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Article

A New Methodology for Measuring Tsunami Resilience Using Theory of Springs

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Abstract: Resilience is a deeply rooted word in theory of elasticity, which is firstly introduced to English by Thomas Young in 1807 in his treatise "A course of lectures on natural philosophy and the mechanical arts". However, recently it is frequently used in ecology, economics, social sciences, and as everyone knows in the disaster literature. The purpose of this article is to investigate the mechanical background of word resilience, discuss lessons we could learn from the theory of elasticity for evaluating tsunami resilience, and finally, to propose a new mathematical model based on theory of springs. The mathematical model is in compliance with a pragmatic conceptual framework for evaluating resilience. The effective resilience of a given area can be calculated by aggregation of three components namely, onsite capacity, instantaneous survivability, and recovery potential of the area. The authors suggest that the magnitude of each component depends on socioeconomic, infrastructural and geographical factors of the area considered. Here, we show that aggregation of the individual components can be done in compliance with the theory of springs by analogizing effective tsunami resilience to effective spring constant. The mathematical model will be useful for evaluating the resilience of townships to hydrological disasters and also planning resilient townships, specifically to tsunami.

Keywords: disasters; engineered sociology; etymology of resilience; Hooke's law; modulus of resilience; theory of elasticity; Thomas Young; tsunami

1. Introduction

The term "resilience" and its derivatives have become fashionable words in the contemporary disaster risk reduction literature. Now, people prefer to build resilient things than strong things. It is a promising attitude towards a sustainable world. The term resilience in the theory of elasticity has strong features of elasticity, proportionality, and a limit. Proportionality in elasticity gives a sense of correlation between stress due to the disaster and social–economical–physical strain the disaster may cause. Again, the resilience in the theory of elasticity has a maximum; in that context, a place or a society which faces a disaster should have an affordable maximum magnitude of disaster.

In the previous literature, the term "resilience" has been defined by many authors, according to their own backgrounds and interests. In the earliest contribution to the contemporary resilient literature, Holling defined resilience as the amount of disturbance that can be sustained by a system before a change in the system occurs [1]. Holling pointed out that the spruce budworm forest community with low stability shows high resilience. This fact gives a clear ecological example for differentiating vulnerability with resilience. A comparative table of 29 definitions of the term compiled by Zhou et al. has proved again the diversity of the term, connecting the term to ecology, climate change, sociology, economics, public health and disasters [2]. The International Strategy for Disaster Reduction (UNISDR) terminology which is based on a broad consideration of different international sources defines resilience as "the ability of a system, community or society exposed to hazards to resist, absorb, accommodate, adapt to, transform and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions [3]".

The relationship between vulnerability and resilience has also been argued by many authors. The key-questions among those arguments are: Is resilience the opposite of vulnerability? Is resilience a factor of vulnerability? Or is it the other way around [4]? Does vulnerability already account for coping capacity and resilience or are they separate and counteracting parameters [5]? Birkmann argues that the promotion of a common language to describe key components of vulnerability is an important task, although it is necessary to acknowledge the different schools of thinking and their justifications [6].

Whatever the field being considered, many definitions have shown no or less influence from the concept of mechanical resilience. In the context of the theory of elasticity, vulnerability and resilience are totally different parameters, because some weaker materials such as rubber can be resilient to some extent. Resilience is to remain strongly functional during an event and to completely recover from it after withdrawing the stress—somewhat analogous to strong and ductile materials such as a particular kinds of steel. We insist that if we follow the theory of elasticity for defining disaster resilience, it may be simply defined as "the power of a system, community or society exposed to hazards to spring back after a straining disaster in a timely and efficient manner". This is our working definition for this article.

Many studies have attempted to evaluate resilience in disaster-prone areas by establishing frameworks, weighting methodologies, and indices. Bruneau et al. have introduced a methodology for quantifying resilience for earthquakes, combining interrelated dimensions such as technical, organizational, social and economic, and they have attempted to bring mechanical theories into measuring resilience [7,8]. Orencio and Fujii have proposed a localized disaster-resilience index to assess coastal communities based on an analytic hierarchy process [9]. Kusumastuti et al. have introduced a simple method to calculate resilience, dividing the preparedness score by the vulnerability score [10]. They have also introduced a set of indicators to evaluate preparedness or vulnerability in a given place. The study has further applied a framework to assess the resilience of two Indonesian disaster-prone cities towards natural disasters.

However, these studies have been unsupported by facts of mechanical resilience and aggregated some effective factors by summation or multiplication or division, rarely giving a reasonable explanation to do so.

The purpose of this article is to investigate the mechanical background of the word resilience, discuss lessons we could learn from the theory of elasticity for evaluating tsunami resilience, and finally, to propose a new mathematical model based on theory of springs. The mathematical model is in compliance with a pragmatic conceptual framework for evaluating resilience proposed by the first author previously [11].

2. Methods

2.1. Etymology of Word "Resilience" and Theory of Elasticity

While many of its users use it disregarding its deep roots, a few authors have thoroughly examined the history and usage of the word resilience. One of the extensive studies done by Alexander has addressed this discourse to trace the history of the term "resilience" in order to illuminate its development and give the modern usage some historical depth and continuity [12]. Alexander has argued that the first serious use of the term resilience in mechanics appeared in 1858, when the eminent Scottish engineer William J. M. Rankine (1820–1872) used it to describe the strength and ductility of steel beams. As resilience is the foundation of the theory of elasticity, pioneering elasticians have also looked for the legacy of the word resilience. In a vigorous expression, an English historian of the theory of elasticity, Todhunter [13], has claimed "Young was, I believe, the first to introduce into

English the term resilience, and to state the general theorem that: the resilience of a prismatic beam resisting a transverse impulse is simply proportional to the bulk or weight of the beam". Young's Theorem 337 simply mentioned that "the resilience of prismatic beams is simply as their bulk" [14]. Furthermore, the theorem has explained the resilience as a joint ratio of the length, breadth and depth.

However, it seems that Young's concept of resilience is a continuation of the older theory of English scientist Robert Hooke (1635–1703), which states that, "It is very evident that the Rule or Law of Nature in every springing body is, that the force or power thereof to restore itself to its natural position is always proportionate to the distance or space it is removed therefrom" [15]. Though Hooke did not use the word "resilience" in the above expression, it addresses the essential phenomenon of contemporary resilience. Mathematically, Hooke's law states that the applied force F equals a constant k times the displacement or change in length δ, or $F = k\delta$.

$$F = k\delta \tag{1}$$

Young's Theorem 337 eventually led to the stress–strain relationship, illustrated in the popular "tensile test", in which a prismatic bar of mild steel is placed in a tensile-testing machine, and while it is slowly being pulled, readings are made of the stresses exerted on the bar and of the strain of the bar. When stress and strain are plotted against each other, a diagram such as Figure 1 results. In Figure 1, we can distinguish three stages, OA, AD, and DA′. During the first stage OA, the diagram is substantially a straight line. If the load at A is left off, the stress-strain plot goes back along the same line AO to O, and in particular the bar returns to point O, which means that after releasing the load there is no "permanent strain". This first stage is called the "elastic stage".

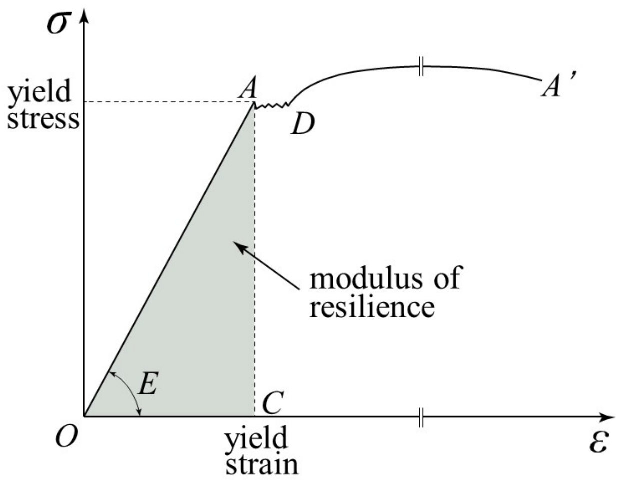

Figure 1. A typical stress–strain diagram of mild steel.

By direct experiment, it has been established for many structural materials that within certain limits the strain of the bar is directly proportional to the tensile stress. This simple linear relationship between the stress and the strain which it produces was first formulated by Robert Hooke in 1678 and bears his name, Hooke's Law [16]. Using the notation:

F = force producing extension of bar;
l = length of bar;
A = cross-sectional area of bar;
δ = total elongation of bar;
σ = stress of bar;
ε = strain of bar;
E = elastic constant of the material, called the modulus of elasticity.

Hooke's experimental law may be given by the following equation:

$$E = \frac{\sigma}{\varepsilon} \tag{2}$$

$$E = \frac{F/A}{\delta/l} \tag{3}$$

$$\delta = \frac{Fl}{AE} \tag{4}$$

E in Equation (4) is a proportionality constant, which has the dimension of stress. This constant is known as the "modulus of elasticity", or also as "Young's modulus", after its inventor Thomas Young (1773–1829). In simple tension of a bar, work done on the bar can be transformed into potential energy of the strain. If the strain remains within the elastic limit, the work done will be completely transformed into potential energy and can be recovered during a gradual unloading of the strained bar. The work done is stored in the body in the form of "elastic strain energy", sometimes also called "resilience" [17]. In the field of theory of elasticity, resilience is colloquially understood to mean the power of a strained body to spring back on the removal of the straining forces [18]. The greatest amount of strain energy per unit volume which can be stored in a bar without the permanent set is called the modulus of resilience. In other words, the modulus of resilience is defined as the maximum energy that can be absorbed per unit volume without creating a permanent set. It is the area contained under the elastic stage of the stress–strain curve for a given material (area of triangle OAC in Figure 1).

2.2. Hooke's Law, Young's Modulus and Springs

Hooke established the relationship between the force and deformation, and suggested several experiments that this relationship can be used in solving very important problems. In 1678, Hooke's paper, "De Potentia Reflitutiva" or "Of Spring", introduced a few elastic bodies including a spring. It is said to be the first published paper in which the elastic properties of materials are discussed [15]. Hooke's and Young's works are the foundation for many theories of structural materials or objects. It can be applied to a spring, which is an object that can be deformed by a force and then return to its original shape after the force is removed. Young's modulus can be applied to define the spring constant k of Equation (1), a characteristic of a spring which corresponds to the resilience, as shown below, by substituting Equation (4) in Equation (1).

$$k = \frac{F}{\delta} = \frac{AE}{l} \tag{5}$$

Therefore, k is directly proportional to E.

$$k \propto E \tag{6}$$

2.3. Modulus of Resilience and Coping Capacity

Figure 2 illustrates how city A and B respond differently on intensity of a given disaster. In Figure 2, the curve OAA′ represents the intensity/damage relationship of the city A, while OBB′ represents the city B. In the context of the theory of elasticity, if the stress remains within the proportional limit up to A or B, the area of triangle OAC or OBC represents the modulus of resilience in each case. The modulus of resilience is higher in the A-case than the B-case because E_A is higher than E_B. The higher the E, the more stress is needed to create the same amount of strain. When the modulus of resilience is higher, k is higher because k is directly proportional to E. We argue that in the context of disasters, the coping capacity, which is the ability to absorb impacts by guarding against or adapting to disasters, corresponds to the spring constant.

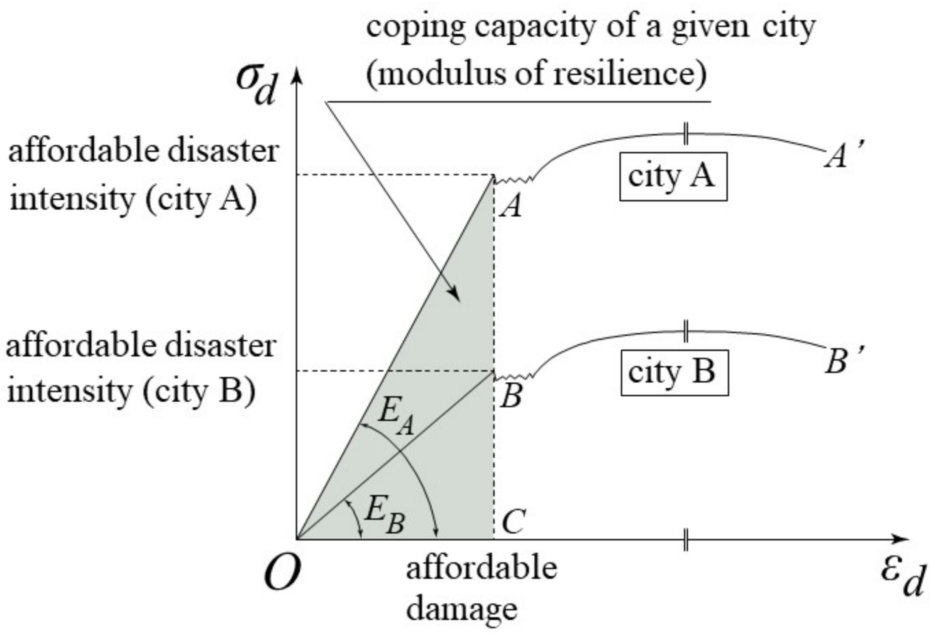

Figure 2. An illustration showing how city A and B respond differently on intensity of a given disaster.

2.4. *A Conceptual Framework for Evaluating Tsunami Resilience*

Previous works have proposed a few conceptual frameworks for evaluating resilience or vulnerability. Despite their differences, a number of common elements have been found: (a) the examination of vulnerability from a socioeconomic perspective; (b) disaster resilience is essentially geographic in nature and (c) the capacity to meet priorities and achieve goals in a timely manner [7,19]. These common elements inspired us with the proposed framework (see Figure 3) in this paper. It is a modified version of the first author's previous work [11]. In order to make this paper self-contained, a concise review on the framework is given here.

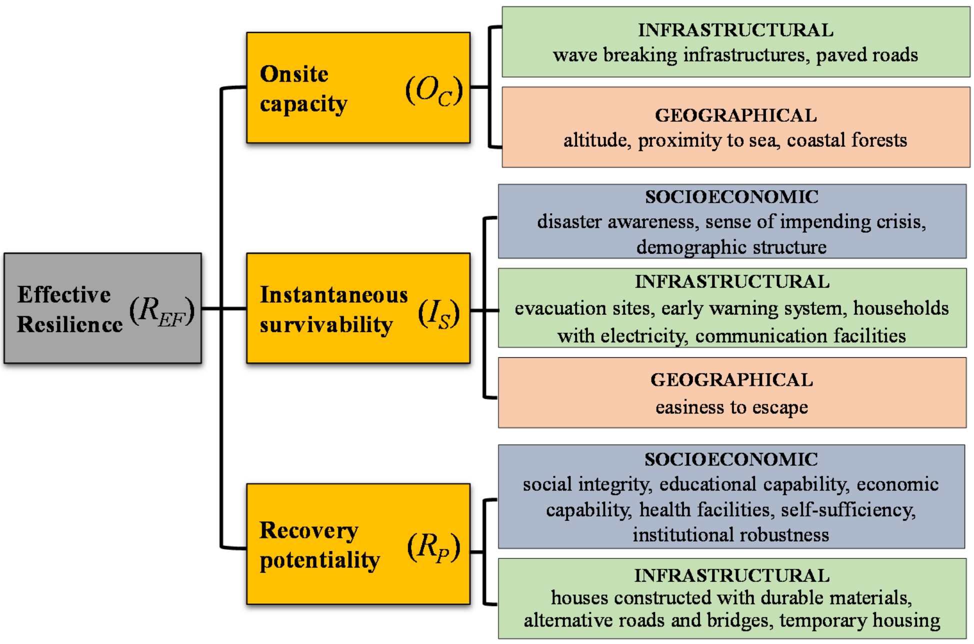

Figure 3. The conceptual framework.

The proposed framework has paid considerable attention to (a) dividing the disaster phenomena into three phases in relation to the temporality of a tsunami, (b) defining the factors influence on a given phase and (c) selecting influential indicators on each factor [11]. Each indicator has been carefully placed in only one phase to avoid double counting. In general, resilience is defined as a function of five components: robustness, redundancy, resourcefulness, response and recovery. These components have been placed in phases in the proposed framework in a temporal manner, distributing in the three phases (requisites) namely, onsite capacity, instantaneous survivability, and recovery potential of an area. Each phase of the framework depends on two or three factors, which can be measured by different indicators and sub-indicators.

The proposed framework assumes that an "ideal resilient region" should fulfil all three requisites. The level of fulfilment in a given phase can basically be evaluated by socioeconomic, infrastructural, and geographical capital of the region in question. Onsite capacity is an ability of a given place to withstand tsunami even before tsunami comes. Instantaneous survivability is an ability to survive during the climax of the disaster. Recovery potential is the ability to recover soon after the disaster, even though the region was destroyed by tsunami.

The indicators in Figure 3 and sub-indicators (see the Supplementary Materials Tables S1–S5) were chosen as appropriate by the authors' firsthand experience of dealing with the two most destructive tsunamis in history, namely The Indian Ocean Tsunami (IOT) and the Great East Japan Earthquake and Tsunami (GEJET); in-depth interviews to the stakeholders and several reports have been published. We also referred the rich list of indicators and facts which have been given in the previous literature [9,10,20–27].

Five-level qualitative classification after field observations can be employed to enumerate wave breaking infrastructures, designated evacuation sites, early warning systems, and ease of escape. Paved roads, altitude, proximity to sea, coastal forests, alternative roads and bridges, and temporary housing can be enumerated by quantile classification using GIS. Five-level quantitative classification after a sample questionnaire survey can be employed to enumerate disaster awareness, sense of impending crisis, and institutional robustness. Others can be calculated using statistical databases. Those indicators and sub-indicators should first be normalized to an index value of 0 to 1. Score of each phase should be calculated by an equally-weighted arithmetic mean of the indicators or sub-indicators. Further details on how to calculate the effective resilience using the mathematical model are provided in the Supplementary Materials.

3. Results and Discussion

3.1. Applying Theory of Springs to Tsunami Resilience

Here, we attempt to apply theory of springs to tsunami resilience in compliance with the conceptual framework proposed in Figure 3. Figure 4 shows the proposed model as an ensemble of series and parallel springs as analogous to that of phases of the conceptual framework. The model has been proposed on the basis of onsite capacity (O_C), instantaneous survivability (I_S), and recovery potentiality (R_P) of a given township as homologous with the spring constants.

A parallel spring with a spring constant equal to 1 and a series spring with a spring constant equal to αO_C (I_S + R_P + 1) are introduced in order to normalize the effective resilience (R_{EF}) of the whole ensemble. This normalization gives O_C an indispensability and avoids division by zero at the worst case. The constant α controls the value of R_{EF}. Onsite capacity O_C has been considered indispensable for prevention of a tsunami. In other words, there is no place that can survive if there is no onsite capacity. I_S and R_P are employed as necessary conditions but are not sufficient. However, the mathematical model depicts that an area maximally scored by all three factors is the ideal, scoring the maximum in the effective resilience. Therefore, no place can be resilient if there are no human activities, because instantaneous survivability and recovery potentiality are only valid if there is a human life. In other words, a township with the ideal onsite capacity can be a strong township in facing tsunami, but it is weaker in resilience.

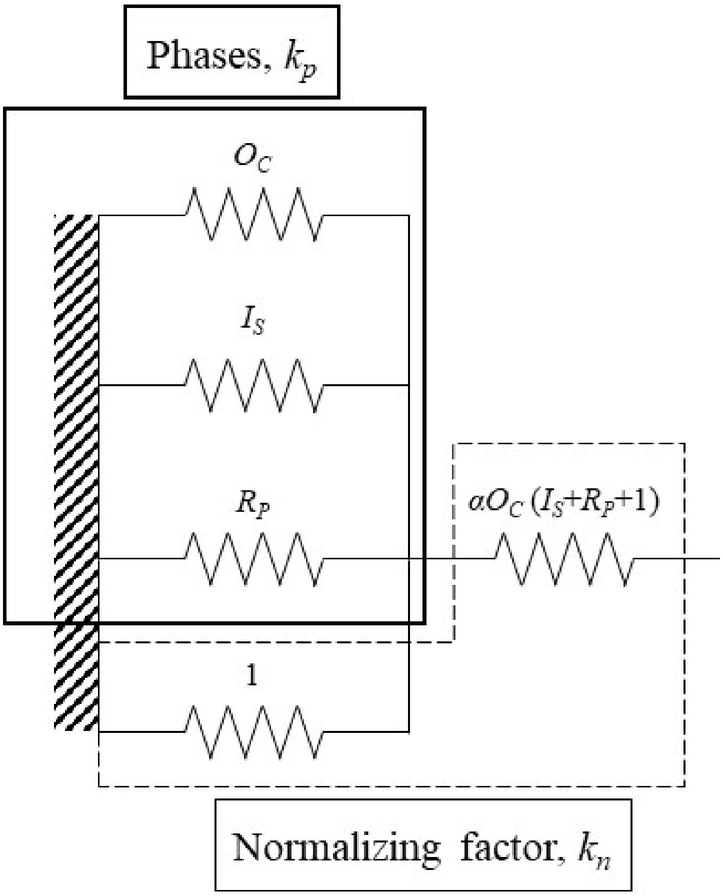

Figure 4. An ensemble of series and parallel springs as analogous to that of phases of the conceptual framework. The model has been proposed on the basis of onsite capacity (O_C), instantaneous survivability (I_S), and recovery potentiality (R_P) of a given tsunami-prone area are homologous with the spring constants.

The ensemble in Figure 4 has four parallel springs and one series spring. The effective spring constant for parallel ensemble (k_p) is given in Equation (7).

$$k_p = O_C + I_s + R_P + 1 \tag{7}$$

The effective spring constant for the whole ensemble (k_e) is given in Equation (8).

$$\frac{1}{k_e} = \frac{1}{k_p} + \frac{1}{\alpha O_C(I_S + R_P + 1)} \tag{8}$$

Therefore,

$$\frac{1}{k_e} = \frac{1}{O_C + I_s + R_P + 1} + \frac{1}{\alpha O_C(I_S + R_P + 1)} \tag{9}$$

$$k_e = \frac{\alpha O_C(I_S + R_P + 1)(O_C + I_s + R_P + 1)}{(O_C + I_s + R_P + 1) + \alpha O_C(I_S + R_P + 1)} \tag{10}$$

Considering the whole ensemble represents a tsunami-prone area, the effective resilience (R_{EF}) can be expressed mathematically as in Equation (11).

$$R_{EF} = \frac{\alpha O_C(I_S + R_P + 1)(O_C + I_s + R_P + 1)}{(O_C + I_s + R_P + 1) + \alpha O_C(I_S + R_P + 1)} \tag{11}$$

If the effective spring constant for whole ensemble (k_e) equals 1, considering the series configuration:

$$\frac{1}{k_e} = 1 \tag{12}$$

When, $O_C = I_S = R_P = 1$,

$$\frac{1}{k_e} = \frac{1}{4} + \frac{1}{3\alpha} \tag{13}$$

Therefore,

$$\alpha = \frac{4}{9} \tag{14}$$

Therefore, the final mathematical model for measuring effective resilience (R_{EF}) is:

$$R_{EF} = \frac{\frac{4}{9}O_C(I_S + R_P + 1)(O_C + I_s + R_P + 1)}{(O_C + I_s + R_P + 1) + \frac{4}{9}O_C(I_S + R_P + 1)} \tag{15}$$

3.2. Properties of the Mathematical Model

If O_C, I_S and R_P are expressed as a value between 0 and 1, the above mathematical model demonstrates the following properties.

1. The maximum effective resilience is 1.
2. The minimum effective resilience is 0.
3. The effective resilience is 0.36, when a place has an ideal onsite capacity (O_C) but no human beings.
4. The effective resilience is 0, when the onsite capacity (O_C) equals 0, disregarding the value of instantaneous survivability (I_S) and recovery potentiality (R_P).

3.3. Limitations of the Mathematical Model

It is necessary that O_C, I_S, and R_P are kept at the same weight. If the indicators are not in the range of 0 to 1, it is necessary to adjust α.

3.4. An Example of Using the Mathematical Model

An example of using the mathematical model is given in the Supplementary Materials. In the example, two disaster-prone municipalities in Sri Lanka were selected as the benchmarks, which were affected by the Indian Ocean Tsunami caused by a magnitude 9.1 earthquake which occurred on 26 December 2004 (see Figure S1). The first of them, Fort Village Officer's (Grama Niladhari) GN Division is sitting in the Dutch fortress of Galle Municipal Council, Southern Province, Sri Lanka (6°1′36″ N, 80°13′03″ E) at an altitude of approximately 15 m above sea level [28]. The 3 to 23 m-high and 1.5 m-width coral, stone and stucco wall served to protect all the buildings inside it and there were no causalities when the tsunami occurred on 26 December 2004.

The second, Manmunai North Divisional Secretariat (DS), is located at an altitude of approximately 5 m above sea level in Eastern Province, Sri Lanka (7°42′58″ N, 81°41′57″ E). It is surrounded by Batticaloa Lagoon. It reported 990 dead and missing people and 3230 completely or partially damaged building units [29].

Galle Fort scored 0.50, while Manmunai North is scored 0.29 in the effective resilience. It has demonstrated that onsite capacity is the governing phase of the effective resilience. The scores are acceptable, as the track record of tsunami has proved. Wave breaking infrastructures bring higher security for the townships despite being in very close proximity to the sea.

4. Conclusions

The proposed mathematical model aggregates the three individual phases into a single parameter using the theory of springs. Aggregation of the individual components has been done in compliance with the theory of springs by analogizing effective tsunami resilience to the effective spring constant. The mathematical model will be useful for evaluating the resilience of townships to disasters and also planning resilient townships, specifically focusing on hydrological disasters including tsunami. Besides, the proposed methodology of distinguishing the effective factors using series or parallel springs, and normalizing set of springs may be useful for any subject matter of engineered sociology.

Supplementary Materials: The following are available online at http://www.mdpi.com/2076-3263/10/11/469/s1, Figure S1: Maps of (a) Galle Fort GN division and (b) Manmunai North DS division, Table S1: A description of indicators/sub-indicators and methodology of enumeration (onsite capacity and instantaneous survivability), Table S2: A description of indicators/sub-indicators and methodology of enumeration (recovery potentiality), Table S3: Summary of the results (onsite capacity), Table S4: Summary of the results (instantaneous survivability), Table S5: Summary of the results (recovery potentiality).

Author Contributions: D.P. conceived the theory, gathered data through the field surveys and statistical databases, calculated the effective resilience and wrote the manuscript. A.S. prepared the Figures 1, 2 and 4. Both authors discussed and interpreted the results. Both authors developed the mathematical model and reviewed the manuscript. All authors have read and agreed to the published version of the manuscript.

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