SEISMIC RELIABILITY ANALYSIS OF UTILITY NETWORKS

A. Rasulo[1], I. Vanzi[2] and C. Nuti[3]

[1] *Dipartimento di Meccanica, Strutture, Ambiente e Territorio, University of Cassino, Cassino, Italy*
[2] *Dipartimento di Progettazione, Riabilitazione e Controllo delle Strutture, University of Chieti, Pescara, Italy*
[3] *Dipartimento di Strutture, University of Roma Tre, Rome, Italy*

ABSTRACT :

Utility systems are essential for assuring a high standard of life in developed countries. Water, electricity and roads are just some of the classical examples. Earthquakes can cause extensive and unforeseen damages to those infrastructures where the mutual dependence of structural and functional failures may give rise to domino – like effects. In the paper, it will be shown that the problem of analyzing the seismic reliability of water, electric power and transportation networks can be treated following the same approach, presenting a complete computational procedure, able to carry on both scenario and probabilistic analysis.

KEYWORDS: Risk analysis, Seismic Reliability, Network Systems.

1. INTRODUCTION

Developed countries need many, and reliable, networks. Earthquakes can cause extensive and unforeseen damages to those infrastructures where the mutual dependence of structural and functional failures may give rise to domino – like effects, both within and between networks. In particular damages due to strong earthquakes may be as high as 3% of a country annual gross national product (GNP), with indirect damages as large as the direct ones (The Economist, 1995, Tiedemann, 1992).
As a synthesis of a couple of decades of research activities, it will be shown that the problem of analyzing the seismic reliability of water, electric power and transportation networks can be treated following the same approach, essentially because the models governing the functioning of those three systems contain many – maybe most - identical parts. The very differences arise, of course, in the assessment of the fragility of components, and in the so – called flow equations, i.e. the mathematical description of the network capability to bring respectively the electric power / water / vehicles from one node to another node of the network.
A complete computational procedure will be presented, able to carry on both scenario and probabilistic analysis (when the details of the future earthquakes are not known). The software is based on a Monte-Carlo analytical scheme: in every simulation there is the generation of an earthquake, the propagation of the effects at the network nodes, the simulation of component failures and the resolution of a flow analysis over the damaged network in order to assess its functionality, both in terms of ability to carry the goods (vehicles, electricity or water) or to assist Civil Protection operations in the aftermath of the seismic event.

2. MODELS IN NETWORKS SEISMIC SAFETY ASSESSMENT

In this section, the different parts which compose the model to assess the seismic safety of the networks are presented, showing how have been assembled together the several components of the computational procedure.

2.1 Model of the seismic action

The Cornell model, with diffused seismicity, is usually assumed for earthquake generation. In this model, the random variables are the position of the epicenter, the earthquake magnitude (a synthetic measure of the energy released by the quake) and the time between two events. The coordinates of the epicenter are assumed independent random variables, with constant distribution between the boundaries of the seismogenic area; the time random variable is modeled with the Poisson distribution; the earthquake magnitude random variable is modeled via the doubly truncated Gutenberg- Richter law. Accordingly, within each seismogenic area, the probability distribution of earthquakes magnitude M is defined by:

$$F_M(m) = 1 - \frac{\exp(-\beta \cdot m) - \exp(-\beta \cdot m_{MAX})}{\exp(-\beta \cdot m_{MIN}) - \exp(-\beta \cdot m_{MAX})}$$
$$\lambda(m) = \lambda(m_{MIN}) \cdot [1 - F_M(m)] \qquad (2.1)$$

In the previous equation, β is the severity parameter, m_{MIN} and m_{MAX} are the lower and upper bound for the earthquake magnitude, λ is the mean rate, according to the Poisson distribution, of events per year and F is the cumulative distribution function. For each area, the parameters of the Gutenberg- Richter law are evaluated on the basis of the historical seismicity.

How an Earthquake affects the area around the epicenter may be expressed via different measures. Common choices are both qualitative measures, like the Mercalli one and quantitative measures, as the spectral acceleration at selected periods. The original procedure for electric power network (Vanzi, 1996; Vanzi, 2000) initially adopted the Modified Mercalli Intensity as input parameter. In more recent applications (Rasulo et al., 2007, Nuti et al., 2007), both the hazard and the fragility of components have been expressed with different measures (spectral acceleration at selected periods or peak ground velocity).

Whatever the choice to measure the effects due to an earthquake, for sake of generality say Y such a measure, the computation of its value around the epicentral area (closest to the fault rupture and therefore the most stroked) is performed through a so – called attenuation law, $f(\cdot)$, usually depending upon earthquake magnitude, source to site distance (in order to account for wave energy dispersion) and soil conditions at site. Below the general format of an attenuation law is reported:

$$Y = f(M, R, Soil) \rightarrow$$
$$\log(Y) = a + b\ M - c \log\sqrt{R^2 + h^2} + d\ S + \sigma\ \varepsilon \qquad (2.2)$$

In the above equation, R is the distance from the epicenter to the site considered, S is a synthetic representation of soil conditions, a, b, c, d and (eventually, since it appears has the depth beneath the ground surface of the seismic source) h are coefficients to be determined as the outcome of experimental regressions, ε is a standard normal random variable accounting for the error obtained by the regression and σ is a measure of the scatter of observed data around the predicted value.

2.2 Seismic structural fragility of network components

It is beyond the aim of this paper to deal, in a general way, with the computation of seismic structural fragility of network components. The structural models which should be used, and its mathematical treatment, are specific for each structural component and network. For the seismic fragility of the components of the three networks presented, electric power, water pipes, roads, the reader is referred to the specific sections in the sequel of the paper.

2.3 System logic and flow equations

Once the models of the seismic action (conceptually similar to the force on the system) and the fragilities (conceptually similar to the resistance of the system) have been set up, the function the network is built for must be examined.

For instance, a water distribution network will satisfactorily perform its task if it delivers, at all nodes, the prescribed amounts of water with the desired water head; similarly, an electric network is required to deliver electric power with specific tension and phase shift; the road network has to let through vehicles at an acceptable average speed. These requirements, which may be generalized in terms of transportation of goods (water, electric power, vehicles) with acceptable quality (pressure, tension, speed), define the function each network is called upon to perform.

The seismic action, by inducing failure in some of the (fragile) structural components, degrades the quality of

the service the network can perform, possibly up to the point that the whole network is unable to deliver anything.
The only feasible way to compute capacitive networks performance is via repeated simulations of its functioning after an earthquake. This is done by: (i) sampling the seismic action (force) (ii) sampling the componential fragilities (resistance) (iii) comparing force vs. resistance and determine the state of each structural component (iv) rewrite the flow equations for the network in the damaged state (v) solve the flow equations (vi) determine the network capability to perform its task. Steps (i) to (vi) are repeated until stability of results is achieved.
The flow chart of the procedure, which belongs to the class of Monte-Carlo methods, is outlined in Figure 1, making reference to the case of electric power networks.

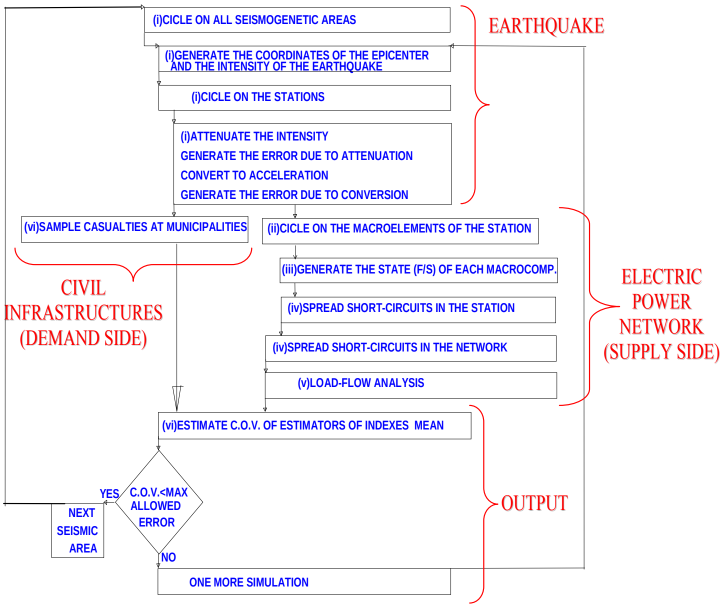

Figure 1. Flow-Chart of the procedure.

The flow-chart basically highlight that a network is conceived to supply a service, which in turn is demanded by the users. When a perturbing cause (the earthquake, for the case at hand) is considered, then proper modeling of supply and demand of the service allows comparison of these two quantities, with final output of the network safety. The simulations are repeated until the output variables statistics are stable, i.e. when at least their mean value is estimated with accuracy.

3. ELECTRIC NETWORK

The reader is referred to previous studies (Vanzi, 1996; Vanzi, 2000; Nuti et al., 2007) for a more detailed description of electric networks; for the sake of completeness some recalls will be made herein.
Electric power networks contain two basic components: nodes (power production, distribution and distribution - transformation stations) and sides of the network (power transmission lines, high tension, HT, between 380 and 220 KV, medium tension, MT, between 150 and 60 KV and low tension, LT, below 60 KV). Power production stations will not be considered herein. Networks of different tension classes are linked at the transformation stations; redundancy in the network generally increases with decreasing voltage (i.e. LT is much more redundant than HT).
The vulnerable elements of electric power networks are contained in the stations and consist of a large number of slender steel-ceramic elements, with a considerable mass on top, together with electronic pieces of equipment whose correct functioning is sensitive to imposed accelerations. The electronic equipment allows to continuously monitor the state of the network and to insulate short-circuits in case of need.
The typical layout of a transformation – distribution station is portrayed in Figure 2. A distribution –

transformation station is organized with power flowing from high to low tension; a distribution station contains only the components on the low tension side. Stations are protected from spread of short – circuits via switches elements which open and insulate malfunctionings. Correct functioning of switches depends on the correct functioning of both power supply and boxes.

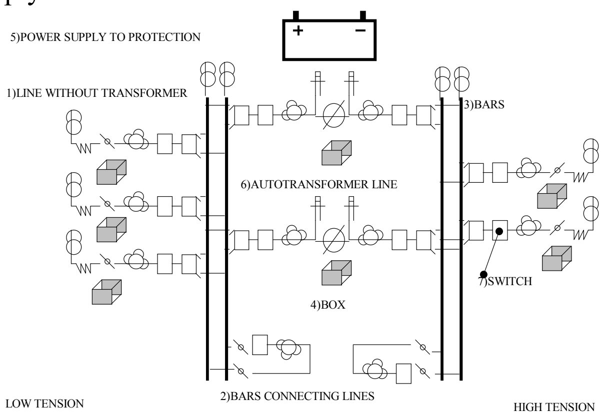

Figure 2. Components in a sub-station.

All these components, herein referred to as microcomponents, are listed in table 1, together with the symbols commonly used in electric engineering to indicate them. Table 1 also shows the parameters (λ,ζ = natural log of the mean and standard deviation) of their lognormal fragility curve (Vanzi, 1996; Vanzi, 2000) expressed as a function of the peak ground acceleration (m/s^2).

Table 1. Electric equipment fragility.

Name	Coil bearing	Switch A	TA	TV	Horiz. Section.	Vertic. Section.	Dis-charger	Bar bearing	Trans-former	Box	Power supply
Number	1	2	3	4	5	6	7	8	9	10	11
Symbol											
λ	1.364	1.662	1.428	1.792	1.746	1.690	2.265	1.476	3.157	2.925	1.399
ζ	0.338	0.328	0.269	0.269	0.223	0.340	0.315	0.438	0.287	0.519	0.162

To simplify the model of the station, serial arrangement of microcomponents have been grouped in macrocomponents. The macrocomponents are shown in Figure 2, numbered from 1 to 7.
Assuming that failures of microcomponents in each macrocomponent are independent events, it is straightforward that:

$$P_S(\text{Macro}) = \prod_{\text{micro}} P_S(\text{micro}) \qquad (3.1)$$

where P_S is the probability of survival, Macro indicates each macrocomponent and micro is an index varying over all the microcomponents in a macrocomponent. Hence the grouping in macrocomponents simplifies the stations model while allowing to evaluate the fragilities in a simple way.
The electric power network model used is capacitive, i.e. accounts for the power transport capability of each link between two generic nodes. The network capability to deliver electric power depends on boundary conditions (power and tension from supply nodes and to demand nodes), on lines admittance, and on the state (fail/safe) of the stations components. A stationary analysis of the power flow in the network is usually termed load-flow (Elgerd, 1977) analysis and is the model used herein. The capability of the L lines of transporting electric power is accounted for in the admittance matrix Y of the network (NxN complex matrix, N being the number of nodes) which is assembled considering the state of the lines, as follows:

$$Y_{p,p} = \sum_q y^L{}_{p,q} + \sum_q \frac{y^T{}_{p,q}}{2}; \quad Y_{p,q} = -y^L{}_{p,q} \qquad (4.2)$$

$y^{L}{}_{p,q}$ = longitudinal admittance of line p,q;

$y^{T}{}_{p,q}$ = transversal admittance of line p,q

$Y_{p,q}$ = p,q element of Y matrix

4. WATER NETWORK

In water distribution networks, the main source of damage comes from buried pipes (O'Rourke and Liu, 1999). On the topic of seismic vulnerability of water ducts, extensive studies have been conducted, and in literature it is possible to find dependable fragility curves, calibrated on observational data from past disruptive earthquakes (ALA, 2001).
The damage model adopted in this study is:

$$\nu = 0.0001 \cdot PGV^{2.25} \tag{4.1}$$

where the damage rate along the pipe, ν (average number of breaks per unit length, 1/km), is a function of the peak ground velocity, PGV (cm/s).
Once the damage rate is known, the number of actual leaks/breaks, N_R, over the pipe with length L has been treated as a discrete random variable, distributed according to the Poisson law:

$$P(N_R) = \frac{(\nu \cdot L)^{N_R}}{N_R!} \exp(-\nu \cdot L) \tag{4.2}$$

The flow analysis on the damaged network has been set using the classical methods of analysis for water distribution networks.
The problem can be condensed in matrix form, writing together the equations of continuity (in number of N, expressing the conservation of mass in each node) and the energy balance equations (in number of L, expressing the friction losses along the pipes) obtaining a system of N+L non-linear equations in N+L unknowns:

$$\begin{cases} \mathbf{A}_N^T \mathbf{q} - \mathbf{Q} = \mathbf{0} \\ \mathbf{R}\ abs(\mathbf{q})\ \mathbf{q} + (\mathbf{A}_N \mathbf{h}_N + \mathbf{A}_S \mathbf{h}_S) = \mathbf{0} \end{cases} \tag{4.3}$$

N is the number of internal nodes (i.e. without tank), S is the number of nodes with a tank (representing a boundary condition for the hydraulic head) and L is the number of links (pipes), **Q** [$N \times 1$] is the vector of discharged flows at nodes; $\mathbf{A}_N$ [$L \times N$] and $\mathbf{A}_S$ [$L \times S$] are the two sub-matrices (namely for internal nodes and tanks) composing the incidence matrix, **A** [$L \times (N+S)$]; $\mathbf{h}_N$ [$N \times 1$] and $\mathbf{h}_S$ [$S \times 1$] together are components of the vector **h** [$(N+S) \times 1$] representing the N hydraulic heads (unknown) in the internal nodes and the S hydraulic heads (known) at the tanks; **q** is the vector [$L \times 1$] of the flows (unknown) circulating in the pipes and finally **R** is a diagonal matrix [$L \times L$] for the coefficients of the friction loss equation for each link (accounting for pipes, pumps and minor loss), for the problem at hand specifically chosen, without loss of generality, of the Darcy-Weisbach type.
In seismic conditions, the flows discharged at nodes **Q** are represented not only by the usual flows distributed to the consumers, $Q_{consumers}$, but also by the water losses due to pipe breaks induced by the earthquake, $Q_{earthquake}$.
Differently from the usual problem of analysis of water networks where it is assumed a-priori the ability of the system to satisfy the demand, Q_{demand}, and flow losses are evaluated as a fixed percentage of the circulating flow, in this case both these quantities cannot be assumed known, and must be evaluated as a function of the network response.
Indeed, the ability to serve the users has been expressed as a function of hydraulic head according the following expression (Gupta and Bhave, 1996):

$$Q_{consumers} = \begin{cases} Q_{demand} & \text{if} \quad h_{demand} < h \\ Q_{demand} \cdot \left(\dfrac{h}{h_{\text{ric}}}\right)^{1/n} & \text{if} \quad h_{\min} \leq h \leq h_{demand} \\ 0 & \text{if} \quad h < h_{\min} \end{cases} \tag{4.4}$$

where h is the water head respect to the ground level, h_{demand} is the water head needed to assure to the consumers their demand, Q_{demand}, and $h_{\min}$ is the minimum water head to be assured in order to have a discharge greater than zero. In this case h_{demand} can be assumed to be equal to the average building height plus 3÷7 m (in order to account for the head losses due to domestic water system), whilst n is a model coefficient controlling the shape of the head dependent demand and to be assumed into the recommended range between 0.5 and 2.0. In this study, dealing with multi-storey buildings for which the effect of the demand, uniformly distributed along the building height, is predominant respect to the head losses in the domestic water system, the value has been set to 1, consistently with the suggestion by Gupta and Bhave (1996).
Water losses due to pipe seismic breakage can be treated using classic theory of the flow through an orifice/weir:

$$Q_{earthquake} = \mu\, A_{eq}\sqrt{2gh} \tag{4.5}$$

where A_{eq} is the equivalent damage area to the pipe, estimated judgementally on the base of the outcome of eq (4.1), h is the water head, g is the acceleration of gravity and μ is the orifice/weir coefficient treated differently if the damage is a leak in the pipe or a complete pipe breakage.
The problem, as formulated above, is substantially different from the conventional ones routinely solved in water distribution analysis, since its solution is no more conditioned by the discharges defined at nodes (*demand driven analysis*), but by the fact that they are a function of water heads (*head driven analysis*).
In this study a direct solution strategy has been implemented, following the Gauss-Newton solution scheme.

6. ROAD NETWORK

The components whose failure can impair road networks can be of several types: bridges, tunnels, embankments, retaining walls, etc. Since it falls outside the scope of this paper to discuss computational techniques for the construction of fragility curves for all the possible elements involved, the interested reader is invited to refer to specific literature, for example (Donferri et al., 1998, Nuti and Vanzi, 2003) for Italian highway bridges. It might suffice to say here that the damaged structures along the road reduce its capacity, c, to let the traffic (expressed in terms of vehicles) flow. In the present study, a simplified approach, adapted from (Ministero della Salute, 2005) has been used:

$$\mathrm{c} = \mathrm{c}_0\left(1 - \alpha\right) \tag{5.1}$$

where c_0 is the road capacity in non seismic conditions and α is a reduction factor, function of seismic intensity and road type. Since the approach is not addressed to specific road elements, in this case the Modified Mercalli Intensity, *MMI*, has been chosen as a suitable measure of seismic input. The reduction factor is correlated with the Modified Mercalli Intensity, *MMI,* as follows.
Motorways:

$$\alpha = \frac{MMI - 6}{8.5 - 6} \qquad \text{with } 0 \leq \alpha \leq 1$$

Main extra-urban roads:

$$\alpha = 0.9\frac{MMI - 6}{8.5 - 6} \qquad \text{with } 0 \leq \alpha \leq 0.9$$

Secondary extra-urban roads:

$$\alpha = \begin{cases} 0 & \text{if } MMI \le 5.5 \\ 0.8\dfrac{MMI-5.5}{8.5-5.5} & \text{if } 5.5 \le MMI \le 8.5 \\ 0.8+0.1\dfrac{MMI-8.5}{12-8.5} & \text{if } 8.5 \le MMI \le 12 \\ 0.9 & \text{if } MMI \ge 8.5 \end{cases}$$

Given a transportation network and the transportation demand, expressed as couples of travel origins and destinations via the Origin Destination (OD) matrix, the traffic assignment problem consists in determining the flows on the links of the network.

Traffic assignment over a road network, can be determined according to Wardrop's two principles:

- travel times in all routes actually used are equal or less than those which would be experienced by a single vehicle on any unused route;
- total travel time is minimum.

The first principle is based on the concept that each user non-cooperatively chooses the route that is optimal in order to minimize his cost of transportation. The traffic flow that satisfies Wardrop's first principle is usually referred to as "user equilibrium" (UE) flow. Specifically, a user-optimized equilibrium is reached when no user may lower his transportation cost through unilateral action.

The second principle is based on the concept that each user behaves cooperatively in choosing his own route to ensure the most efficient use of the whole system. The traffic flow that satisfies Wardrop's second principle is usually referred to as "system optimal" (SO).

It is important to notice that the second principle represents an ideal behaviour as individuals may not attempt to follow the system optimal configuration, the first principle, instead, has become the most widely used behavioural principle to describe the flow pattern that results from the spreading of trips over alternate routes due to congestion. In the following the User Equilibrium principle is assumed.

The UE principle has been expressed through the Beckmann's transformations (Beckmann, McGuire and Winsten, 1956) as an optimization mathematical problem, usually referred to as the standard UE assignment problem:

$$\begin{array}{lll} \text{minimize} & z(\mathbf{x}) = \sum_a \int_0^{x_a} t_a(w,c)\,dw & \\ & x_a = \sum_{pq}\sum_k X_k^{pq}\delta_{a,k}^{pq} & \\ \text{subject to} & \sum_k X_k^{pq} = D_{pq} & \forall\, p,q \\ & X_k^{pq} \ge 0 & \forall\, p,q,k \end{array} \qquad (5.2)$$

where t_a is the travel time over the link a, as defined through the congestion function (usually dependent on the traffic volume, w, and link capacity, c, as defined by eq. 5.1); x_a is the traffic flow over the link a; X_k^{pq} is the same quantity over the path k connecting the Origin Destination pair p-q; D_{pd} is the travel demand between the Origin Destination pair p-q; $\delta_{a,k}^{pq}$ is an indicator variable defined by:

$$\delta_{a,k}^{pq} = \begin{cases} 1 & \text{if link } a \text{ is on path } k \text{ (connecting } p\text{-}q\text{)} \\ 0 & \text{otherwhise} \end{cases}.$$

7. CONCLUSIONS

The paper presents a general methodology for the seismic analysis of complex network systems. The difficulty of the task has been overcome recurring to the Monte-Carlo reliability analysis technique. The power of the approach is both in the ability to consider the main sources of uncertainty under which the analysis is conducted and to treat the networks as capacitive. This has required to model the seismic action (accounting for possible seismogenetic sources, the probability of occurrence of earthquakes and the source to site attenuation process), to model the effects of the ground shaking on the network components (understanding possible interactions between mechanical and structural damage and functionality reduction) and finally to model the flow of the circulating goods across the system (in the applications presented electric power, water and vehicles). The last aspect in particular is crucial since requires to deal with the peculiar mathematical models that govern the specific networks at study.

For lack of space it has not been possible to present possible application of the procedure to the three systems to show the feasibility and capabilities of the approach proposed.

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