16th World Conference on Earthquake, 16WCEE 2017

Santiago Chile, January 9th to 13th 2017

Paper N° 2689

Registration Code: S- V1463181583

RESILIENCE QUANTIFICATION OF COMMUNITIES BASED ON PEOPLES FRAMEWORK

O. Kammouh[(1)], A. Zamani Noori[(2)], C. Renschler[(3)], G.P. Cimellaro[(4)]

[(1)] *Ph.D. candidate, Politecnico di Torino, omar.kammouh@polito.it*
[(2)] *Ph.D. candidate, Politecnico di Torino, ali.zamani@polito.it*
[(3)] *Associate professor, University at Buffalo (SUNY), rensch@buffalo.edu*
[(4)] *Associate professor, Politecnico di Torino, gianpaolo.cimellaro@polito.it*

Abstract

This paper presents a new methodology for computing *community resilience*. This topic has gained attention quickly due to the recent unexpected natural and man-made disasters; nevertheless, measuring resilience is still one of the most challenging tasks due to the complexity involved in the process. In previous studies, several attempts have been made to measure resilience, but none of them could outline a simple, yet exhaustive approach to reach this goal. Since "indicators" are perceived as important instruments to measure the resilience, in this correspondence, a complete indicator-based approach for measuring community resilience within the PEOPLES framework is proposed. PEOPLES is a holistic framework for defining and measuring disaster resilience of communities at various scales. It is divided into seven dimensions, and each dimension is further divided into several sub-components. Our method starts by collecting all the indicators available in the literature then classifying them under the seven dimensions of PEOPLES, creating a condensed list of indicators. Each indicator is accompanied by a measure, allowing the quantitative description of the indicator. To make the process quasi-dynamic, the measures are not characterized by a scalar value, but rather a normalized continuous function that marks out the functionality of the measure in time. If the measure could only be described by one value, a uniform function is considered. The service-time function of each measure could be obtained in two ways: the first is through a set of parameters that define the outline of the serviceability function (e.g. initial capacity, initial demand, capacity drop, recovery speed, etc.), while the second is by taking a group of serviceability measurements (snapshots) over the defined time window, and the line connecting all measurements is the serviceability function. All serviceability functions are weighted according to their contribution to the overall goal of achieving resilience and then aggregated into a single service-time function whose parameters are known. The final function (i.e., resilience function) describes the serviceability of a community over time and can be compared with the resilience functions of other communities. The present work contributes to this growing area of research as it provides a universal tool to quantitatively assess the resilience of communities at multiple scales.

Keywords: resilience; PEOPLES framework; disaster resilience; indicators; recovery

1. Introduction

Community resilience has gained a great deal of attention quickly due to the recent unexpected natural and man-made disasters. Resilience itself is a broad and multidisciplinary subject. In the field of engineering, resilience is the ability to "withstand stress, survive, adapt and bounce back from a crisis or disaster and rapidly move on" [1]. Allenby and Fink (2005) defined resilience as "the capability of a system to stay in a functional state and to degrade gracefully in the face of internal and external changes" [2]. According to Bruneau et al. (2003), resilience is "the ability of social units to mitigate hazards, contain the effects of disasters when they occur, and carry out recovery activities in ways to minimize social disruption and mitigate the effectors of further earthquakes" [3]. For the purpose of this discussion, the definition by Bruneau et al. (2003) is adopted.

Measuring resilience is one of the most demanding tasks due to the complexity involved in the process. While "indicators" are perceived as important instruments to measure the resilience of a system, developing a standardized set of resilience indicators is obviously challenging for such a dynamic, constantly re-shaping and context-dependent concept. Recently, there have been few serious, yet incomplete attempts to measure resilience. Cutter et al. (2014) reported that research on measuring community resilience is still in the early stages of development [4]. Although many attempts have been made to consolidate research on community resilience indicators (e.g. [5], [6], [7]), no accepted method exists so far and there are still difficulties in developing concrete assessment approaches and reliable indicators [8].

In this paper, we present an exhaustive quantitative method for computing the resilience of communities using PEOPLES framework [9]. PEOPLES is a holistic framework for defining and measuring disaster resilience for a community at various scales. It is divided into seven dimensions (components), and each dimension is further divided into several sub-components. PEOPLES did not identify a clear procedure to quantitatively compute resilience, but rather a qualitative assessment and description of resilience. The idea is to convert PEOPLES from a qualitative to a quantitative framework. This was attained by collecting a vast number of indicators with their corresponding measures and allocating them to PEOPLES' sub-components. The measures are not characterized by a scalar value, but rather a normalized serviceability function that marks out the functionality of the system in time. If a system could only be interpreted by a single value, a uniform serviceability function is considered. All functions are then weighted according to their contribution to the overall goal of achieving resilience. Finally, the functions are summed up into a single resilience function whose parameters are known. We expect the findings of this work to make a significant contribution to the field of resilience engineering as it provides a universal tool to assess resilience at multiple scales.

2. Resilience evaluation

2.1 Resilience evaluation as introduced by Bruneau et al. (2003) [3]

Bruneau et al. (2003) suggested that computing the resilience of a system depends on its serviceability performance. The conceptual approach is illustrated in Fig. 1. The performance ranges from 0% to 100%, where 100% indicates no drop in service and 0% means no service is available. If a disastrous event occurs, it could cause a damage to the system so that its serviceability is immediately dropped to a lower level. While the quality drops immediately, the restoration of the system occurs over time, as indicated in Fig. 1, until it reaches its initial and functional state. The loss of resilience is thought to be equal to the quality degradation of the system under study over the whole restoration period. Mathematically, it is defined as follow:

$$LOR = \int_{t_0}^{t_1} \left[100 - Q(t)\right] dt \qquad (1)$$

where LOR is the loss-in-resilience measure, t_0 is the time at which a disastrous event occurs, t_1 is the time at which the system recovers to 100% of its initial serviceability, Q(t) is the serviceability of the system at a given time t.

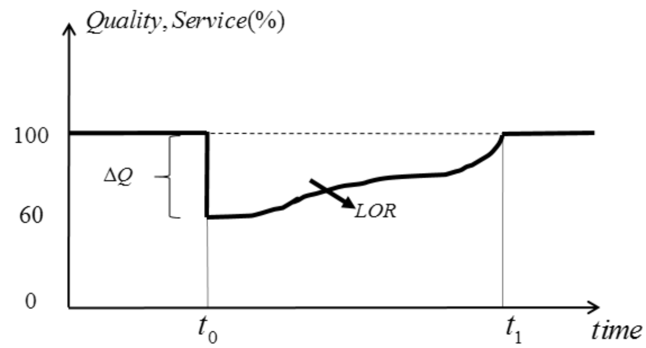

Fig. 1 – Measure of seismic resilience, as introduced in [3]

The approach suggested by Bruneau et al. (2003) does not allow the comparison between different systems as the initial serviceability is always 100% (Q_0=100%). This implies that the resilience of a system does not depend on its initial serviceability; therefore, all systems are considered fully resilient before disasters. To allow the comparison among them, the initial serviceability should be represented by the actual functionality (Q_0), and normalized in such a way to be ranged between 0% and 100% (Fig. 2); where 0% indicates no service and 100% denotes a full service is provided.

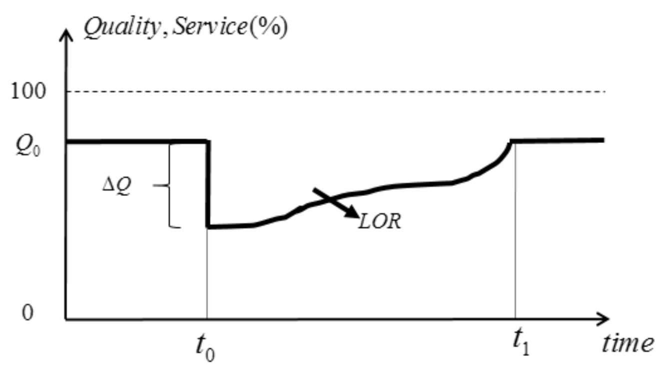

Fig. 2 – A modified version for computing resilience taking into account the initial service provided by the system

It is worth noting that if different systems are to be compared, LOR has to be normalized to be time-independent. This can be done by dividing over T_c (the control time of the period of interest) [10]. Thus, Eq. (1) can be replaced by Eq. (2):

$$LOR = \int_{t_0}^{t_1} \frac{\left[100 - Q(t)\right]}{T_c} dt \tag{2}$$

2.2 Resilience evaluation as introduced by Didier et al. (2015) [11]

In this approach, the lack of resilience is the amount of demand that cannot be met by the damaged supply (Fig. 3). Graphically, it is the area between the capacity curve *Q(t)* and the demand curve *D(t)* (Eq. (3)). The functionality of a given system is assumed to return back to its initial state after the restoration phase. This phase starts at the time of disaster and ends at the time where both supply and demand are recovered.

$$LOR = \int_{t_0}^{t_1} \left[Q(t) - D(t)\right] dt \tag{3}$$

where *D(t)*, is the demand of a system at a given time *t*.

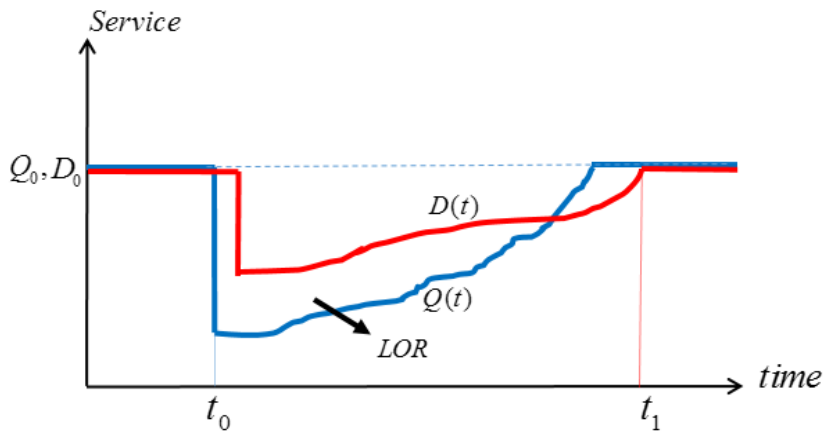

Fig. 3 – Evaluating resilience as introduced in [11]

The approach by Didier et al. (2015) calculates the loss in resilience as the area between capacity and demand, which implies that if both capacity and demand have dropped to low, yet equal levels, there would be no loss in resilience. The authors believe that the area between the capacity and the demand does not reflect the loss in resilience but rather the rapidity of meeting the residual demand following a disaster. Furthermore, using their approach, Eq. (3) should be computed for the time interval from t_0 to the time where the two curves meet. If otherwise, the whole time interval between t_0 and t_1 is considered (Fig. 3), a negative area (the portion where the capacity is larger than the demand) would add up affecting the LOR result.

3. PEOPLES framework

PEOPLES framework is an expansion of the research on resilience. Its attributes were developed at the Multidisciplinary Center of Earthquake Engineering Research (MCEER) [9]. The framework is capable of measuring the community resilience at different scales (spatial and temporal) by evaluating the infrastructures' performances considering their interaction. The framework comprises seven different dimensions (hereafter referred to as *components*) of community summarized with the acronyms PEOPLES. The seven components are:

1- *Population and demographics:* describes and differentiates the focal community population to understand the ability of the society to cope with adverse impacts and to recover rapidly after a disaster;
2- *Environmental and ecosystem*: represents the ability of the ecological system to withstand a disturbance and return to its pre-event state;
3- *Organized governmental services*: indicates to what extent community sectors are prepared to respond to a hazard event. This component plays a key role in increasing community resilience both before (preparedness and mitigation plans) and after (response and recovery) a disaster;
4- *Physical infrastructure*: focuses on facilities and lifelines that have to be restored to a functional state after the disaster;
5- *Lifestyle and community competence*: represents both the raw abilities of a community (e.g., skills to find multifaceted solutions to complex problems through the engagement in political networks) and the perceptions of a community (e.g., perception to have the ability to do a positive change through a common effort that relies on PEOPLES' aptitude to resourcefully envision a new future and then move in that direction);
6- *Economic development*: includes both the current economy (static state) of a community and its future growth (dynamic development). This component represents the ability of the society to sustain in the aftermath of a disaster by means of good substitution, employments, and services redistribution;
7- *Social-cultural capital*: describes to what degree the people would be willing to stay in their place and be able to help their community to bounce back after a disastrous event.

Further details on each of the above components can be found in [9].

4. The methodology: resilience quantification of communities based on PEOPLES

4.1 PEOPLES' components, sub-components, indicators, and measures

PEOPLES is a framework for defining and measuring disaster resilience of a community at various scales. It is divided into seven *components* and each of them is divided into several *sub-components*. The framework does not identify a clear procedure to quantitatively compute resilience, but rather a qualitative assessment and description of resilience. The goal is to convert PEOPLES from a qualitative to a quantitative framework. To do so, a large number of *indicators* available in literature have been collected and then allocated to PEOPLES' sub-components, creating a condensed list of 115 indicators. A sample of the indicators is presented in Table 1, while the full list of indicators will be included in further publication.

A single *measure* is assigned to each indicator to make it quantifiable. The measures are then normalized to be ranged between 0 and 1. This is done by introducing a new parameter, the *standard number* (SN). SN is a quantity that represents the reference point of the corresponding measure, defined by the competent authority. For example, if we consider the measure "*Red cross volunteers per 10,000 people*", the measure would give us an absolute number of volunteers as an output. This quantity cannot be integrated with other measures unless it is normalized; therefore, the result is divided over SN, which in this case represents the "BEST" number of volunteers per 10,000 people (e.g. SN=100 volunteers /10,000 people). If the ratio between the value of the measure and SN is less than one, it means that the indicator can still be improved, whereas if it is larger than one, the measure is considered "resilient", and a value of 1 is assigned to that measure. Having all measures normalized enables the comparison among systems of similar or different types (e.g. hospitals and water networks).

Measures are classified according to their relationship (*Rel.*) with resilience. A letter "*P*" (positive effect) is assigned to the measures that contribute to the favor of increasing resilience, while a letter "*N*" (negative effect) is assigned to those that do the converse. In addition, each indicator contributes with a certain degree towards the goal of achieving resilience; therefore, the measures are also classified according to their importance. An importance factor "*I*" has been assigned to each measure. This factor ranges from 1 to 3; where 1 means low importance and 3 means high importance. What's more, two types of measures are identified: "static measures (*S*)", assigned to the measures that are not affected by the disastrous event, and "dynamic measure (*D*)" or event-sensitive measures, assigned to the measures whose values change after a hazard takes place.

Table 1 shows a list of PEOPLES' dimensions, sub-components, indicators, and measures, with their corresponding importance factors (I = 1, 2, or 3), relationships with resilience (Rel. = N (negative) or P (positive)), and indicators' nature (Nat. = S (static) or D (dynamic)). For the sake of clearness, only two components of the PEOPLES' seven components have been included and expanded in the table. The full table will be included in the journal paper following the conference event.

Table 1 – PEOPLES' components, sub-components, indicators, and measures with corresponding importance factors (I), relationships with resilience (Rel.), and indicators' nature (Nat.)

Component/ sub-component/indicator	**Measure (0 ≤value ≤1)**	**Ref.**	**Rel.**	**I**	**Nat.**
1- Population and demographics				**2**	
1-1- Distribution\ Density				3	
-Population density	Average number of people per area ÷ SN		N	3	D
-Population distribution	% population living in urban area		P	2	D
1-2- Composition				2	
-Age	% population whose age is between 18 and 65		P	3	S
-Place attachment-not recent immigrants	% population not foreign-born persons who came within previous five years	[12]	N	1	S
-Population stability	% population change over previous five year period	[12]	N	2	S
-Equity	% nonminority population – % minority population		P	3	S
-Race/Ethnicity	Absolute value of (% white – % nonwhite)		N	1	S

-Family stability	% two parent families	[12]	P	2	S
-Gender	Absolute value of (%female–%male)		N	1	S
1-3- Socio- Economic Status				2	
-Educational attainment equality	% population with college education – % population with less than high school education		P	3	S
-Homeownership	% owned-occupied housing units	[4]	P	2	S
-Race/ethnicity income equality	Gini coefficient	[12]	N	3	S
-Gender income equality	Absolute value of (% male median income – % female median income)		N	2	S
-Income	Capita household income ÷ SN	[13]	P	3	S
-Poverty	% population whose income is below minimum wage		N	3	S
-Occupation	Employment rate %		P	3	S
2- Environmental and ecosystem				**2**	
2-1- Water				3	
-Water quality/quantity	Number of river miles whose water is usable ÷ SN		P	3	D
2-2- Air				1	
-Air pollution	Air quality index (AQI) ÷ SN		N	2	D
2-3- Soil				2	
-Natural flood buffers	% land in wetlands ÷ SN	[14]	P	1	S
-Pervious surfaces	Average percent perviousness	[15]	P	1	S
-Soil quality	% land area that does not contain erodible soils	[16]	P	1	S
2-4- Biodiversity				1	
-Living species	% species susceptible to extinction		N	2	S
2-5- Biomass (Vegetation)				2	
-Total mass of organisms	Harvest index (HI) the ratio between root weight and total biomass		P	2	S
-Density of green vegetation across an area	Normalized difference vegetation index (NDVI)	[9]	P	2	D
2-6- Sustainability				3	
-Undeveloped forest	% land area that is undeveloped forest ÷ SN	[17]	P	2	S
-Wetland variation	% land area with no wetland decline	[17]	P	2	S
-Land use stability	% land area with no land-use change ÷ SN	[18]	P	1	S
-Protected land	% land area under protected status ÷ SN	[19]	P	2	S
-Arable cultivated land	% land area that is arable cultivated land ÷ SN	[18]	P	2	S

4.2 Weighting factors

Each of the components, sub-components, and indicators was given an importance factor (I) ranging from 1 to 3. This factor represents the extent to which an element (component, sub-component, or indicator) contributes towards achieving resilience (Table 1).

For the sake of convenience, elements were arranged in groups, as follows:

a) Indicators classified under a sub-component are treated as group;
b) Sub-components classified under a component act as a group;
c) All components (PEOPLES' seven dimensions) make a group.

Eq. (4) transforms the importance factor (I) into a weighting factor (w). The equation is applied to each group independently. Weighting factors are then multiplied by their corresponding serviceability functions (q), as indicated in Eq. (5). Further details on the serviceability function will be given in the next section.

$$w_i = \frac{I_i}{avg(I_1, I_2, \cdots, I_j)} = \frac{I_i}{\sum_1^j (I_i)} j \tag{4}$$

where w_i is the weighting factor of element i, I_i is the importance factor of element i, j is the number of elements in the studied group.

$$q_i^* = w_i \times q_i \tag{5}$$

Where q_i^* is the weighted serviceability function of element i, q_i is the serviceability function of element i.

4.3 Deriving the final serviceability function "*Resilience curve*"

Each measure is defined using a serviceability function (uniform function for event-non-sensitive measures "static measures", and non-uniform function for event-sensitive measures "dynamic measures"), as shown in Fig. 4. The service-time function of each measure can be defined in two ways: the first is by using a set of parameters that specify the outline of the serviceability function (e.g. initial capacity, initial demand, capacity drop, recovery speed, etc.), and the second is by using a group of static measurements (snapshots) over the defined period of time, where the line connecting all the measurements is the serviceability function. It is to note that the definition of the serviceability functions of the measures will be the subject of future research. All serviceability functions are weighted according to their contribution towards achieving resilience, as described in section 4.2, and then summed up into a single service-time function whose parameters are known, as shown in Fig. 5. The final function (i.e., resilience function) describes the functionality of a community following a disastrous event, and it can be compared with those of other communities.

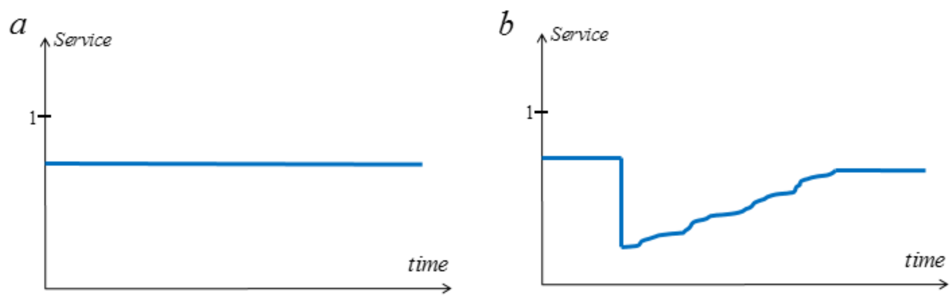

Fig. 4 – a) Static/event-non-sensitive measure (uniform function) b) Dynamic/event-sensitive measure (non-uniform function)

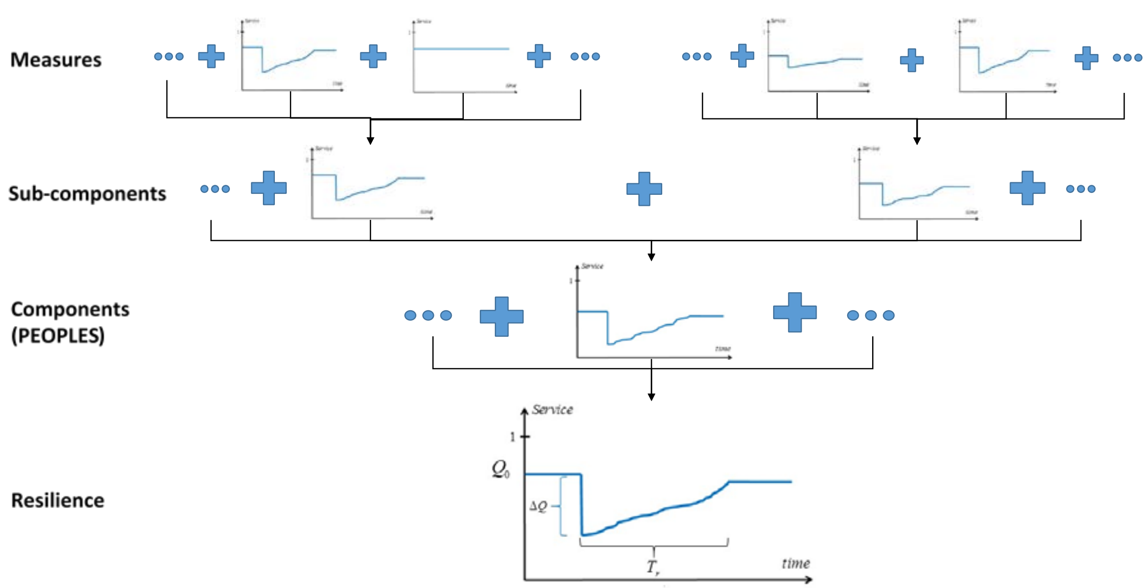

Fig. 5 – Deriving the serviceability function of a community

5. Conclusion

A comprehensive methodology for computing community resilience was presented in this paper. The methodology is based on “PEOPLES framework for assessing resilience”. First, a large number of indicators were collected and then allocated to each of PEOPLES’ sub-components. Each indicator is accompanied by a measure allowing it to be quantitatively described. The measures are characterized by serviceability functions (uniform functions for static measures, and non-uniform functions for dynamic measures). After obtaining a serviceability function for each measure, weighting factors are introduced to specify the importance of each indicator towards the goal of achieving resilience. Then, all the measures are aggregated into a single serviceability function (resilience function), which describes the resilience of the whole community. The final service-time function is known as it is derived from multiple known functions (serviceability functions of the measures).

The work presented here is considered a promising attempt to evaluate the resilience of any system ranging from a small entity to a whole community. A case study applying the presented methodology is currently under development. In addition, future research will be geared towards deriving the serviceability functions of the measures.

6. Acknowledgements

The research leading to these results has received funding from the European Research Council under the Grant Agreement n° ERC_IDEAL RESCUE_637842 of the project IDEAL RESCUE—Integrated Design and Control of Sustainable Communities during Emergencies.

7. References

[1] Wagner I, Breil P (2013): The role of ecohydrology in creating more resilient cities. *Ecohydrology & Hydrobiology*, **13**(2), 113-134.

[2] Allenby B, Fink J (2005): Toward Inherently Secure and Resilient Societies. *Science*, **309**(5737), 1034-1036.

[3] Bruneau M, Chang SE, Eguchi R T, Lee GC, O’Rourke TD, Reinhorn AM, Winterfeldt DV (2003): A Framework to Quantitatively Assess and Enhance the Seismic Resilience of Communities. *Earthquake Spectra*, **19**(4), 733-752.

[4] Cutter SL, Ash KD, Emrich CT (2014): The geographies of community disaster resilience. *Global Environmental Change*, **29**, 65-77.

[5] Twigg, J. (2009): Characteristics of a disaster-resilient community. a guidance note (version 2).

[6] Norris FH, Stevens SP, Pfefferbaum B, Wyche KF, Pfefferbaum RL (2008): Community Resilience as a Metaphor. *Theory, Set of Capacities*.

[7] Cutter SL, Burton CG, Emrich CT (2010): Disaster resilience indicators for benchmarking baseline conditions. *Journal of Homeland Security and Emergency Management*, **7**(1).

[8] ABELING T, HUQ N, WOLFERTZ J, BIRKMANN J (2014): Interim Update of the Literature. *Technical report, Deliverable 1.3, emBRACE project*.

[9] Cimellaro GP, Renschler C, Reinhorn AM, Arendt L (2016): PEOPLES: A Framework for Evaluating Resilience. *Journal of Structural Engineering*, 04016063

[10] Cimellaro GP, Reinhorn AM, Bruneau M (2010): Framework for analytical quantification of disaster resilience. *Engineering Structures*, vol. 32, pp. 3639-3649.

[11] Didier M, Sun L, Ghosh S, Stojadinovi (2015): Post-earthquake recovery of a community and its electrical power supply system. *5th International Conference on Computational Methods in Structural Dynamics and Earthquake Engineering*, Greece.

[12] Sherrieb K, Norris FH, Galea S (2010): Measuring capacities for community resilience. *Social Indicators Research*, **99**(2), 227-247.

[13] Tobin GA (1999): Sustainability and community resilience: the holy grail of hazards planning. *Global Environmental Change Part B: Environmental Hazards*, **1**(1), 13-25.

[14] Beatley T, Newman P (2013): Biophilic Cities Are Sustainable, Resilient Cities. *Sustainability*, **5(**8), 3328.

[15] Brody SD, Peacock WG, Gunn J (2012): Ecological indicators of flood risk along the Gulf of Mexico. *Ecological Indicators*, **18**, 493-500.

[16] Bradley D, Grainger A (2004): Social resilience as a controlling influence on desertification in Senegal. *Land Degradation & Development,* **15**(5), 451-470.

[17] Cutter SL, Barnes L, Berry M, Burton C, Evans E, Tate E, Webb J (2008): Community and regional resilience: Perspectives from hazards, disasters, and emergency management. *Community and Regional Resilience Initiative (CARRI) Research Report, 1*.

[18] UNDE (2007): *Indicators of sustainable development: Guidelines and methodologies*: United Nations Publications.

[19] IOTWSP (2007): *How resilient is your coastal community? A guide for evaluating coastal community resilience to tsunamis and other coastal hazards*. Bangkok, Thailand: U.S. Agency for International Development.