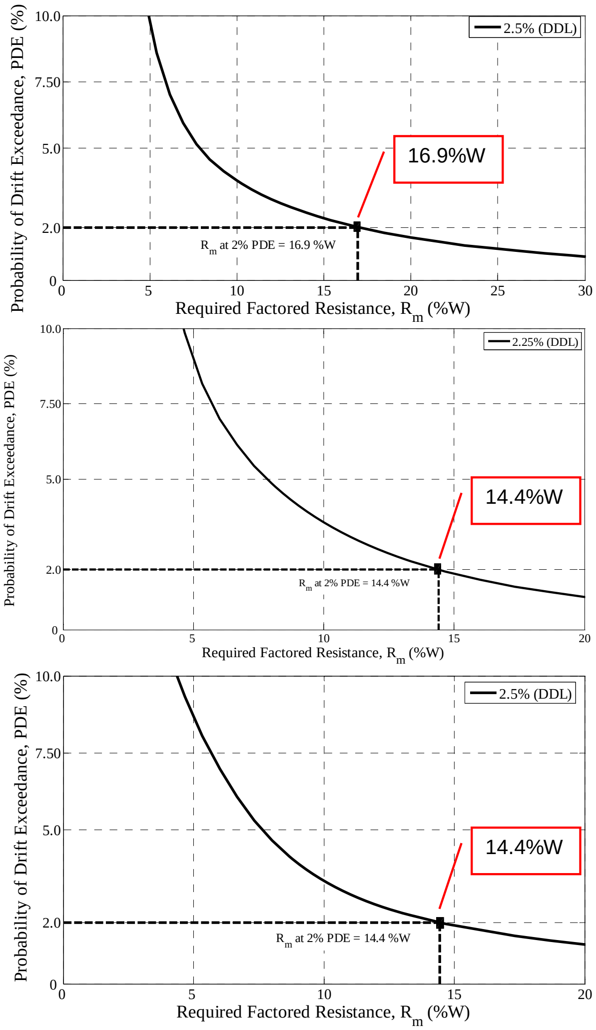

Figure 8. Probability of Drift Exceedance at DDL for prototypes S-1 (DDL=2.5%), S-7 (DDL=2.25%) and S-8 (DDL=2.5%) for site class C in Vancouver

The SPC has two potential options for the estimation of seismic risk and two potential options for running retrofit options of LDRSs: Basic Risk Assessment, Detailed Risk Assessment, Basic Risk Retrofit and Detailed Risk Retrofit (options in the left-side of the four screens shown in Figure 9). Lists of options are displayed for input variables such as Community, Soil Type, Prototype, Resistance, Drift Limit and Drift. Two action buttons are available for the user: Analysis and Print. Information stored in the database is instantly displayed by clicking the Analysis button. A summarized report of the information displayed will be printed by clicking the Print button (this summary can be used to support or complement the engineering calculation report). Figure 9 shows a preliminary version of the SPC. The final version will be released on September of 2011 and will be available for local engineers through the intranet of the Association of Professional Engineers and Geoscientists of BC, APEGBC.

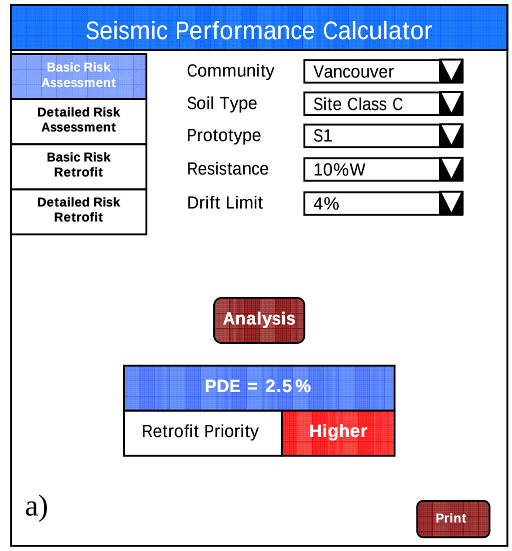

Figure 9. A preliminary version of the Seismic Performance Calculator for the seismic risk assessment/retrofit of BC schools

9 FINAL REMARKS

This paper described a procedure for estimating the risk of damage of school buildings in British Columbia with conventional steel constructions. The procedure estimates a deaggregated risk for crustal, subcrustal and subduction earthquakes that occur in British Columbia. The compound probability of all intensity increments was calculated for each earthquake type and aggregated to obtain a total annual probability of drift exceedance. Examples of characteristic steel structural systems in British Columbia were used to illustrate the proposed procedure. The proposed seismic risk assessment procedure uses incremental non-linear dynamic analysis technique with full range of ground motion intensity increments; it combines structural analysis results with current seismic hazard data with an insight into structural response to different earthquake types; the risk assessment methodology has the ability to mitigate earthquake damage to any drift deformation and can be described as a rational quantitative method of assigning risk.

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