Management of Earthquake Risks using Condition Indicators

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Abstract: The present paper describes the early developments of a generic decision theoretical framework for the consistent quantitative and rational management of earthquake risks. It is anticipated that the decision support framework shall support decision makers responsible for the safety of personnel, environment and assets of a larger area such as e.g. a region or a city. The framework shall be generic in the sense that it is formulated in terms of characteristic descriptors which can be observed and which may easily be adapted to the specific characteristics of a specific region or city. The main emphasis is directed on the risks due to potential failures and collapse of building structures as well as infrastructure systems such as bridges and tunnels. An important feature for the decision framework is that it should provide cost efficient decision support on how to optimize investments into risk reducing measures in three situations, namely, prior, during and after an earthquake.

1 Introduction

Efficient management and consistent quantification of natural and man-made risks is increasingly becoming an issue of societal concern. Sustainable and consistent societal decision making requires that a framework for risk management is developed, which, at a fundamental level allows for the comparison of risks from different natural hazards such as the comparison between risks due to earthquakes with the risks due to flooding or due to draughts.

The present paper describes an approach consisting of two levels, namely an integral, interdisciplinary level and a process or disciplinary oriented level. At the integral level, the general problem is formulated within the framework of the

Bayesian decision theory in a rather ambitious attempt to develop a generic and consistent basis for the quantification and management of earthquake risks. The process oriented parts of the proposed research project aim to establish the building stones required to develop the risk management framework. The results will not only be of significance for earthquake risk assessment and management but, due to its generic nature, be adaptable to other types of risks.

Initially the view angle, taken within the present project to earthquake risk management, is described and existing approaches and methodologies in regard to earthquake hazard, damage and risk management are reviewed. Thereafter the basic framework for risk management within the present project is outlined and finally the important aspect of the development of indicators is addressed.

2 Decision Problems related to Earthquake Hazard

From the structural engineers point of view two questions are of major interest: the estimation of the possible damage before and the assessment of the existing damage after the event. Numerous methods are in use to handle especially the former. But since risk is not only defined by the probability of occurrence of an event, but also by the consequences, the decision problems needs to be formulated in a broader sense.

The decision problems can be categorized in three different situations, before-during-after (see Figure 1). Before an earthquake the main questions are to identify the probability of the occurrence of the earthquake event and to estimate its effect on the building stock. This information may be rendered by the decision maker in order to allocate the available resources optimally for the risk reduction. Decisions regarding e.g. retrofitting or rebuilding of the buildings indicated as vulnerable may be made based on these.

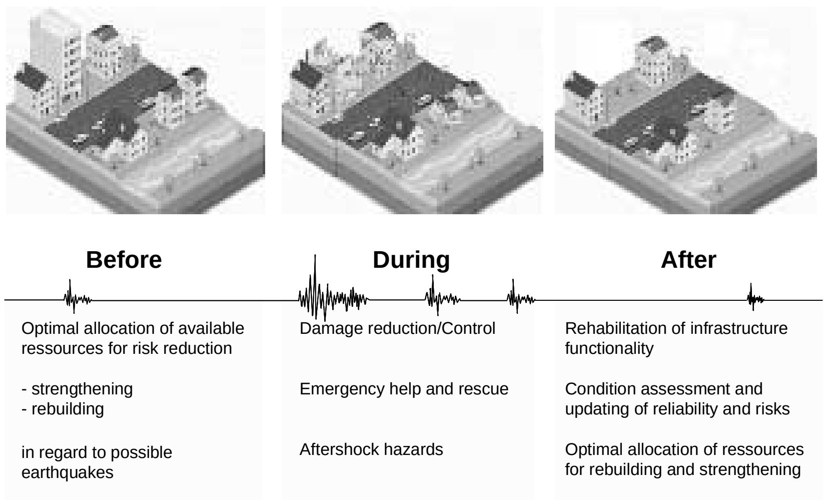

Figure 1. Illustration of the different decision problems in earthquake risk management (adapted from Aslantürk, 2003: http://www.milliyet.com.tr/content/interaktif/depremsiddeti.html).

During an earthquake the decision problems are rather different. Here a fast detection of the actual condition of the building stock of the affected region is nec-

essary in order to optimize the emergency help and rescue. Another main emphasis will be on the risks due to potential failures and collapse of building structures as well as infrastructure systems in case of strong aftershocks. It should be noted here that the 'during' situations include a longer period (several weeks) after the major shock, where strong aftershocks may occur.
After the aftershocks attenuate the decision situation is similar to the "before" situation, but with the difference that the models used in the previous steps can be updated based on numerous sources of information. Main decision problems are the rehabilitation of the infrastructure functionality and the optimal allocation of available resources for rebuilding and retrofitting of the structures.

3 Earthquake Damage Assessment - State of the Art

Over the last three decades various damage assessment methods were developed. These methods differ in expenditure and accuracy and depend highly on the availability of data and technology.

3.1 Damage assessment by vulnerability functions

In cases where extensive data on damage to structures are available, systematic statistics in form of damage probability matrices can be generated. From a field survey covering about 1600 buildings damaged during the San Fernando Earthquake of 1971 (Whitman et al., 1974) generated first of such damage probability matrices. The matrix displays the probability that a specific building class will experience a particular level of damage in case of a specific earthquake intensity. A more generic approach was attempted by generating damage probability matrices based on experts opinions (ATC-13, 1985). The experts had to fill out a check-list with their estimates for the expected damage for a specific building type. The major shortcoming of this approach is that it is highly case sensitive, hence not directly transferable to regions with a different building stock.
A more refined method for identifying vulnerable structures focuses on structural deficiencies. These so-called "score assignment procedures" identify potential structural deficiencies from a detailed review of building performance observed in past earthquakes. The aim is to identify weaknesses in the structure, which may result in structural failure. The deficiencies are quantified, weighted and calibrated by experts and loss estimations achieved by correlating the structural score to damage (McCormack & Rad, 1997; Faccioli et al., 1999).

3.2 Damage assessment by estimation of structural deformations

Recent development of simplified methods to predict the non-linear seismic behaviour of structures has a significant impact on vulnerability assessment strategies. Among these are: the "Direct Displacement Design Method" by Priestley and Calvi (Priestley, 1997; Priestley et al., 1996), the "N2 Method" (Fajfar, Gašperšic, 1996), the "Capacity Spectrum Method" (Freeman, 1998; Freeman et al., 1975). A variation of this method, where inelastic response spectra instead of highly damped response spectra are used, is presented in (Fajfar, 1999).

Common characteristic of these methods is the representation of the non-linear behaviour of the structure using a so-called pushover curve, i.e. the base shear - top displacement relationship of a simplified model. Many vulnerability assessment methods make use of these new non-linear analysis techniques. The pushover curves may be estimated basically relying on expert opinions (HAZUS, 1999) or calculated analytically using simplified structural models and assumptions on the nonlinear material behaviour (Lang, 2002; Calvi, 1999). In (Fajfar & Gašperšic, 1996) the pushover curve of a single building is computed by means of finite element analysis after numerical discretization of the structure.

Recognizing the importance of structural displacements in the evaluation of damage, all these methods deliver as a main output the maximum displacement reached by the structure during an earthquake. The maximum displacement is then correlated to the damage by fragility curves. Fragility curves may be modelled as lognormal distributions and are defined by a median value $\bar{s}_d$, corresponding to the mean threshold of the associated damage-state and by a logarithmic standard deviation. In defining the parameters for the fragility curves either a detailed damage survey on different building classes after a severe earthquake or estimates of experts on the expected damage for building classes are necessary (Kircher et al., 1997; Dumova-Jovanoska, 2000).

As an example of simplified methods able to estimate structural deformation, the Capacity-Spectrum Method is schematically given in Figure 2.

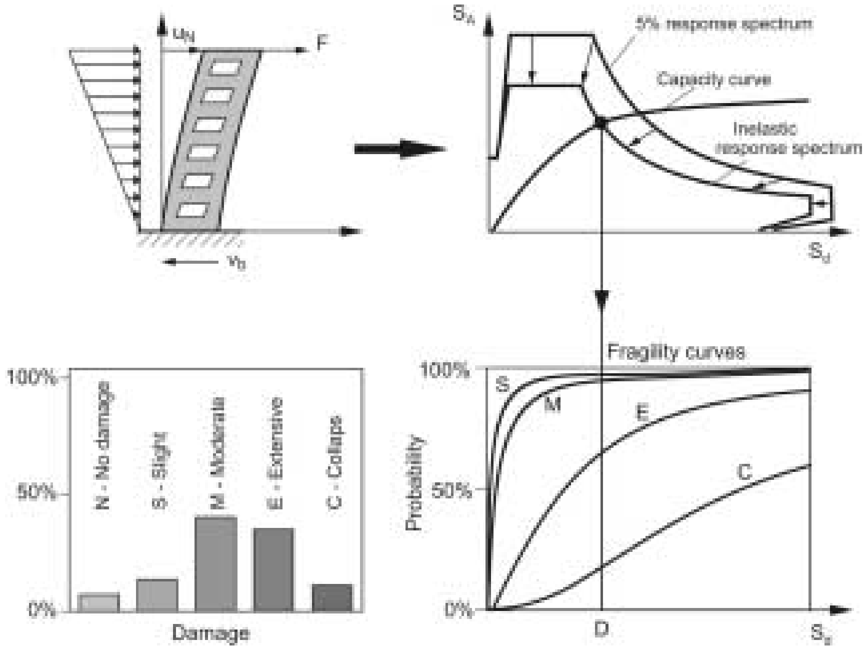

Figure 2. Capacity-Spectrum-Method for estimating the damage for a building class.

3.3 Damage assessment by refined analysis procedures

For the seismic performance assessment of single buildings refined analysis procedures are available. Most of them require a detailed and time-consuming modelling of the building and also the analysis, especially in the case of non-linear transient response computations, can become a heavy burden. However, in most cases they are able to predict local deformations that, through detailed modelling or comparison with experimental evidence, can be directly related to damage.

Despite being unsuitable for the damage assessment of a large number of buildings because of their numerical complexity, such methods are very valuable during the development and the calibration of simplified methods.

The majority of the methodologies presented here focus on risk assessment before an earthquake, considering only partly the initial damage state of the investigated building stock. Only few tools, e.g. (Eguchi et al., 1997) and (Marzorati et al., 2003), make use of modern data acquisition techniques to acquire real-time or quasi real-time information to help decision making right after the event.

4 Decision Theoretical Framework for Earthquake Risk Management

The overall theoretical framework for the risk management is the Bayesian decision theory. The risks will be quantified using Influence Diagrams or Bayesian Probabilistic networks utilizing indicators. As a first activity the different decision problems are identified and formulated such that they may be represented and assessed individually in prior decision analysis for the purpose of identifying activities for efficient risk reduction. Furthermore they will be assessed by means of pre-posterior decision analysis for the purpose of identifying how additional information may be efficiently used to reduce the risks. A uniform basis will be developed and specified for use in the project for the representation of the uncertainties dominating the decision problems, i.e. uncertainties associated with the earthquake loading, behaviour of the structures and soil as well as the uncertainties associated with the condition indicators.

4.1 Uncertainty Modelling for Decision Analysis

Risk analyses are typically made on the basis of information, which at least partly is subject to uncertainty or just incomplete. In fact the variables influencing a decision / risk analysis may be subject to several sources of uncertainty broadly categorized as aleatoric uncertainty (inherent randomness) and epistemic uncertainty (lack of knowledge, modelling uncertainties and statistical uncertainties). It is likely that modelling and statistical parameter uncertainties will be reduced as the understanding of the variable increases, e.g. through the collection and analysis of additional data and the development of improved predictive models. However, future events are not always directly related to historical data and difficulties may be encountered when trying to predict the occurrence of events beyond this data range.

The sources of uncertainty, even for the same facility, are very dependent on the purpose of the risk analysis. For example, for design of a new structure or system the uncertainties may be based on analysis of historical data (i.e. past experience) covering a range of existing facilities. However, these predicted uncertainties may fail to capture the actual uncertainties of this new “as built” structure or system (e.g., the quality of concrete or the operating environment might be different from that predicted). Thus, a posterior risk analysis will provide more accurate results.

In many cases it is not possible to include all sources of uncertainty in the probabilistic models used in a risk analysis. These sources of uncertainty are essentially non-quantifiable and are normally associated with say bias of analysts preferences for particular probability models, expertise of system representation study team, inclusion of all failure events, human error, unforeseen modes of failure, etc. To overcome this problem it is in the present project envisaged to adopt the (JCSS Probabilistic Model Code, 2001) and other relevant standardized probabilistic guidelines and data bases, aiming to achieve a more broadly acceptable basis for the performed risk analyses.

4.2 Bayesian Probabilistic Networks

Several decision support tools and techniques have been developed over the years, facilitating the analysis of various aspects of risks. One of the more promising developments in this regard is a special type of influence diagram namely the Bayesian Probabilistic Networks (BPNs) (see e.g. Jensen, 1996). Without going into the theory behind BPNs the basic feature of these in risk assessment may be described by the following steps:

(i.) Formulation of causal interrelations of events leading to one of the events of interest (consequences). This is graphically shown in Figure 3 in terms of nodes (events) connected by arrows (causal interrelations)

(ii.) Assignment of a probability structure describing the conditional state probabilities for each node

(iii.) Assignment of the consequences corresponding to the events in the BPN.

Having defined the BPN in terms of events (nodes), the causal interrelation between events (arrows) and their probability structure (matrices with conditional probabilities), the probability of any state represented in the network is defined.

For each decision situation as given in chapter 2 a BPN is established. A BPN for a decision situation “structural condition assessment” is exemplarily demonstrated in Figure 3. Table 1 shows as an example the properties of one of the nodes. Please note that for illustrative purposes only a few of the properties like soil types, saturation and earthquake duration are included.

Due to their mind mapping characteristic of BPNs comprise a significant support in the early phases of a risk analysis, where the main task is to identify the potential hazard scenarios and the interrelation of events leading to adverse events. Provided that the nets have been formulated and the conditional probability tables together with the consequences of the adverse events defined, the BPNs readily quantify the expected consequences also known as risks. BPNs furthermore provide a very strong tool for the updating of the quantified risks because information about any state represented in the nets can be input – and the risks correspondingly updated. This feature is especially valuable within a Bayesian probabilistic framework where knowledge may be provided in more or less precise form e.g. as condition indicators. Furthermore, BPNs also provide a tool for diagnosing a system, i.e. identifying the event scenarios which, with the large likelihood lead to specific adverse events of interest.

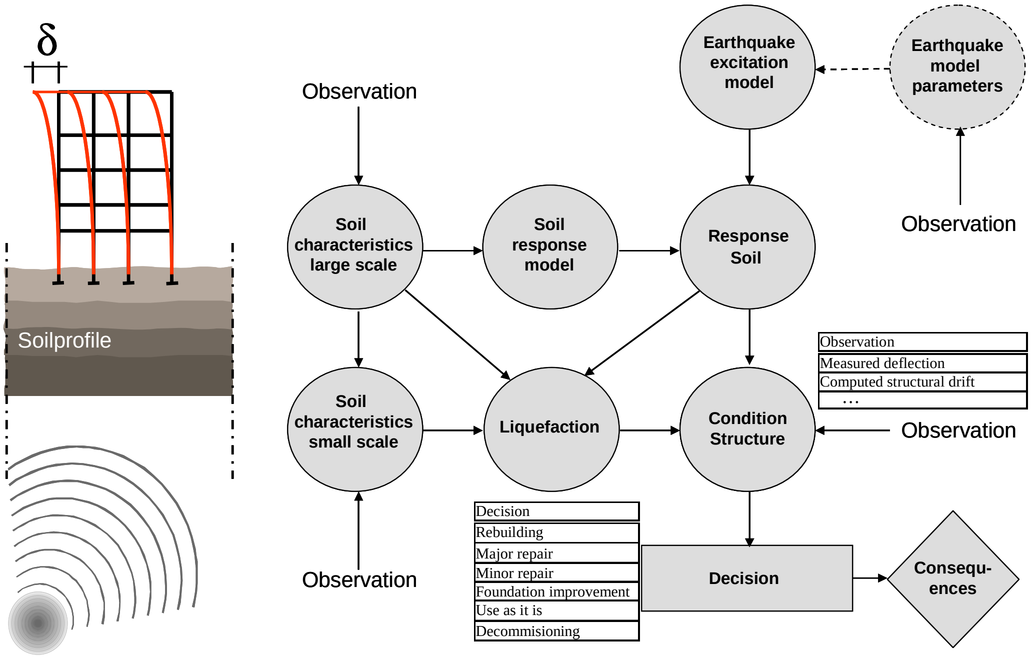

Figure 3. An example of a Bayesian network

Table 1. Conditional probability assignments for the child event in the BPN.

Liquefaction																
Response Soil	Duration-long (>40s)								Duration-short (<40s)							
Soil charac. Large	Profile-sand		Profile-silt		Profile-clay		Profile-rock		Profile-sand		Profile-silt		Profile-clay		Profile-rock	
Soil charac. Small	*uw*	*w*	*uw*	*w*	*uw*	*w*	*uw*	*w*	*uw*	*w*	*uw*	*w*	*uw*	*w*	*uw*	*w*
Yes	1*	1	0*	1*	0	0	0	0	0	1*	0	1*	0	0	0	0
No	0*	0	1*	0*	1	1	1	1	1	0*	1	0*	1	1	1	1

*further indicators need to be regarded in the ongoing research

Previously no Bayesian net has been formulated for the purpose of management and decision support considering natural hazards and earthquake risks in particular. However, other applications such as e.g. reported in (Faber et al., 2002) have proven the feasibility of the methodology.

5 Identification of Condition Indicators

An important point in the pursued methodology is to identify and quantify the effect of various types of information (indicators) on the characteristics of the buildings and life-line systems leading to the predefined damage states. In a first phase the risk indicators concerning the soil behaviour and the structural behaviour will be included. Further on, the actual damage state of the buildings and life-line systems will be assessed in terms of various measurement techniques.

5.1 Indicators concerning soil behaviour

With the intention of formulating indicators concerning soil behaviour, many influencing parameters are involved. These different influencing parameters include the physical and mechanical properties of the respective soils or groundwater regime in direct connection with incoming hazard. They need to be considered to implement the most important factors in a risk assessment procedure. As an example, the dependence of the condition of the upper soil layers on the development of ground acceleration from an incoming earthquake is one of the important condition indicators. Focus is given in this project in detail on liquefaction potential of silty soils, which are less understood and for which indicators are more difficult to define.

The main condition indicators describing the soil behaviour under cyclic loading are the graduation curve and the water content. Further indicators are the density and thus the layering conditions and with less importance for sands, intensity and duration of the incoming earthquake. Thus, liquefaction prone situations for sands are given by full saturation, but might appear in loose layers also for unsaturated conditions with high water content. Full liquefaction is the worst part of cyclic softening, which in case of saturated granular soils subjected to an earthquake includes an increase in pore water pressure similar to the total stress, so that effective stress reduces towards zero. Cyclic hardening on the other hand will occur due to volumetric compression and particle rearrangement, while no significant increase in pore water pressure will be observed. Deformation on the surface might be visible after the event, but due to the particle rearrangement the risk for the next event is reduced.

Sand has a low liquefaction resistance and the grains neither exhibit plasticity nor are platy in shape. Condition indicators and criteria can be derived for sand from the extensive studies being reported in the literature. The shape of silt grains is similar to that of sands. Therefore, the characteristics of silts are assumed to be similar to that of sand.

Another approach carried out experimentally will focus on silt and the variations of silt - sand content in interaction with e.g. the loading function, which represents the incoming earthquake. Existing indicators or design criteria are given on purely recognition of single parameter (Idriss et al. 1999, Finn, 1994) or are based on mostly empirical correlation between field investigation, soil classes and earthquake hazard (Youd et al., 2001). Criteria or condition indicators will be formulated for the liquefaction potential of silts and silty soils, which should be able to couple single influencing parameters.

Clay has a high liquefaction resistance due to its platy form of its grains and its low permeability. Pore water pressure build up during the relatively short earthquake can be neglected, which allows to exclude clay from the particular study. But also for clays high deformations have been reported after recent earthquakes (Ansal et al., 2001). Main parts of the condition indicators can be formulated based on an extensive literature review for soils, which includes a re-establishing of the results in terms of defining combined condition indicators.

5.2 Indicators concerning structural behaviour

The most significant indicator characterizing the seismic performance of structures is the structural drift, since it is directly related to the strains expected in the materials, hence to the damage. In the proposed method, deformations are either measured using the most modern methods of photogrammetry or estimated by means of recognized theoretical assessment tools.

For most structures the seismic damage has, in the past, been expressed by means of response indices related to the maximum deformation of the structure during an earthquake. However, the maximum deformation can be measured during an earthquake only for selected structures (lifelines) that are provided with appropriate measuring devices. Therefore, it can hardly be used as an updatable condition indicator. Among other researchers, (Christopoulos et al., 2003) and (Pampanin et al., 2003) recently pointed out the importance of residual deformations in the assessment of the seismic performance of the structure. While it is quite straightforward to conclude that large residual displacements means a reduction of both safety and serviceability of the structure - hence damage - small residual displacements not always means full safety and serviceability, this mainly because of shake-down effects. Therefore, extensive investigation of the nonlinear dynamic behavior of typical structures belonging to given building classes will be performed in order to get better handle on this problem. Measured and computed residual deformations will then be compared and related to the condition of the structure. Of course, to allow a reliable characterization of the condition of the structure, additional indicators, like e.g. number of story, year of construction, crack widths in main structural elements, will be needed. The definition of such indicators is still pending and will be a mayor challenge within the structural task.

5.3 Indicators concerning large scale damages

The development of new generations of digital imaging devices opens the possibilities for enhanced on-line information extraction procedures which are

also of great interest to the problems decribed here. Using digital aerial photogrammetry will allow the acquisition and processing of a large amount of data in a short time. This includes the generation of Digital Surface Models, 3D City Models and individual objects as buildings, roads and bridges (Zhang, Gruen, 2003, Gruen et al.,2003). In a time span of four to five hours after image acquisition it will be possible to assess the deformed shape and the change in volume of the building stock of a 4 km^2 area with a precision up to ±1 dm. Lowering the flight height of the camera an even higher precision can be reached to the cost of a larger data acquisition and reduction time. Terrestrial mobile mapping systems will allow the measurement of the deflected shape of a damaged building within some 30 minutes with a precision up to ±1 cm. For selected buildings and special smaller features these methods allow a precision of a few millimeters.
Aerial digital camera data will be used in the immediate aftermath of the seismic event to detect collapsed structures (change in volume) and to roughly assess the residual drift of structures (displacements). This data of course is only meaningful in case of large displacements, i.e. by large drift of small structures or by small drift of large structures. Data from terrestrial mobile mapping systems will be used to calculate important damage assessment parameters like the tilting of a structure and the residual local interstory drift. The acquisition and reduction of these data will start in the immediate aftermath of the seismic event and will be carried out until it is deemed necessary to have a better understanding of the damage state of the investigated area. The data of each building surveyed in this fashion will allow an update of the risk assessment model and hence allow for a more precice assessment of the risks. The sequence of the surveying can be based on a pre-earthquake decision or on the information provided by aerial photogrammetry.

6 Discussion and Conclusions

The decision problems related to earthquake hazard are complex. This complexity results not only due to the fact that the whole functional chain of the phenomenon “earthquake” from the earthquake source mechanism to the structural damage exhibits high uncertainties, but is also due to the possibility of the emergence of extreme consequences. The decision theory serves as a proper mathematical framework for the consistent treatment of such problems.
The majority of the present damage estimation methodologies focus on risk assessment prior to an earthquake. Real-time information right after the event are scarcely involved. A more systematic approach is suggested in the present paper. The decision problems are classified into three categories: before, during and after an earthquake and formulated in terms of characteristic descriptors (indicators), which can be observed and/or measured. Bayesian Probabilistic Net-

works (BPN) are used for the consistent integration of all aspects for each decision problem.
The elaboration of the relevant condition indicators for the BPNs requires an interdisciplinary research group. At an integral level the decision theoretical framework and the uncertainty modelling of the indicators are studied at the Institute of Structural Engineering, Group Risk and Safety (Prof. Faber) as well at the Section of Forest Engineering (Dr. Hollenstein). The development of the indicators at a process oriented level are pursued in the relevant disciplines; Indicators concerning the soil behaviour at the Institute of Geotechnics (Dr. Laue), indicators for the structural behaviour at the Institute of Structural Engineering, Group Earthquake Engineering (Prof. Dazio), indicators concerning the measurement of damages at the Institute of Photogrammetry and Remote Sensing (Prof. Grün). Finally the important aspect of consequence assessment is being considered by the Institute for Construction Engineering and Management (Prof. Schalcher).

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