Lifeline seismic hazards: a GIS application

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Abstract

In every urbanized area, lifelines and essential facilities play a very important role and they become essential after natural disasters, such as earthquakes, floods, landslides and so on. The purpose of this research is to develop a working tool to assess lifeline seismic risk, overlaying information about the studied area's seismic hazard (referring to a seismic scenario) and lifelines that could expect damage. In damage models parameters are required, some representing pipes, others representing the soil behaviour and finally, at the very least a synthetic parameter representing the seismic hazard of the studied area (PGA, PGV or PGD). The evaluation of the network intrinsic vulnerability will be done in terms of a synthetic parameter called the Repair Rate. PGDs will be evaluated referring to attenuation laws and to earthquake induced slope displacements according to the Newmark approach. An application of the proposed model, developed by GIS techniques, will be applied to the case of a Sicily (Italy) important water network.

Keywords: lifelines networks, damage models, attenuation laws, slope instability, Newmark approach.

1 Introduction

Lifelines and essential facilities are vital systems for communities in an industrialized society. They can be divided into two categories: utility systems (water, wastewater, gas, telecommunications and electrical power) and transportation systems (highways, railways, airports, ports). Their network structures are often complex (treelike, with loops or mixed) and a different typology of nodes can be found in each system. Moreover, lifelines are often highly inter-dependent.

Due to the usual geographical discrepancy between resource and demand, lifeline networks spatial distribution often widely exceeds the urban area. This

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implies a spatial variability of seismic motion (ground acceleration and velocity) and a higher probability of exposure to permanent ground displacement induced by fault offset, liquefaction phenomena, or landslides.

Seismic soil deformations can seriously damage lifeline networks. Direct damage can be pipe crushing and cracking, or joint breaking or pulling, caused by faults or permanent ground deformations (landslides or liquefaction) or by wave propagations; indirect damage is that caused by a compromised functionality due to difficulty in reaching and repairing damage due to road interruptions caused by landslides or slumps.

In this work a model to evaluate lifelines seismic risk will be described and applied to the case of a water network feeding 20 towns in the Etnean area, referring to three seismic scenario events. This approach will be developed in a GIS environment, by "Spatial Analysis" and "Field Calculation" techniques. First of all a seismic hazard zonation will be made, applying some selected attenuation laws in terms of Arias Intensity (I_a), peak ground acceleration (*PGA*), peak ground velocity (*PGV*) or permanent ground displacements (*PGD*). Then, a vulnerability model in terms of slope instability will be applied, according to Newmark's approach. Finally, damage models suggested by "RISK-UE" (2005) regarding seismic risk will be used to describe seismic damage to buried pipes, detailing the "Repair Rate" ("RR"), combining breaks (complete fracture of the pipe) and leaks that require the water agency to perform a repair.

2 Seismic hazard zonation

During recent years, the importance of seismic geotechnical safety has been taken into account more and more by competent authorities, above all for the relevant incidence of catastrophic local effects during the more recent destructive earthquakes. The need for seismic hazard zonation imposes the design of methods to locate the critical zones and allow one to adopt safety measures to prevent damages to strategic utilities.

The stability of a site during an earthquake depends on various factors, such as local amplification, site geotechnical conditions, shear strength parameters, etc. To design a zonation method, one or more representative parameters and analyses criteria must be chosen to quantify the site vulnerability. Then a zonation map will be produced, in which zones with different risk classes can be identified.

To encourage the application of standardized methodologies taking into account the site specific peculiarities, during recent years various specific guidelines have been written, such as those of the Technical Committee TC4 of the International Society of Soil Mechanics and Geotechnical Engineering (ISSMGE) [1].

A "seismic zonation" refers to a "seismic scenario", which can be defined, for example, through empirical methods, using attenuation laws, which are statistical correlations between synthetic seismic parameters, such as I_a, *PGA*, *PGV*, or *PGD*, a geometrical parameter describing the distance of a site from the epicentre (epicentral distance "*R*" [km]) and one or more parameters describing geotechnical and seismic soil features (S_1 and S_2). The reliability of each attenuation law is deeply correlated with the mathematical model adopted for its development and with the features of the seismic records database used.

The following attenuation laws have been selected from the literature as suitable for the studied area, based on the seismic records database they are built on.

$$\log_{10} Y = a + b \cdot M + c \cdot \log_{10} \sqrt{R^2 + h^2} + e_1 \cdot S_1 + e_2 \cdot S_2 \pm \sigma \qquad (1)$$

$$\log_{10} PGV = -0.195 + 0.390 \cdot M - 1.074 \cdot \log_{10} \sqrt{R^2 + 4.5^2} + 0.142 \cdot S_1 + 0.185 \cdot S_2 \qquad (2)$$

$$\log_{10} PGD = -4.68 + 1.08 \cdot M - 0.95 \cdot \log_{10} R \qquad \text{(Herrero)} \quad (3)$$

$$\log_{10} PGD = -1.8944 \cdot \log_{10}(R + 14) + 0.4144 \cdot M + 1.1026 \qquad \text{(Sirovich)} \quad (4)$$

$$\log_{10} PGD = -1.4642 - 0.5512 \cdot \log_{10} R \qquad \text{(Langer)} \quad (5)$$

$$\log_{10} I_a = -2.35 + 0.75 \cdot M - 2 \cdot \log_{10} R_{hyp} \qquad (6)$$

They are the law proposed by Sabetta et al. [2] (eq. (1)) in terms of PGA, Bommer et al. [3] (eq. (2)) in terms of PGV, INGV 2004-2006 [4] (eqs. (3)–(5)) in terms of PGD and Keefer et al. [5] in terms of Arias Intensity. In the above equations, Y is the peak acceleration $PGA(g)$, or response peak velocity $PGV(cm/s)$; R [m] is the epicentral distance (or the distance from the fault), $R_{hyp} = \sqrt{R^2 + h^2}$ [km] is the hypocentral distance and h is the hypocenter depth, M is earthquake magnitude, S_1 and S_2 are dummy variables for the site class (S_1=1 and S_2=0: shallow soil; S_1=0 and S_2=1: deep soil; S_1 = S_2=0: stiff soil) and σ is the standard deviation of $\log_{10} Y$ (Sabetta et al. [2]; Bommer et al. [3]).

In Tab.1, referring to eq. (1), coefficients for velocity response spectra, PGA and PGV for the horizontal component and epicentral distance are listed.

Table 1: Coefficients for velocity response spectra, PGA and PGV for the horizontal component and epicentral distance (Sabetta et al. [2]).

	a	b	c	e_1	e_2	h	σ
PGA (g)	-1.845	0.363	-1	0.195	0	5.0	0.190
PGV (cm/sec)	-0.828	0.489	-1	0.116	0.116	3.9	0.249

For a scenario earthquake, the spatial distribution of the seismic parameters at the ground level could be evaluated applying one of these attenuation laws.

3 Vulnerability

Seismic stability conditions and post-seismic functionality of lifelines and overstructures are deeply connected with the permanent seismic deformation entities and with the potentially induced damage to natural slopes or earth structures. To evaluate potential displacements induced by a scenario event, the displacement method (Newmark [6]) can be applied, identifying a critical acceleration value a_c. When seismic acceleration exceeds a_c, the slope reaches a limit equilibrium condition and the potentially instable soil mass starts sliding. It will stop only when the relative seismic acceleration, (a-a_c), changing its sign, will cancel relative velocity of the sliding mass. Afterwards the slope will not show any displacement until the relative seismic acceleration value will be exceeded again. According to this approach several statistic correlations, developed applying the displacement method to various database of accelerograms and then relating the value of the induced displacement to one or more seismic parameters describing imposed seismic acceleration history have been proposed.

The critical acceleration of a slope is related to the examined kinematism and it is a function of the geometry and mechanical features of the slope. We can refer to an indefinite slope scheme in seismic conditions: in this case, the safety factor in seismic conditions is the following:

$$F_s = \frac{c' + \left[\gamma \cdot h \cdot \cos\beta \cdot \left(\cos\beta \cdot - k \cdot sen\beta - r_u \cdot \cos\beta\right) - \Delta u\right] \cdot \tan\varphi'}{\gamma \cdot h \cdot \cos\beta \cdot \left(\sin\beta + k \cdot \cos\beta\right)} \tag{7}$$

where c', f', g and g_w are respectively the soil shear strength parameters, and the soil and the water unit weight; h is the unstable mass thickness, h_w is the distance between the sliding surface and the water table, b is the surface basic element slope; k represents the inertial effects ($k_h = k \cdot \cos\vartheta$; $k_v = k \cdot \sin\vartheta$).
r_u=m g_w/g and m = $h_w/h = (h-z_w)/h$ are respectively the pore pressure and the water table coefficient.

This equation is valid for sliding and flow mechanism. Its application can be justified in case of shallow landslides at their first activation, without appreciable pore pressure effects. In those conditions $m \cong 0$.

For reactivated landslides, or in case of liquefactible soils, the sliding mechanism can be influenced by pore pressures and this can be taken into account by convenient coefficients r_u (Biondi et al. [7]). The critical seismic coefficient $k_c = a_g/g$ can be determined for a safety factor F_s=1.

$$k_c = \frac{\dfrac{c'}{\gamma \cdot h \cdot \cos\beta} - \sin\beta + \left[\left(1 - r_u\right) \cdot \cos\beta - \dfrac{\Delta u}{\gamma \cdot h \cdot \cos\beta}\right] \cdot \tan\varphi'}{\cos\left(\beta + \vartheta\right) + \sin\left(\beta + \vartheta\right) \cdot \tan\varphi'} \tag{8}$$

For active landslides, even in static conditions F_s=1, then k_c=0 can be assumed. In drained conditions Δu can be neglected. Moreover, in case of a dry soil, r_u=0.

In this work, $J = J_{cr} = f - b$ has been hypothesized, to obtain the minimum value for critical seismic coefficient k_c and then to perform a precautionary estimation of induced permanent displacements. So, eq. (8) becomes:

$$k_c = \frac{c' \cdot \cos\varphi'}{\gamma \cdot h \cdot \cos\beta} + \sin\left(\varphi' - \beta\right) \tag{9}$$

4 Ground displacement assessment and lifelines seismic damage prevision

With the aim to design a risk mitigation strategy, once vulnerability (capability of resist under a fixed kinematism) is known, the reference hazard for a structural damage risk evaluation is peak ground displacement.

The induced residual deformation entity could be estimated by statistical correlations between displacement values and a seismic acceleration threshold value, function of geometrical and geotechnical soil parameters. The most reliable literature correlation to evaluate permanent displacement induced in an infinite slope scheme are those proposed by Ambraseys and Menu [8] (eq. (10)), and by Ambraseys and Srbulov [9], both obtained using a database of worldwide earthquake accelerometric records with magnitude varying from 5.5 to 7.5:

$$\log_{10} d = \log_{10}\left[(1-q)^{2.53} \cdot q^{-1.09}\right] + 0.90 \qquad (0.1 < q < 0.9) \quad (10)$$

$$\log_{10} d = -2.41 + 0.47 \cdot M_s - 0.010 \cdot R_{hyp} + \log_{10}\left[(1-q)^{2.64} \cdot q^{-1.02}\right] \quad (11)$$

Similarly, Simonelli and Fortunato [10] suggested an empirical correlation valid for the Southern Appennine:

$$\log_{10} d = 2.652 - 3.333 \cdot q \quad (12)$$

Correlations between the induced residual deformations, d , and Arias intensity I_A and k_c are due to Jibson et al. [11] (eq. (13)) and to Miles and Ho [12] (eq. (14)):

$$\log_{10} d = 1.521 \cdot \log I_A - 1.9931 \cdot R_{hyp} + \log k_c - 1.546 \quad (13)$$

$$\log_{10} d = 1.46 \cdot \log I_A - 6.642 \cdot k_c + 1.546 \quad (14)$$

In the above equations, R_{hyp} is the hypocentral distance, $q = a_c / a_{\max}$, a_c is the critical acceleration, $a_{\max}$ is the peak ground acceleration calculated multiplying *PGA* on bedrock for specific amplification coefficients and *d*[cm] is the induced permanent displacement value.

Comparing the calculated displacement value with the potential induced permanent ground displacements and an admissible value for the examined structures, a judgement about a certain seismic scenario event effect on a water network can be expressed.

The definition of an admissible threshold for displacements must consider the displacements effects on partial or total pipes serviceability losses. Moreover it is important to take into account how much money and how long will it take to recondition the network and the importance the temporary unserviceability of this pipe has on socioeconomic life of the interested region. This is a very complex problem that is affected by the unavoidable subjectivity of the opinion.

Both national and international laws regarding pipeline seismic damage are extremely poor. The Alaska Geotechnical Evaluation Criteria Committee established five damage classes: minor (d < 3 cm); moderate (d <15 cm); very high (d < 30 cm); extensive (d < 90 cm) and catastrophic (d < 300cm) (Idriss [16]).

Seismic damages to buried pipes can be expressed as "Repair Rate" (RR) per unit length of pipe, that is the rate between the number of repairs and the length [km] of a pipe exposed to seismic hazard: this number is a function of pipe material, joint type, soil conditions and diameter size, and of ground shaking, in terms of PGA or PGV or ground failure, in terms of PGD.

To evaluate Repair Rate RR, "RISK-UE" (European prescriptions regarding seismic risk - A.L.A. [13]), for water and gas pipelines, referring to seismic wave propagation and to ground failure, propose the following equations:

$$\text{RR (repair/km)} = \frac{0.00187}{0.3048} \cdot K_1 \cdot \left(\frac{PGV}{0.0254} \right) \tag{15}$$

$$\text{RR(repair/km)} = \frac{1.06}{0.3048} \cdot K_2 \cdot \left(\frac{PGD}{0.0254} \right)^{0,319} \tag{16}$$

where RR is Repair Rate, that is the number of repair per unit length of pipe [km]; K_1 and K_2 are coefficients according to various pipe material, joint type, soil type and conditions and diameter size: they have been determined experimentally, and can be found in specific tables (American Lifelines Alliance, 2001). PGA, PGV e PGD are, respectively, Peak Ground Acceleration and Velocity and Permanent Ground Displacements, whose spatial distribution can be evaluated using one of the attenuation laws shown previously (eqs. (1)–(6), (10)–(14)).

Table 2: Serviceability of the analysed water network (% of length) versus repair rate RR (ALA [13]).

Repair Rate (repair/km) (ALA [13])	**Serviceability**	**Damage States**
≥ 0.60	≤ 10%	Complete
0.15-0.60	10 – 50%	Extensive
0.05 – 0.15	50 – 85%	Moderate
≤ 0.05	≥ 85%	Minor

5 The case of ACoSEt water network

5.1 Description of the network

ACoSEt S.p.A. manages a very important water supply system feeding 20 Etnean towns (Catania district - Italy), involving about 90.000 customers (about 400.000 people). The water network develops from the western Etnean flank, with two main adduction pipes, to the southern-western and southern flank, were the distribution network feeds the customers.

The adductor pipes are “Maniace” Aqueduct, with a concrete main line about 46 Km long (diameter varying from 300 to 450 mm) and three secondary lines, and “Ciapparazzo” Aqueduct, completed in 1975, with a main line about 34 km long and 11 secondary lines, all in cast iron (diameter varying from 400 to 800 mm). These two main lines, after a nearby parallel route, along which some bounding bridges can be found, feeds the distribution network.

The information stored in the water agency database are quite good for the two main pipes, while are fragmentary and sometimes inadequate for the distribution network. The whole 1327 km of pipes have been detected: 271.39 km are adductor pipes, 871.27 km have a distribution function, 53.57 km have a relaunch function and the remaining part is not defined. The material the pipes are made of is unknown for 29.54% of them. 23.22% of pipes are cast iron, 18.94% steel and other small percentages are made of other materials. Over 90% of pipes cross non-corrosive soil, which is mainly volcanic. Only a small percentage cross colluvial or clayey outcroppings, which easily retain moisture and tend to be corrosive. Diameter is known for over 90% of detected pipes. For the remaining 10% a small diameter, typical of distribution pipes, has been hypothesized. As for all pipes the joint type, the most influent factor for pipe seismic performance, is unknown, the worst condition of rigid joints have been hypothesized.

5.2 Seismic scenarios

Lifelines seismic vulnerability must be evaluated relating to one or more seismic scenarios, to calculate PGA, PGV or PGD.

Analysing Eastern Sicily’s seismic history, and more specifically that of the Etnean area (Azzaro et al. [14]), two kinds of seismicity can be distinguished: tectonic and volcanic. The tectonic seismicity is bounded to the Hyblean-Malta fault system, which is the likely source of the 1693 earthquake. Frequent creep phenomena also occur both associated with seismic events and/or volcanic eruptions, and independent from them. These surface deformations are mainly confined in the eastern sector of the volcano apparatus and result from the interaction between regional tectonics and local volcano-tectonic processes.

The following scenario events can be considered: the “Val di Noto” earthquake of January 11, 1693 (M = 7.3; Imax= X MCS; TR = 250-500 years) as first level seismic scenario event; the “Etna” earthquake (Acicatena, south-eastern Etnean flank) of February 20, 1818 event (M = 6.2; Imax= IX MCS; TR = 250-500 years) as second level seismic scenario event; another “Etna” earthquake of October 31, 1832 (M = 3.4), with a epicentre localised near Bronte municipality (located about 54 km northwest of Catania) as moderate scenario event. In fact, in spite its local magnitude is quite small, it is undoubtedly over the average, and its epicentre geographical allocation is quite near the first part of Maniace Aqueduct, one of the main pipe feeding the distribution network, so it could cause significant damage to one of the main adductor pipes.

5.3 Damage models implementation in a GIS environment

A geodatabase has been created, containing a cartographic background constituted by the Regional Technical Cartography - CTR (1:10.000 scale; sections 612100 and 612140); a Digital Terrain Model (DTM) of Catania District, 20x20 settlement, derived from isolines 1:25.000 scale (by Italian Geographic Military Institute – IGMI); a Lithological Map of Sicily, derived from a simplification of Italian Geological Map 1:100.000 scale. Moreover, the pipeline network geodatabase, the road network of Catania District and the scenario earthquakes (1693, 1818, 1832) epicentre shape files were available.

Calculations have been implemented in a GIS environment by Spatial Analysis techniques, using ArcGIS (ESRI) Model Builder.

From DTM, by the “Slope” interpolation algorithm (ArcGIS “Spatial Analyst”), the map of slopes has been obtained (Fig. 1(a)). To assign soil mechanical features a vectorial map of the district area, surface lithology has been used: based on the literature data, a value of f’, c’, h, S_1, S_2 has been assigned for each lithotype and the corresponding grid themes have been created.

To calculate the critical seismic factor k_c of Newmark displacement method, eq. (9) has been used, implementing it by Map Algebra, with f’ and b GRID as input. A new GRID of k_c (Fig. 1(b)) has been obtained. For the next calculations cells were $k_c < 0$ have been omitted, as they correspond to a static safety factor value numerically smaller than one, but not necessarily it identifies a slope static instability context, as it could be due to the unavoidable approximation in the estimation of f’ average values.

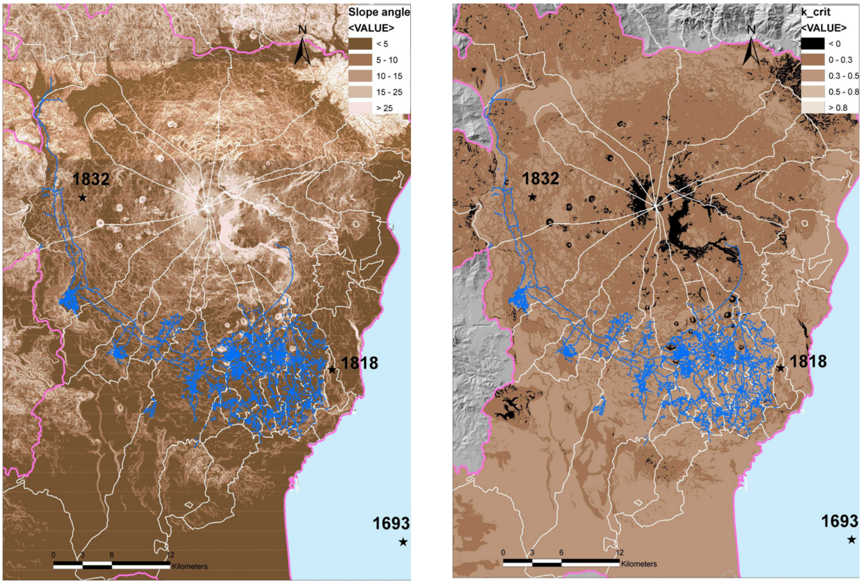


Figure 1: (a) Map of slopes β ; (b) map of critical seismic coefficients, k_c.

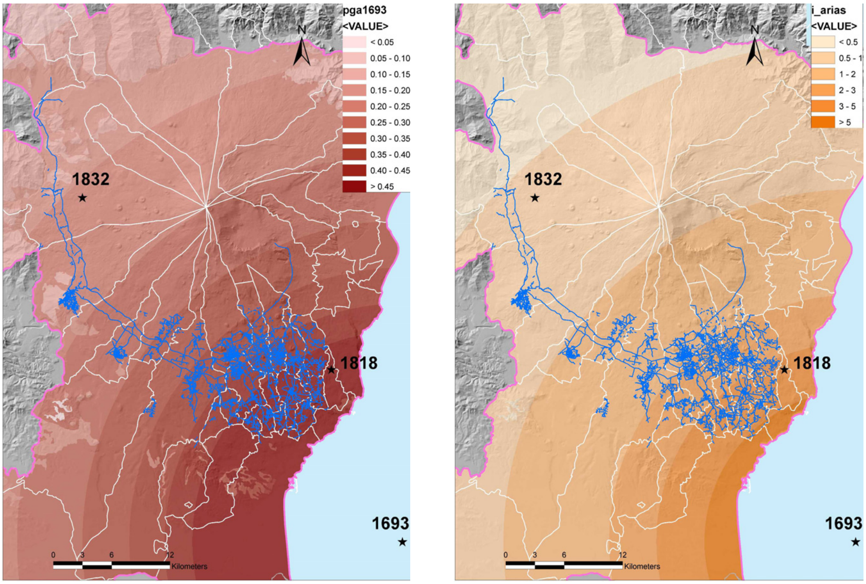


Figure 2: Scenario earthquake 11/01/1693: (a) map of PGA; (b) map of I_A.

Equations (1)–(6) GIS implementation let us obtain the grids of PGA, PGV, PGD and I_a spatial distribution in Catania district area for every input earthquake (1693, 1818, 1832). The concerning thematic maps have been created. Fig. 2(a) is the map of PGA evaluated by eq. (1), while Fig. 2(b) is the map of I_a evaluated by eq. (6).

According to the infinite slope scheme, permanent displacements can take place when $q < 1$. Fig. 3(a) is the map of unstable zones, dependent on q values. For the unstable cells, for every scenario earthquake, the value of the induced permanent displacements d have been calculated by eqs. (10)–(14) (Fig. 3(b)). Fig. 3(c) is the map of PGV evaluated by eq. (2).

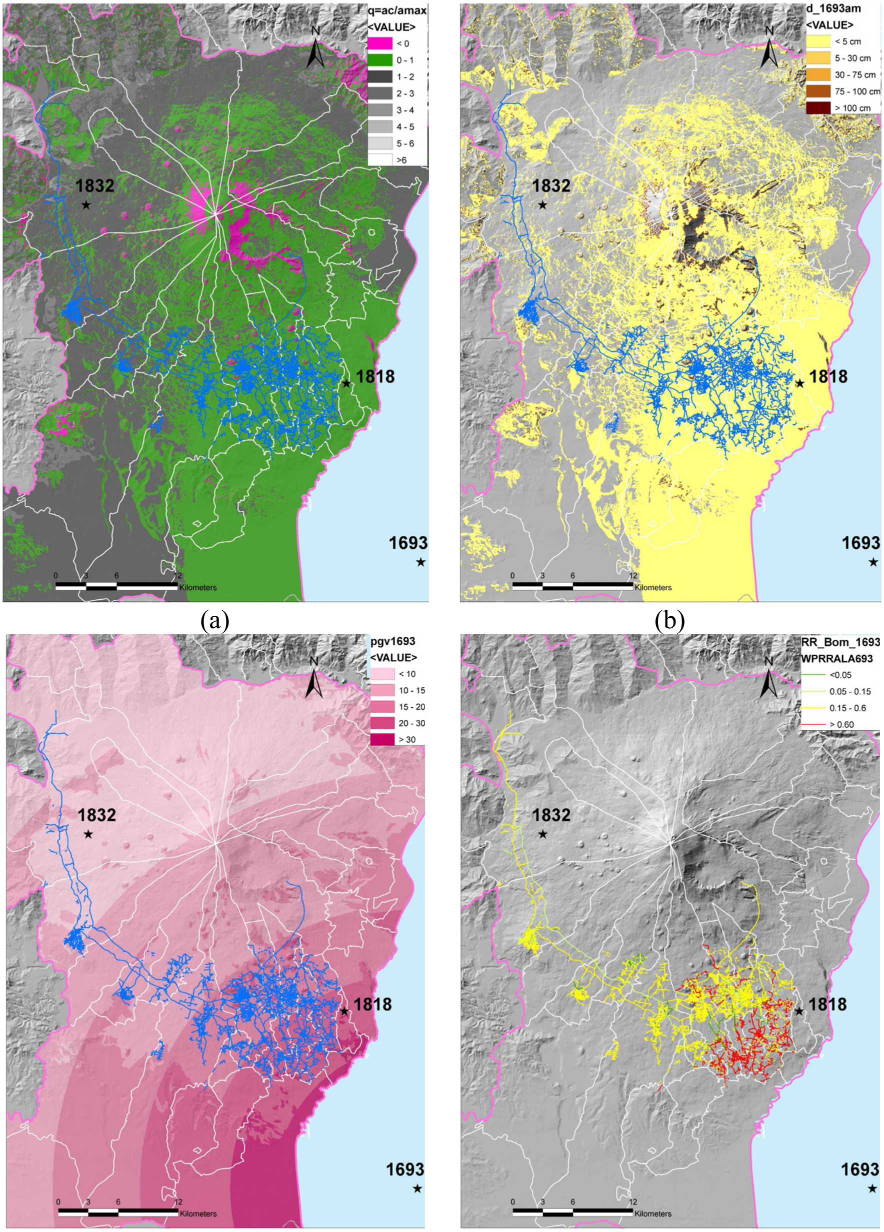
The raster maps of PGV and PGD have been converted in shape files, to overlay information about seismicity and about pipes and then calculate “RR” by different approaches (eqs. (15)–(17)).

For example, in Fig. 3(d) the thematic map of “Repair Rates” evaluated by eq. (15) with a PGV evaluated by eq. (2) is drawn.

6 Main results

Observing the obtained thematic maps it can be noticed that, as expected, the parameters PGA, PGV and PGD attenuates with distance from the epicentre of the chosen scenario earthquake (it goes from dark to tan colours).

The seismic scenarios of 1693 and 1818 show significant ground accelerations k_{max} (even over 0.45 g). However, the interested areas are also characterized by high critical seismic coefficients k_c values, due to small slope angles b or to the big shear strength angle values f’ assumed. Consequently the



(a) (b)

(c) (d)

Figure 3: Scenario earthquake 11/01/1693: (a) map of unstable zones ($q<1$); (b) map of PGV (Bommer et al. [3]); (c) map of displacements (Ambraseys and Srbulov [9]); (d) map of Repair Rates (eq. (15)): PGV has been calculated by eq. (2).

potentially unstable areas are not wide, and most of them are characterised by not significant permanent displacement arising (lower than 5 cm).

All the more so, for 1832 seismic scenario, k_{max} values being lower, for the same critical seismic coefficients values k_c, the potentially unstable areas are less than the previous cases and focus near the epicentral area. However this epicentre is very close to the two main aqueduct fonts, so that the potentially induced displacements by such an earthquake would involve the first part of Maniace aqueduct. Since it is a big cement pipe with quite rigid joints, it could be damaged with consequent water losses. Basing on Idriss [16] classification (Table 2), in Fig 3(d) we can observe that the scenario earthquake of 1693, for example, would cause a complete destructions of the distribution water network feeding the municipalities near Catania but, as expected for such a strong earthquake, damages would be extensive on the entire water network.

Similar thematic maps have been produced for the other two studied scenario earthquakes, but they are not plotted in the present paper.

7 Concluding remarks

This experience shows that GIS environment is a very efficient and highly productive tool for large-scale calculation and representation of numerical models, even if they are complex. It has been possible to calculate the parameters of interest and produce geo-referred thematic maps of a very large territory in a relative short time: this is very important for preventive risk analysis and for emergency management.

In this paper only the results obtained for a first level scenario earthquake have been shown: as expected, the obtained repair rate "RR" total values are higher in the areas closest to the earthquake epicentre, were a complete damage would be reached. Moreover, a quite high percentage of the network would undergo extensive damages. Different results have been observed under different seismic scenarios, but they cannot be presented here.

Of course, it must be considered that a significant uncertainty in the estimation is due to missing information about pipelines and above all about joint types.

The information provided estimating pipelines damages could be used to develop statistical investigations with the aim of design the essential actions to mitigate seismic risk of the studied area and to plan any improvement works in the network nodes or pipes where a greater vulnerability has been found. Moreover, with the help of the obtained thematic maps, pre-emptively appropriate procedures of emergency management could be designed.

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