Supplementary Materials for

A New Methodology for Measuring Tsunami Resilience Using Theory of Springs

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In the main article, only the mathematical model has been introduced. This document demonstrates an example for using the model for evaluating the effective resilience. It should be noted that the purpose of this supplementary materials is to demonstrate that how the model works rather than measuring resilience of a particular place.

1. Background

Two disaster-prone municipalities in Sri Lanka were selected as the benchmarks for the study, which were affected by Indian Ocean Tsunami caused by magnitude 9.1 earthquake occurred on 26th December 2004. Through an extensive fieldwork, we have confirmed that Fort in Galle Municipal Council as the most resilient benchmark and Manmunai North in Batticaloa Municipal Council as the least resilient for mathematical model (see Figure S1).

Figure S1. Maps of **(a)** Galle Fort GN division; **(b)** Manmunai North DS division. Source: Google Earth & Survey Department, Sri Lanka [1]

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 [1]. Built on a promontory, with walls to withstand cannon fire, the ramparts and bastions surrounding the 350-year old Dutch fort acted as a wave breaker against 2004 Indian Ocean tsunami, saving the township from devastation. The 3 m to 23 m-high

and 1.5 m-width coral, stone and stucco wall served to protect all the buildings inside it and remain no causalities when the tsunami occurred on 26th December 2004.

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 has reported 990 dead and missing people and 3,230 completely or partially damaged building units [2].

2. Methodology

Here we describe the methodology employed in collecting the indicators and calculating the effective resilience. The proposed framework in the Figure 3 shows that the indicators for evaluating the score of each factor are different with the phase where the factor sits. A description of indicators/sub-indicators, quantity considered for enumeration, and methodology of enumeration is given in the Tables S1 and S2. Those indicators and sub-indicators 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 published. We also referred the rich list of indicators and facts, which have been given in the previous literature [3-10].

Five-level qualitative classification after field observations can be employed to enumerate wave breaking infrastructures, designated evacuation sites, early warning system, and easiness to 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 sample questionnaire survey can be employed to enumerate disaster awareness, sense of impending crisis, and institutional robustness. A representative 5% sample of affected housing units from different ethnic and religious groups was selected for the survey. Approximately half of them are still living in the same land, where they have faced the tsunami on 26th December 2004. Other indicators and sub-indicators were mainly calculated using Census of Population and Housing 2012, published online by Department of Census and Statistics, Sri Lanka. Those indicators and sub-indicators were first normalized to an index value of 0 to 1, using Equation (S1). To do this, "goalposts" of the maximum and minimum limits on each metrics were set as 1 and 0, respectively, unless otherwise specified. The index is therefore 1 in a township that achieves the maximum value and it is 0 for a township that is at the minimum value. Household income index was calculated with the actual value for a given township, and the national maximum and minimum limits as 77,723 and 23,687, respectively. Expenditure flexibility index was calculated with the actual value for a given township, and the national maximum and minimum limits as 63,030 and 20,581, respectively.

$$Index = \frac{act.\ value - min.\ value}{max.\ value - min.\ value} \quad . \tag{S1}$$

The effective resilience was calculated using Equation (15) and numerical data given in Tables S3, S4 and S5.

For the case of Galle Fort $O_C = 0.67$, $I_S = 0.59$, and $R_P = 0.48$.

Then, the effective resilience (R_{EF}) for Galle Fort is given by,

$$R_{EF} = \frac{\frac{4}{9} \times 0.67(0.59 + 0.48 + 1)(0.67 + 0.59 + 0.48 + 1)}{(0.67 + 0.59 + 0.48 + 1) + \frac{4}{9} \times 0.67(0.59 + 0.48 + 1)}$$

Therefore, $R_{EF} = 0.50$.

For the case of Manmunai North $O_C = 0.37$, $I_S = 0.59$, and $R_P = 0.47$.

Then, the effective resilience (R_{EF}) for Manmunai North is given by,

$$R_{EF} = \frac{\frac{4}{9} \times 0.37(0.59 + 0.47 + 1)(0.37 + 0.59 + 0.47 + 1)}{(0.37 + 0.59 + 0.47 + 1) + \frac{4}{9} \times 0.37(0.59 + 0.47 + 1)}$$

Therefore, $R_{EF} = 0.29$.

3. Results and Discussion

Tables S3, S4 and S5 show the summary of the results of individual phases, factors, indicators and sub-indicators. Galle Fort has scored 0.50, while Manmunai North is 0.29. 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 the higher security for the townships despite of very close proximity to the sea.

Socioeconomic factor in the instantaneous survivability phase shows a comparatively lower score in the case of Galle Fort. This is due to the lower disaster awareness and sense of impending crisis. The sample questionnaire surveys and accompanied interviews for the people currently lived in the township have showed innate propensity to believe tsunami will not come for another 1000 years; and the fort will protect them without doubt even though tsunami comes again.

It is reasonable to assume that the effective resilience 0.50 is a maximum level value befitting the situation of Sri Lanka, because lack of wave breaking infrastructures in most of the coastal townships in the island nation.

Table S1. A description of indicators/sub-indicators and methodology of enumeration (onsite capacity and instantaneous survivability).

CODE	INDICATOR/SUB-INDICATOR	QUANTITY CONSIDERED FOR ENUMERATION	METHOD OF ENUMERATION
O-1	Wave breaking infrastructures	Perimeter of littoral infrastructure	Five-level qualitative classification after field observations
O-2	Paved roads	Length of road per square km	Quantile classification using GIS
O-3	Altitude	Average altitude of 200 m buffer zone	
O-4	Proximity to sea	Length from the shoreline to the centre of the area	
O-5	Coastal forests	Forest area per square km in 200 m buffer zone	
I-1	Disaster awareness	Number of persons with disaster awareness per 100 population	Five-level quantitative classification after sample questionnaire survey
I-2	Sense of impending crisis	Number of persons with sense of impending crisis per 100 population	
I-3	Demographic structure		Average of the following 4 sub-indicators
I-3.1	Population density indicator	Population per area (normalized to an index value of 0 to 1)	Estimated using statistical database [11]
I-3.2	Gender indicator	Males to female ratio	
I-3.3	Age wise physically active population	Ratio of age 5-64 to total population	
I-3.4	Population without difficulties (aged 5 years and over)	Ratio of population without difficulties to total population	
I-4	Designated evacuation sites	Number of sites per square km	Five-level qualitative classification after field observations
I-5	Early warning system	Number of sirens for early warning per square km	
I-6	Households with electricity	Ratio of households with electricity to total households	Estimated using statistical database [11]
I-7	Communication facilities		Average of the following 3 sub-indicators
I-7.1	Housing units occupied with radio	Ratio of housing units occupied with radio to total housing units	Estimated using statistical database [12]
I-7.2	Housing units occupied with television	Ratio of housing units occupied with television to total housing units	
I-7.3	Mobile phones per capita	Ratio of persons used mobile phones to total population	
I-8	Easiness to escape	Qualitatively assessed by considering the inclination of the area	Five-level qualitative classification after field observations

Table S2. A description of indicators/sub-indicators and methodology of enumeration (recovery potentiality).

CODE	INDICATOR/SUB-INDICATOR	QUANTITY CONSIDERED FOR ENUMERATION	METHOD OF ENUMERATION
R-1	Social integrity		Average of the following 2 sub-indicators
R-1.1	Ethnic integrity	Ratio of ethnic majority to total population	Estimated using statistical database [11]
R-1.2	Religious integrity	Ratio of religious majority to total population	
R-2	Educational capability		Average of the following 2 sub-indicators
R-2.1	Literacy ratio	Ratio of population that are literate	Estimated using statistical database [11]
R-2.2	Population more than 10-year schooling (5 years and over)	Ratio of population with more than 10-year schooling	
R-3	Economic capability		Average of the following 5 sub-indicators
R-3.1	Household income	Household income (normalized to an index value of 0 to 1)	Estimated using statistical database [13]
R-3.2	Expenditure flexibility	Cost of living (normalized to an index value of 0 to 1)	
R-3.3	Population living above poverty line	Ratio of population above poverty line	
R-3.4	Population living abroad for employment	Persons living abroad for employment per 10 population	
R-3.5	Population economically active	Ratio of population economically active	
R-4	Health facilities		Average of the following 4 sub-indicators
R-4.1	Beds in hospitals	Ratio of beds in hospitals to 100 population	Estimated using statistical database [14]
R-4.2	Distribution of medical officers	Ratio of medical officers to 1000 population	
R-4.3	Distribution of nurses	Ratio of nurses to 100 population	
R-4.4	Distribution of midwives	Ratio of midwives to 100 population	
R-5	Self-sufficiency of staple food	Ratio of annual paddy production to requirement of paddy for human consumption	Estimated using statistical database [15]
R-6	Institutional robustness	Number of persons agreed as they have robust governance per 100 population	Five-level quantitative classification after sample questionnaire survey
R-7	Houses constructed with durable materials	Ratio of houses constructed with durable materials to total houses	Estimated using statistical database [11]
R-8	Alternative roads and bridges	Number of roads and bridges per square km	Quantile classification using GIS
R-9	Temporary housing	Number of temporary housing per square km	

Table S3. Summary of the results (onsite capacity).

Phases	Galle Fort	Man-munai	Factors	Galle Fort	Man-munai	INDICATORS sub-indicators	Galle Fort	Man-munai
Onsite capacity (O_C)	0.67	0.37	Infrastructural	1.00	0.60	WAVE BREAKING INFRASTRUCTURES	1.00	0.20
						PAVED ROADS	1.00	1.00
						AVERAGE	**1.00**	**0.60**
			Geographical	0.33	0.13	ALTITUDE	0.60	0.20
						PROXIMITY TO SEA	0.00	0.00
						COASTAL FORESTS	0.40	0.20
						AVERAGE	**0.33**	**0.13**
			Average	**0.67**	**0.37**			

Table S4. Summary of the results (instantaneous survivability).

Phases	Galle Fort	Man-munai	Factors	Galle Fort	Man-munai	INDICATORS sub-indicators	Galle Fort	Man-munai
Instantaneous survivability (*Is*)	0.59	0.59	Socioeconomic	0.34	0.76	DISASTER AWARENESS	0.20	0.60
						SENSE OF IMPENDING CRISIS	0.00	0.80
						DEMOGRAPHIC STRUCTURE	0.81	0.87
						population density indicator	0.70	0.81
						gender indicator	0.78	0.90
						age wise physically active population	0.82	0.85
						population without difficulties (aged 5 years and over)	0.91	0.93
						average	**0.81**	**0.87**
						AVERAGE	**0.34**	**0.76**
			Infrastructural	0.63	0.62	DESIGNATED EVACUATION SITES	0.80	0.80
						EARLY WARNING SYSTEM	0.20	0.60
						HOUSEHOLDS WITH ELECTRICITY	0.94	0.67
						COMMUNICATION FACILITIES	0.58	0.39
						housing units occupied with radio	0.73	0.43
						housing units occupied with television	0.82	0.56
						mobile phones per capita	0.20	0.18
						average	**0.58**	**0.39**
						AVERAGE	**0.63**	**0.62**
			Geographical	0.80	0.40	EASINESS TO ESCAPE	0.80	0.40
						AVERAGE	**0.80**	**0.40**
			Average	**0.59**	**0.59**			

Table S5. Summary of the results (recovery potentiality).

Phases	Galle Fort	Man-munai	Factors	Galle Fort	Man-munai	INDICATORS sub-indicators	Galle Fort	Man-munai
Recovery potentiality (R_P)	0.48	0.47	Socioeconomic	0.51	0.62	SOCIAL INTEGRITY	0.54	0.77
						ethnic integrity	0.54	0.89
						religious integrity	0.54	0.65
						average	**0.54**	**0.77**
						EDUCATIONAL CAPABILITY	0.77	0.70
						literacy ratio	0.98	0.95
						population more than 10-year schooling (5 years and over)	0.55	0.45
						average	**0.77**	**0.70**
						ECONOMIC CAPABILITY	0.50	0.50
						household income	0.30	0.03
						expenditure flexibility	0.66	0.79
						population living above poverty line	0.90	0.81
						population living abroad for employment (per 10 per.)	0.24	0.44
						population economically active	0.42	0.45
						average	**0.50**	**0.50**
						HEALTH FACILITIES	0.37	0.37
						beds in hospitals	0.38	0.36
						distribution of medical officers	0.16	0.02
						distribution of nurses	0.45	0.29
						distribution of midwives	0.49	0.79
						average	**0.37**	**0.37**
						SELF-SUFFICIENCY OF STAPLE FOOD	0.31	1.00
						INSTITUTIONAL ROBUSTNESS	0.60	0.40
						AVERAGE	**0.51**	**0.62**
			Infrastructural	0.44	0.31	HOUSES CONSTRUCTED WITH DURABLE MATERIALS	0.91	0.93
						ALTERNATIVE ROADS AND BRIDGES	0.40	0.00
						TEMPORARY HOUSING	0.00	0.00
						AVERAGE	**0.44**	**0.31**
			Average	**0.48**	**0.47**			

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