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The Role of Redundancy of Infrastructures on the Seismic Resilience (SR) of Sustainable Communities

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Abstract: Infrastructures are fundamental links in sustainable communities, and they need to remain at a level of functionality during and after natural events. In particular, assessing the seismic resilience of infrastructures has become an interesting topic in earthquake engineering. The estimation of indirect losses due to seismic events is still a topic under discussion, especially for infrastructures. In this regard, the paper focused on including the level of redundancy inside an analytical formulation of the seismic resilience (SR). The main idea is to explore the possibility of alternative infrastructures that allow the circulation of services and people when the flow on the original infrastructure is interrupted or reduced. This goal is fundamental for preserving the resilience for sustainable communities. Therefore, the proposed formulation consists of considering the reduction in losses when the infrastructure is redundant by introducing the concept of the level of redundancy. In particular, indirect costs were herein defined with a new formulation that includes the level of redundancy inside the calculation of SR. The paper presented a case study that implements the formulation with the aim to demonstrate the efficiency of the proposed methodology. Several levels of infrastructural redundancy have been applied in the calculation of the SR of an infrastructure subjected to an ensemble of 100 seismic motions in order to scope the role of redundancy in improving the SR of the system.

Keywords: sustainable communities; redundancy; seismic resilience; infrastructures

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1. Introduction

The definition of losses after the impacts of natural hazards is fundamental in defining the resilience of infrastructures that is a fundamental issue for sustainable communities. In this regard, many methodologies consider the calculation of the direct losses, such as the physical damages without accounting for the losses associated with traffic flow. As shown in [1], realistic assessments of the losses need to include both direct and indirect costs. Adey et al. [2], defined direct costs as those losses that the owners sustain to recover the infrastructure. For example, they may consist of the material and labor costs due to recovering procedures (e.g., deck replacement, column protection, etc.). Indirect costs consists of the losses that the users experience due to the closure of the infrastructure (e.g., travel time and vehicle operating costs). In particular, the main source of indirect losses consists of the network conditions and the preparedness of the community and the surrounding region. In this regard, the most significant indirect losses consist of time delays, interruptions of goods and services, as shown in [3]. In particular, redundancy has several definitions depending on which level is considered. For example, infrastructure redundancy is defined as the chance of connection loss and, thus, it significantly affects the economic losses when travelling is reduced and/or not possible on that particular infrastructure [3].

On the other side, structural redundancy is defined by the ASCE standard for Mitigation of Disproportionate Collapse Potential in Buildings and Other Structures, as the availability of alternative load paths that would allow for a load to be transferred from the point(s) of application to the point(s) of resistance in the event of structural compromise of the primary load path by a hazard scenario [4]. Before this, the definition of redundancy was built up to consider the different characteristics of structural systems [5–9]. In this regard, ref. [5] describes the progressive collapse of bridges in the several aspects of analysis and design. Moreover, disproportionate collapses have been discussed in [6], with particular attention to the terminology and procedures. The redundancy of bridges configurations has been described in [7–9]. In particular, ref. [7] considered the role of redundancy and robustness in the design and evaluation of European and North American bridges. Considering redundancy of single structures, the alternative load paths may prevent failures since they may allow redistributions of the original forces that the failed components need to carry [10]. In this regard, the vulnerability of bridges is particularly important for the assessment of the indirect losses of infrastructures, and many techniques (e.g., [11,12]) have been proposed in order to ensure their redundancy. As shown in [13], indirect losses need to be estimated by expert judgments by considering the socio-economic consequences on the infrastructures. In particular, ref. [14] estimated indirect losses for highway bridges, while [15] considered that they may range between 5% and 15%.

In addition, ref. [3] showed that the role of interdependency is fundamental in the assessment of the resilience of infrastructures and thus to ensure the sustainability of communities. In particular, redundancy is affected by the level of interdependency between infrastructures, their geographical proximity, or the sharing of their functions and operations. Therefore, there could be interactions between the impacts due to the natural events on the infrastructures and, thus, the assessment of the redundancy is of fundamental importance in the evaluation of the resilience of the various systems. For example, when a disruption or a failure in the main infrastructure occurs, it may compromise the delivery and the transportation of products, services and people on the other interconnected infrastructures. Moreover, because of the level of interconnectivity, the functionality of the linked infrastructure may reduce and be degraded. This may cause problems to the whole community in terms of indirect losses (loss of connectivity and prolongation of time, as discussed in [3]).

In this background, resilience calculation is based on the definition of the Loss Model that consists of calculating the losses due to a natural event, such as earthquakes, floods, fires, etc. In this paper, a new formulation for the Loss Model was proposed to account the role of redundancy over the time in the case of infrastructures subjected to earthquakes. In particular, the possibility to alternative routes that allow to substitute the damaged infrastructure was included in the general formulation that relates the losses to the functionality of the system. It is important to note that [16] proposed the 4R framework that considered the role of four factors: Robustness, Redundancy, Resourcefulness and Rapidity. The loss model particularly depends on two performance criteria: robustness and redundancy. While the effects of robustness in reducing the losses have been investigated by several contributions, the novelty of this paper is to concentrate on the role of redundancy. In particular, ref. [17] considered the loss model at the level of the community, while other studies concentrated on several typologies of infrastructures, such as tunnels [18], HP/HT unburied subsea pipelines [19] and bridges [20]. Apart from earthquake engineering, the quantification of community resilience (CR) has been proposed by few methodologies, such as [21,22]. In particular, indirect losses were assessed by considering the contribution of [23], which proposed two sources: economic costs and losses due to casualties. Furthermore, ref. [24–27] applied the methodologies to assess indirect costs of natural hazards. In particular, ref. [25] considered the microinsurance for natural disasters in developing countries, ref. [26] investigated role of embodied technical change in cases of natural hazards and [27] discussed how natural disasters may impact a macroeconomic model with endogenous dynamics.

The main novelty of the paper consists in including the level of redundancy inside an analytical formulation of the seismic resilience (SR). The proposed formulation describes the reduction in losses when the network is redundant by introducing the concept of the level of redundancy. The functionality and the losses have been defined with a new formulation that allows to include the level of redundancy inside the calculation of SR. The originality is to include redundancy inside the definition of the indirect losses, that together with the direct losses define the loss model. In order to demonstrate the efficiency of the proposed methodology, the formulation is applied to a case study that compares several levels of infrastructural redundancy by calculating the resilience of the system at 100 seismic motions.

The paper is divided in five sections. The description of the seismic resilience (SR) of infrastructures is presented in Section 2, which introduces the principal variables and parameters considered in the paper. The loss model is detailed in order to introduce the concept of redundancy that is defined and described in detail in Section 3. In particular, a new formulation to describe infrastructure redundancy is proposed in terms of functionality Q and the losses L. A case study is presented in Section 4 in order to demonstrate the efficiency of the proposed formulation to represent the role of redundancy on the SR of infrastructures. Finally, the summary and key conclusions made in the study are discussed in Section 5.

2. Seismic Resilience of Infrastructures

The resilience of infrastructures has been the object of many publications (e.g., [28–35]), being a fundamental property for assessing the vulnerability of an infrastructure. In this regard, sustainable communities are particularly affected by the failure of infrastructures since their economy depends on the state of the infrastructures. Two perspectives can be considered when the resilience of infrastructure is considered. Firstly, resilience may be considered the ability to maintain a certain level of functionality after that an event occurs. In particular, the events may cause disruptions or failure of the infrastructure itself. Therefore, the second definition of resilience takes into consideration the time and resources required to repair or restore a suitable level of functionality. In this regard, when earthquakes are considered, the disruption occurs at one time and, thus, the losses are defined simply as the difference between the original functionality and the functionality after the occurrence of the event. Other natural hazards (e.g., floods or hurricanes) are disruptions potentially last for longer periods of time and, thus, it is not correct to concentrate all the losses on the vertical axes.

Following [21], which introduced the formulation to calculate the resilience of a system, the seismic resilience (SR) is calculated herein calculated by defining two models: the loss model and the recovery model (Figure 1).

$$SR = \int_{T0E}^{T0E+RT} \frac{Q(t)}{RT} dt \tag{1}$$

where

T_{0E} is the time of occurrence of the event E;
RT is the repair time due to system for the recovery process;
$Q(t)$ is the variation of the functionality over the time: it models the recovery process to reach a new level of functionality.

Both RT and $Q(t)$ describes the process of recovery from the instant when the event occurs until the system has recovered a suitable level of functionality. The recovery process is described with an analytical formulation and the area below the curve first describes the resilience (Formula (1)). The loss model is represented by the reduction in Q at the time of occurrence (see Figure 1). It is worth noting that, herein, the losses are considered equal to the inoperability $(1 - (t))$. This assumption is a simplification because a more developed relationship between the losses and the inoperability should be defined. Loss model depends on two sources of losses: direct and indirect [3] and, thus, on the definition of the redundancy of infrastructures.

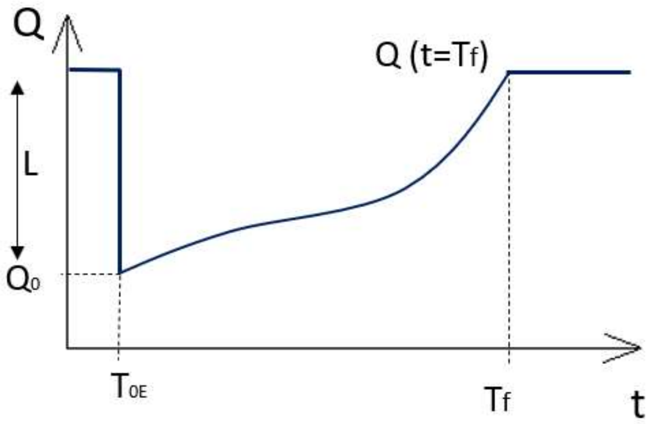

Figure 1. Definition of Seismic Resilience (*SR*, t = time, L = losses; T_f = time of finishing the repair work; Q = functionality; T_{0E} = time of occurrence of the earthquake).

3. Infrastructure Redundancy

As shown in [29,33], redundancy may be considered a dimension on which resilience depends. In particular, Bruneau et al. [16] firstly proposed a R4 framework that considers four properties of resilience: robustness, redundancy, resourcefulness and rapidity. In addition, as described in [36], infrastructure resilience depends on the possibility of maintaining the circulation of services and movements of people, valuable goods and services across the network. Road redundancy consists of being joined, linked and/or fastened together in alternative ways and it becomes fundamental when one or more infrastructures fail. Such property may be called redundancy and it may be considered the possibility to provide alternative paths for traffic, so that service can keep working even in the event of failure. In other words, redundancy means more reliability of the infrastructure by reducing the probability that a failure may take the infrastructure down. However, the level of redundancy is relatively challenging to be defined, since it depends on the ways in which networks are interconnected [37], the topological structure of the network and the flow patterns of traffic. As shown in [38], the definition of the level of redundancy requires measurements of the infrastructure performance in order to estimate the network recovery time and long-term reliability.

The level of redundancy is particularly important in the case of interdependent infrastructures, such as road networks. For example, integrated systems in urban regions, such as metro and bus service network, intermodal transport network, etc. Redundancy is the parameter that measures the level of interconnection between intermodal transportation since the traffic demand may be transferred from different transportation modes in case of a congestion or a disruption occurs in one mode of the network. On the contrary, complexity of the network may be caused by high interdependence among different infrastructures or modal systems, leading to problem of management during the eventuality of damage or failures (e.g., cascading effects). In this regard, the level of redundancy needs detailed estimations, and future research is necessary to examine the methods to define such parameter on the basis of scientific criteria.

A formulation that relates the losses with infrastructure redundancy ($Q(r)$) is herein proposed with the aim to investigate the role of redundancy on the seismic resilience of infrastructures. In particular, the main idea is that there is a limit r_0 above that the functionality of the infrastructure does not vary with the redundancy. For values of redundancy smaller that r_0, the losses vary from zero to one (100%) with a crescent function that depends on the exponent c:

$$Q(r) = \left(\frac{r}{r0}\right)^{1/c} \tag{2}$$

where

r is the level of redundancy (variable);
r_0 is the limit level of redundancy;
c is the exponential that represents the trend of grown of the functionality with the level of redundancy. In particular, for c bigger than 1, there is a grown of the functionality that is bigger than linear, while for $0 < c < 1$, the growth is less than linear (Figure 2).

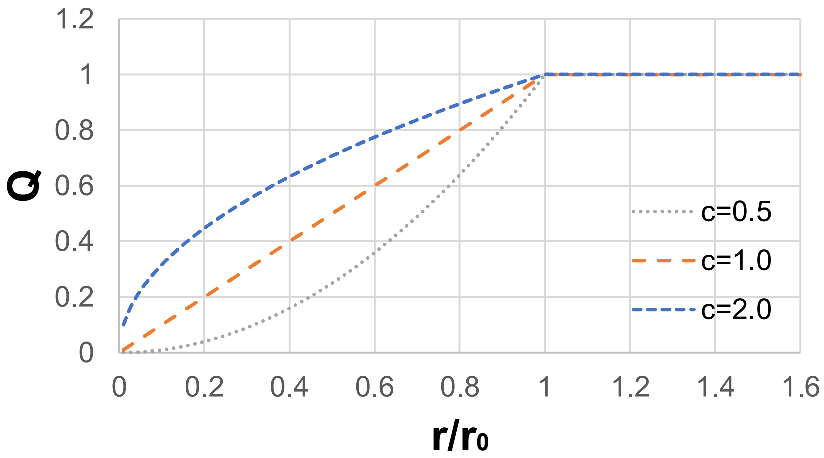

Figure 2. Definition of redundancy (r) based on Equation (2).

Considering that the losses depend on the functionality as the complement to 1 (100%), Equation (2) may be used to derive the indirect losses due to the lack of redundancy. In other words, redundancy modifies the losses of the infrastructure: the more redundant the infrastructure is, the less the losses become.

$$L = 1 - Q = 1 - \left(\frac{r}{r0}\right)^{1/c} \quad (3)$$

In particular, for c bigger than 1, there is a grown of the functionality that is bigger than linear, while for $0 < c < 1$, the grown is less than linear (Figure 3). Figure 4 shows the flow chart for the implementation of the level of redundancy inside the framework. In particular, once the redundancy of the infrastructural system is assessed, both the loss model and the recovery model need to consider its role on the *SR*. Therefore, Equation (2) is implemented inside the framework, respectively, by calculating the losses (Equation (3)) and the trend which describes the recovery process. The calculation of *SR* is the consequence of such implementation. In the next section, a case study is presented in order to implement Equation (3) to calculate the *SR* of a infrastructure where is characterized by the presence of a bridge.

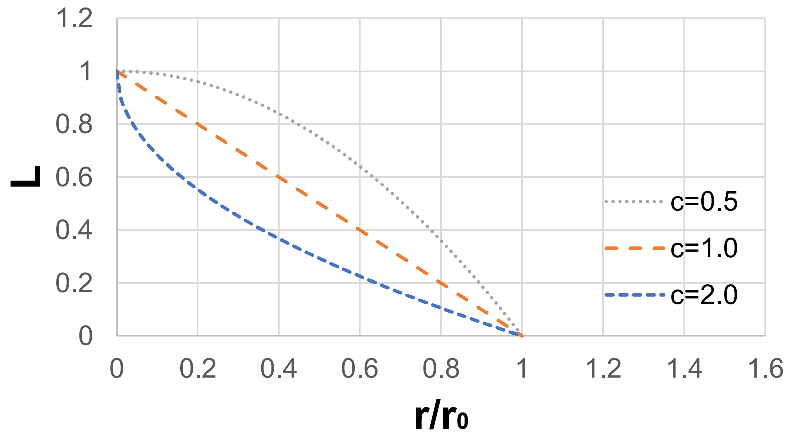

Figure 3. Definition of losses (L) based on Equation (2).

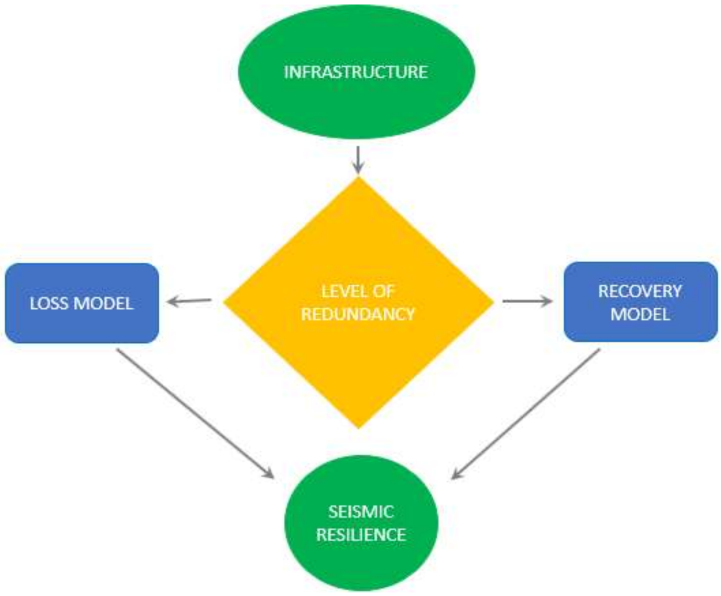

Figure 4. Flow chart of the framework.

4. A Case Study

In this section, a case study (Figure 5) is considered on the basis of the previous paper [36]. The present paper considers infrastructure 1 that consists of a road network built up with the previous typology of bridge named B1 (number of total of bridges: 3), as shown in Figure 4. PGA (Peak Ground Acceleration) is considered since this *Im* does not depend on the structural properties (such as modal shapes), more details in [36]. The hypothesis herein is that the functionality ratio is considered 1, meaning that the infrastructure is fully operating. Also, the costs (direct and indirect) were calculated by considering the losses due to the bridges (other losses neglected), as in [36].

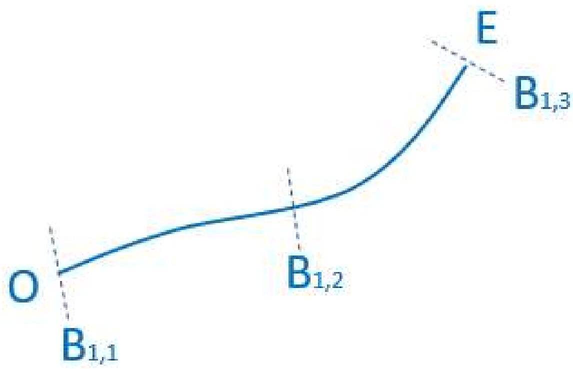

Figure 5. Scheme of the road infrastructure considered in the case study.

4.1. Benchmark Bridge

The scheme of the bridge was the same studied in [36] with the name B1 (Figure 6). It consisted of a benchmark scheme that represent the ordinary standard bridges (OSBs) used in the Californian highways and designed by considering the Caltrans Seismic Design Criteria [39]. The connections between the deck and the abutments were realized with sliding isolators that were modeled with the simplified two-spring model (more details in [36]) in the longitudinal direction. The vertical and transversal directions of the abutments and the connection between the column and the deck were fixed in all directions. Since the isolation was assumed to perform correctly, the deck (length: 90.00 m; width: 11.90 m; depth: 1.83 m; cross area: 5.72 m^2, transversal inertia: 2.81 m^4 and vertical inertia: 53.9 m^4, weight per unit length: 130.3 kN/m) and the column (height: 6.71 m) were herein modeled with non-linear beam column elements and considered fixed at the base (soil structure interaction effects were neglected). More details can be found in [36].

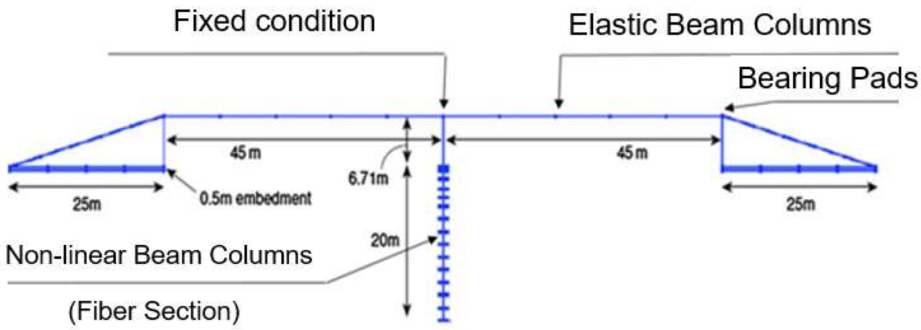

Figure 6. Numerical model of Bridge B1 (vertical view).

4.2. Seismic Scenario

The selected seismic scenario consisted of an ensemble of 100 input ground motions retrieved from the NGA database that can be seen in Table 1, in terms of their duration and the peak ground acceleration (PGA). The input ground motions were selected as the most representative ones of a wide range of intensities, with PGA values ranging between 0.05 g and 0.89 g, as already performed in [20]. The input ground motions were applied at the base of the structure, along the longitudinal direction. The nodes at the base of the structure were considered fixed and, thus, there was no need to introduce links of elements and to consider the effects due to the presence of the soil. In order to avoid convergence problems, the nonlinear dynamic analyses were performed by considering the approach adopted in Forcellini [40], which consisted of three steps: (1) linear properties of the structural material were considered; (2) the associated loads were applied to the structure and the properties were changed into non-linear. Modelling non-linearity is particularly challenging and, thus, it was necessary to divide this step into twenty-five load steps to guarantee numerical convergence. Finally, Step 3 consisted of the input ground motion application at the base of the model as longitudinal acceleration time history. The NewtonLineSearch algorithm was used to perform these analyses as proposed by Mazzoni et al. [41].

Table 1. Selected input ground motions.

Number	Earthquake	Station	Duration (s)	PGA (g)
1	A-ELC	1968 Borrego Mountain	40.00	0.13
2	A2E	1989 Loma Prieta	39.96	0.18
3	FMS	1989 Loma Prieta	39.76	0.20
4	HVR	1989 Loma Prieta	39.96	0.14
5	SJW	1989 Loma Prieta	39.96	0.10
6	SLC	1989 Loma Prieta	39.58	0.20
7	BAD	1989 Loma Prieta	35.00	0.11
8	CAS	1994 Northridge	39.80	0.10
9	CEN	1994 Northridge	30.00	0.49
10	DEL	1994 Northridge	35.36	0.15
11	DWN	1994 Northridge	40.00	0.17
12	JAB	1994 Northridge	35.00	0.11
13	L01	1994 Northridge	32.00	0.09
14	LOA	1994 Northridge	40.00	0.09
15	LV2	1994 Northridge	32.00	0.10
16	PHP	1994 Northridge	60.00	0.07
17	PIC	1994 Northridge	40.00	0.11
18	SOR	1994 Northridge	36.48	0.07
19	SSE	1994 Northridge	35.00	0.14
20	VER	1994 Northridge	30.00	0.13

Table 1. *Cont.*

Number	Earthquake	Station	Duration (s)	PGA (g)
21	AGW	1989 Loma Prieta	40.00	0.18
22	CAP	1989 Loma Prieta	39.96	0.55
23	G03	1989 Loma Prieta	39.96	0.59
24	G04	1989 Loma Prieta	39.96	0.45
25	GMR	1989 Loma Prieta	39.96	0.24
26	HCH	1989 Loma Prieta	39.10	0.27
27	HAD	1989 Loma Prieta	39.64	0.29
28	SVL	1989 Loma Prieta	39.26	0.21
29	CNP	1994 Northridge	25.00	0.39
30	FAR	1994 Northridge	30.00	0.30
31	FLE	1994 Northridge	30.00	0.17
32	GLP	1994 Northridge	30.00	0.37
33	LOS	1994 Northridge	20.00	0.44
34	NYA	1994 Northridge	30.00	0.20
35	PEL	1994 Northridge	40.00	0.25
36	RO3	1994 Northridge	30.28	0.31
37	Z-PEL	1954 Ferndale	28.00	0.22
38	B-ICC	1987 Superstition Hills	40.00	0.38
39	B-IVW	1987 Superstition Hills	44.00	0.17
40	B-WSM	1987 Superstition Hills	40.00	0.18
41	H-PVB	1983 Coalinga	39.96	0.40
42	H-AEP	1979 Imperial Valley	11.16	0.36
43	H-BCR	1979 Imperial Valley	37.62	0.63
44	H-CXO	1979 Imperial Valley	37.82	0.29
45	H-E05	1979 Imperial Valley	39.30	0.55
46	H-ECC	1979 Imperial Valley	40.00	0.23
47	H-SHP	1979 Imperial Valley	15.72	0.30
48	I-ELC	1979 Imperial Valley	40.00	0.33
49	G02	1989 Loma Prieta	39.96	0.39
50	GOF	1989 Loma Prieta	39.96	0.30
51	Z-HVR	1984 Morgan Hill	39.98	0.17
52	637	1994 Northridge	47.78	0.81
53	JEN	1994 Northridge	28.62	0.62
54	NWH	1994 Northridge	40.00	0.63
55	RRS	1994 Northridge	19.92	0.89
56	SCS	1994 Northridge	40.00	0.66
57	SYL	1994 Northridge	40.00	0.65
58	C08	1966 Parkfield	26.12	0.24
59	A-JAB	1987 Whittier Narrows	34.30	0.24
60	A-SOR	1987 Whittier Narrows	28.72	0.15
61	B-ELC	1968 Borrego Mountain	40.00	0.07
62	H-C05	1983 Coalinga	40.00	0.16
63	H-C08	1983 Coalinga	32.00	0.10
64	H-CC4	1979 Imperial Valley	28.54	0.12
65	H-CMP	1979 Imperial Valley	36.00	0.20
66	H-DLT	1979 Imperial Valley	99.92	0.24
67	H-NIL	1979 Imperial Valley	40.00	0.12
68	H-PLS	1979 Imperial Valley	18.76	0.05
69	H-VCT	1979 Imperial Valley	40.00	0.13
70	A-STP	1980 Livermore	33.00	0.05
71	SJB	1984 Morgan Hill	28.00	0.05
72	Z-CAP	1984 Morgan Hill	36.00	0.11
73	Z-HCH	1984 Morgan Hill	28.34	0.08
74	H06	1986 North Palm Springs	40.00	0.07
75	INO	1986 North Palm Springs	30.00	0.07
76	A-BIR	1987 Whittier Narrows	28.62	0.26
77	A-CTS	1987 Whittier Narrows	39.96	0.05
78	A-HAR	1987 Whittier Narrows	40.00	0.06
79	A-SSE	1987 Whittier Narrows	22.94	0.05

Table 1. *Cont.*

Number	Earthquake	Station	Duration (s)	PGA (g)
80	A-STC	1987 Whittier Narrows	40.00	0.17
81	H-CAL	1979 Imperial Valley	39.54	0.14
82	H-CHI	1979 Imperial Valley	40.00	0.29
83	E-E01	1979 Imperial Valley	39.04	0.15
84	H-E12	1979 Imperial Valley	39.02	0.15
85	H-E13	1979 Imperial Valley	39.52	0.12
86	H-WSM	1979 Imperial Valley	40.00	0.08
87	A-KOD	1980 Livermore	20.98	0.17
88	A-SRM	1980 Livermore	40.00	0.06
89	Z-AGW	1984 Morgan Hill	59.96	0.03
90	Z-G02	1984 Morgan Hill	29.98	0.17
91	Z-G03	1984 Morgan Hill	39.98	0.21
92	Z-GMR	1984 Morgan Hill	29.98	0.20
93	PHN	1946 Point Mugu	23.20	0.12
94	BRA	1966 Westmore	28.42	0.17
95	NIL	1966 Westmore	40.00	0.11
96	A-CAS	1987 Whittier Narrows	31.18	0.36
97	A-CAT	1987 Whittier Narrows	32.92	0.05
98	A-DWN	1987 Whittier Narrows	40.00	0.24
99	A-W70	1987 Whittier Narrows	31.94	0.21
100	A-WAT	1987 Whittier Narrows	29.70	0.11

4.3. Calculation of Resilience

Following the previous studies [42,43], The Pacific Earthquake Engineering Research (PEER) Centre methodology, ref. [44], was applied to assess the recovery time (RT). In particular, the direct losses were calculated by applying the Caltrans Comparative Bridge Costs database [39] and by implementing the LLRCAT methodology (more details in [44]). Indirect losses were calculated herein by implementing Equation (3) and by considering that indirect losses were the 10%, as the mean value between those indicated in [15]. The recovery curve was considered linear, since no information on the recovery process was available. The results were herein expressed in terms of RT (unit: crew working days, CWD). In particular, Figure 7 shows that at lower intensities (PGA < 0.68 g), RT values were less than 60 CWD, while most of the damage (and, thus, the costs) at PGA = 0.68 g, after which the losses were almost constant. In particular, several values of exponential c (0.5, 1.0 and 2.0) were considered and three levels of r/r_0 (0.25, 0.50 and 0.75). The values of L are shown in Table 2 (compare with Figure 2).

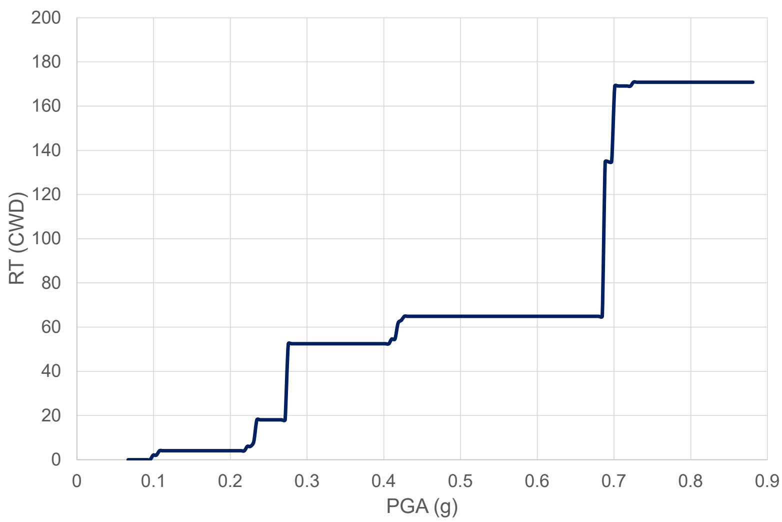

Figure 7. Repair time (CWD).

Table 2. Values of the indirect losses calculated with Equation (3) for different values of the coefficient c (0.50, 1.00 and 2.00) and three levels of r/r_0 (0.25, 0.50 and 0.75).

r/r0	c = 0.5	c = 1.0	c = 2.0
0.25	0.938	0.750	0.500
0.50	0.750	0.500	0.293
0.75	0.438	0.250	0.134

Figures 8–10 show the role of redundancy (r/r_0 = 0.25, 0.50 and 0.75) for the various coefficients c (0.5, 1.0 and 2.0, respectively Figures 7–9). It is worth noting that SR decreased with the intensities. For low intensities (PGS < 0.20 g), all the systems were resilient, with SR values around 85–95%. Between 0.20 g and 0.40 g, there was big reduction (around 1/3 of the previous values) in SR for all the systems, followed by a plateau between 0.42 g and 0.68 g. For high intensities (PGA > 0.70 g), SR was significantly reduced. Overall, the results demonstrate that the redundancy had positive effects on the SR of the entire infrastructure, since the biggest values of SR were obtained for SR-0.75–2.0 (c = 2.0 and r/r_0 = 0.75).

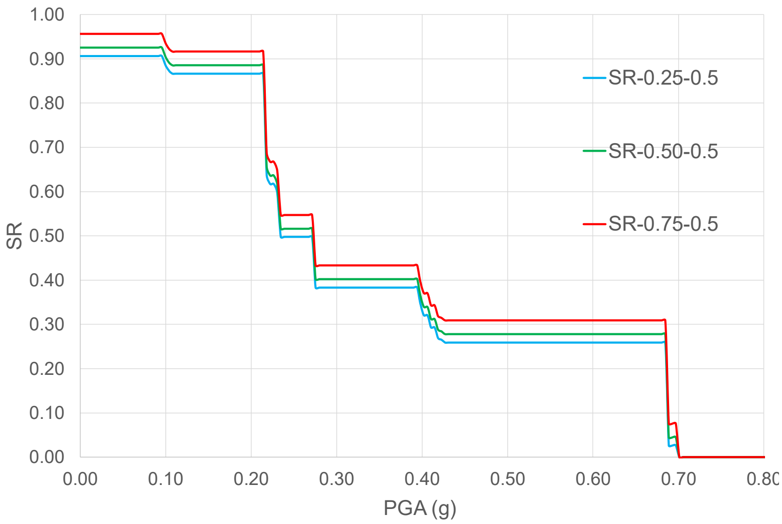

Figure 8. PGA (g) Vs SR (c = 0.5 and r/r_0 = 0.25, 0.50, 0.75).

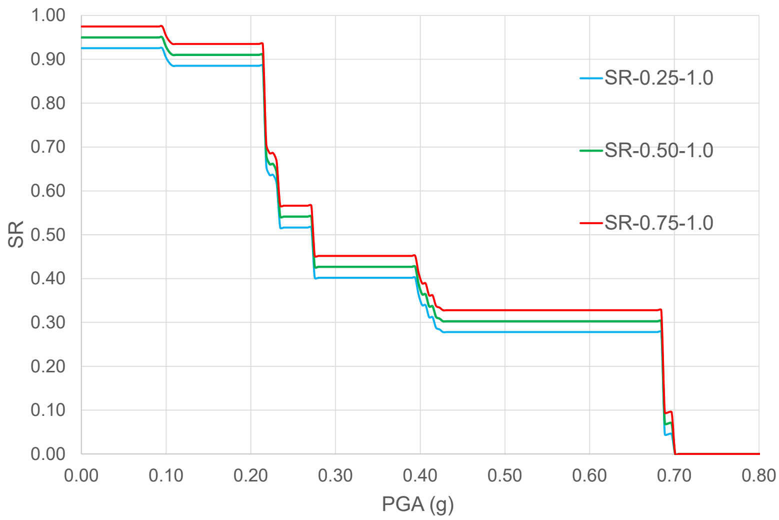

Figure 9. PGA (g) Vs SR (c = 1.0 and r/r_0 = 0.25, 0.50, 0.75).

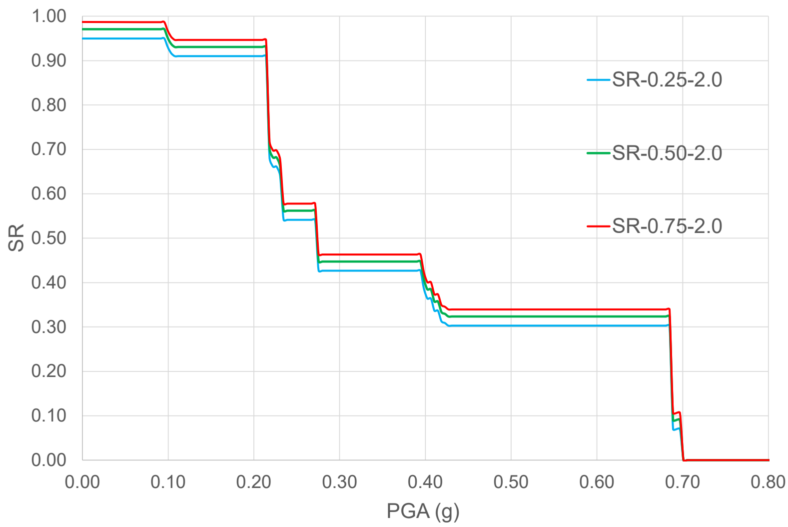

Figure 10. PGA (g) Vs SR (c = 2.0 and r/r_0 = 0.25, 0.50, 0.75).

5. Summary and Conclusions

The paper proposed a novel approach to assess the redundancy inside the calculation of the seismic resilience (SR) of infrastructures. In this regard, the role of redundancy was assessed by proposing two formulations for the functionality and the losses that enable to calculate the SR. In this regard, the resilience may be used as a key parameter to consider the performance of infrastructures during seismic events and, thus, to ensure the sustainability of the community. Two parameters were used to describe the role of redundancy on SR: the level of redundancy and the coefficient of grown of the functionality because of the present of redundancy. Several values were selected and tested within a case study of an infrastructure built up with three bridges with same characteristics of a benchmark one. The results confirmed that the redundancy had a positive effect on improving the SR of the selected infrastructure. In addition, the proposed formulation may help the decision makers to study the role of redundancy on the evaluation of the seismic resilience of infrastructures. Overall, this paper may be considered a first attempt to include the concept of redundancy inside the assessment of SR. The limitations of the study relate to the hypotheses that were herein assumed. In particular, (1) infrastructure redundancy was considered only in the definition of the indirect losses and not in the determination of the repair time, (2) redundancy was implemented inside the resilience to earthquakes without consider other natural hazards, (3) the losses of the infrastructure were assumed those connected with the structural damages of the bridges. (4) The relationship between the losses and the inoperability will be the object of a more developed approach. Future works are necessary to extend the presented methodology with the aim to propose a more comprehensive framework to investigate the sustainability of communities.

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