

Article

## Building Damage and Business Continuity Management in the Event of Natural Hazards: Case Study of the 2004 Tsunami in Sri Lanka

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**Abstract:** The Sumatra Earthquake and Indian Ocean Tsunami event on the 26 December 2004 has provided a unique and valuable opportunity to evaluate the performance of various structures, facilities and lifeline systems during the tsunami wave attacks. There are especially meaningful observations concerning the structural changes due to the tsunami forces, which open up a wide area of research to develop the mitigation procedure. The business restoration process of business companies in terms of buildings, facilities and lifelines have shown greater research interest. In this study, we investigated the restoration process of business sectors in East and South coastal region in Sri Lanka after the 2004 Indian Ocean Tsunami. A field survey was conducted in East and South coast of Sri Lanka, in order to study the affecting parameters to damage assessment in the restoration process of the business companies. The results of the questionnaire-based field survey are then compared with the statistical analysis results. Finally, the factors affecting the restoration process after the tsunami are identified. As a main conclusion, financial support could be

the most important reason for delays in restoration. Moreover, it has been observed that the tsunami inundation level of higher than one meter may have had more effect concerning the damage to the structures and requires additional time for restoration than other areas.

**Keywords:** BCM; BPM; tsunami; building damage; Sri Lanka; restoration

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## 1. Introduction

The most powerful earthquake in 40 years occurred under the Indian Ocean near Sumatra on 26 December 2004. This massive earthquake of magnitude 9 on the Richter scale caused giant deadly tsunami waves to crash ashore in nearly a dozen countries, killing tens of thousands of people [1]. A long stretch of Sri Lanka's coast was devastated by these killer waves, with more than 40,000 dead and a staggering 25 million people displaced. Although 1600 km from the epicenter, the waves struck with huge force and swept inland up to a 5 km range [2]. Tidal waves as high as 6 m crashed into coastal villages, sweeping away people, vehicles and even a train with 1,700 passengers. It was the worst human disaster in the history of Sri Lanka. This has resulted in severe damage to life, property, livelihoods and infrastructures in the affected areas of the country. Even though such a destructive disaster occurred, we should be capable of restoring the damages quickly using disaster preparedness and management. Currently government, non-government sectors and private companies all over the world are getting interested in Business Continuity Management (BCM) and Business Process Management (BPM) [3]. This study uses this concept of BCM to analyze the business restoration process for the post tsunami Sri Lanka.

### *Business Continuity Management*

Business Continuity Management (BCM) means taking every possible measure to insure the continuity, or uninterrupted delivery, of operations and services. BCM is an on-going process with several different, but complementary, components, and the Business Continuity Planning (BCP) is a comprehensive process that includes disaster recovery, business recovery, business resumption and contingency planning. BCM can be defined as that critical business function which involves the preparation of plans, the allocation of resources and the implementation of processes such that an organization can recover quickly and safely from an interruption (crisis, emergency, event, *etc.*), with minimum negative impact to the people, premises, assets and operations [4].

BCM can offer protection from many potential risks that can threaten the company or industry by disrupting critical business processes. These risks include natural disasters such as earthquakes, tsunami, fires, floods and hurricanes, as well as risks from terrorism, cybercrime, computer failures, riots and employee sabotage. Any one of these events can be extremely disruptive and detrimental to the business, yet all of the potential damage from each of them can be substantially minimized through business continuity management. Some organizations and research groups have also done few researches similar to this study for example ATC-25 [5]. In the previous studies, some researches have analyzed the seismic vulnerability of lifeline systems and the economic impact of disruption that are

based on an assessment of three factors; seismic hazard, lifeline inventory and vulnerability functions. The principle tool for BCM is the Business Continuity Plan. In order to build the BCM for system before disaster, the assessment of vulnerability of business components is important. This study proposed evaluation method of restoration for facility, lifeline and business itself against the tsunami hazard. Therefore this study analyzes collected data from tsunami affected Ampara district (East coast) and Galle (South coast) during the 2004 Indian Ocean Earthquake and Tsunami. The data was collected by a field survey which directly interviewing the business sectors through a questioner in the effected coastal regions.

## **2. Sumatra Tsunami Earthquake and Questionnaire Survey**

### *2.1. Outline of Tsunami Disaster in Galle and Ampara District in Sri Lanka*

Galle is considered as the southern capital (116 km from Colombo), Sri Lanka's fourth biggest town with a population of around 100,000, and is connected by railway to Colombo and Matara. The Galle seaport was developed in the late 19th century and it still handles shipping and cruising yachts today. Its main attraction is the fort called "Santa Cruz" that has been declared a world heritage site by UNESCO. The fort was built by the Portuguese in 1619 and subsequently expanded and developed by the Dutch and the British, which were the one time colonial masters of the island. On 26 December 2004 the Galle city was devastated by the tsunami caused by the earthquake that occurred in the Indian Ocean a thousand miles away of the coast of Indonesia. Other than the damages to livelihood, 18 secretariat divisions, which are located along southern coastal belt, have been directly affected due to tidal waves.

Ampara was the district most severely affected by the tsunami in East Sri Lanka, from the 11 out of 20 divisions. More than 10,000 people died and 38,000 families were displaced. Of a total of 16,180 fishing families residing in the district, about 6000 families were affected by the tsunami, and around 2100 boats were destroyed while 500 were partly damaged. Besides fisher folk, a large number of people in the formal and informal sectors lost their sources of income. Many irrigation channels were damaged by the tsunami and later by heavy rain, while paddy lands were covered by sea sand. Damage included 390 ha of agricultural land (of which 290 is paddy land) and loss of 29,500 poultry, 3400 cattle and 1100 goats. In the tourism sector, 34 hotels and guesthouses located in Arugam Bay were damaged [6].

### *2.2. Questionnaire Survey*

#### **Outline of Survey**

The questionnaires were collected from industries in Galle and Ampara. These areas are located in Southern and East part of Sri Lanka. The total of 258 questionnaires have been collected from various types of industries including lifelines such as water, electricity and telecommunication facilities, all of which support urban activities and civil life as shown in Figure 1. The format of the questionnaire is comprised as follows;

- (1) Type of the industry.
- (2) Scale of the industry.
- (3) Statistics of damage to the industry facilities such as buildings, natural resources, industrial facility, machines and stores due to tidal waves.
- (4) The damage percentage, restoration time and impact condition of each facility such as electricity, water supply, sewage water, gas, telecommunication, oil, transportation, customers and stores *etc.*
- (5) Restoration process of the production and selling rate after the tsunami.

**Figure 1.** Questionnaire survey among the industries in the tsunami affected area.



(a) Field survey at Galle



(b) Field survey at Ampara



(c) Construction Material  
(Coconut fiber loop factory)



(d) Construction Material  
(wood)



(e) Damaged Ice Plant



(f) Cinnamon Oil Production

The main enumeration of the survey is concerned with the tsunami damage and the restoration process of the business companies their buildings, facilities and lifelines. The summary of answers and 258 related industries are presented in Table 1.

**Table 1.** Industrial classification of answered companies for the questionnaire.

Industry type	Quantity of answers	Summery and description
Agriculture	15	Low level (rice), High level (vegetable)
Fishery	50	Deep sea fishery, Shallow sea fishery
Manufacturing (construction)	20	Construction material (rope, limestone)
Manufacturing (others)	40	Cinnamon Oil, Ice, Wood production
Wholesale /Retail trade	40	Shoes, Souvenir sale
Financial Industry	20	Banks
Tourism (hotels)	35	Hotels, Resorts
Tourism (except hotels)	5	Tourism-related
Lifelines	20	Electricity, Water supply, Telecommunication
Others	13	Hospital, Public services
Total	258	

The collected questionnaires during the field survey are employed to construct the database. The statistical data of the damage to companies and lifeline facilities are explained and the restoration process of the facilities is analyzed.

According to the survey conducted by Industrial Development Board (IDB), the tsunami has affected about 4,500 industries within the country, which were in food, beverages, tobacco products, textile, apparels, leather products, wood, wooden products, coir based products, chemical based products, pharmaceuticals, rubber, plastic products, non-metallic mineral products, fabricated metal products, agriculture, ornamental fishery, paper, paper products, handicrafts, gem and jewelry industry, trading, retail, services and manufacturing. Among them, this study collected data from fishery, agriculture, housing and manufacturing, tourism and its related industries. The survey has also found out that some employees and employers died and some are disabled due to the disaster. The inundation waves caused damage to machinery, tools, equipment, raw materials, and semi-finished and finished goods and vehicles of the industries.

### 2.3. Database and Analysis

#### 2.3.1. Damage due to the Tsunami Inundation

The inundation height is different due to the vastness of tsunami, distance from the shoreline and topography. The study area is almost flat and situated between the shoreline and 1 km inland. Sometimes the ground is slightly elevated due to hills on the inland side. However, most of the effected business institutions were located in a flat area. According to the answers, in some cases the tsunami hit with 8m inundation height. The “Galle Fort”, world famous as a heritage site made by the



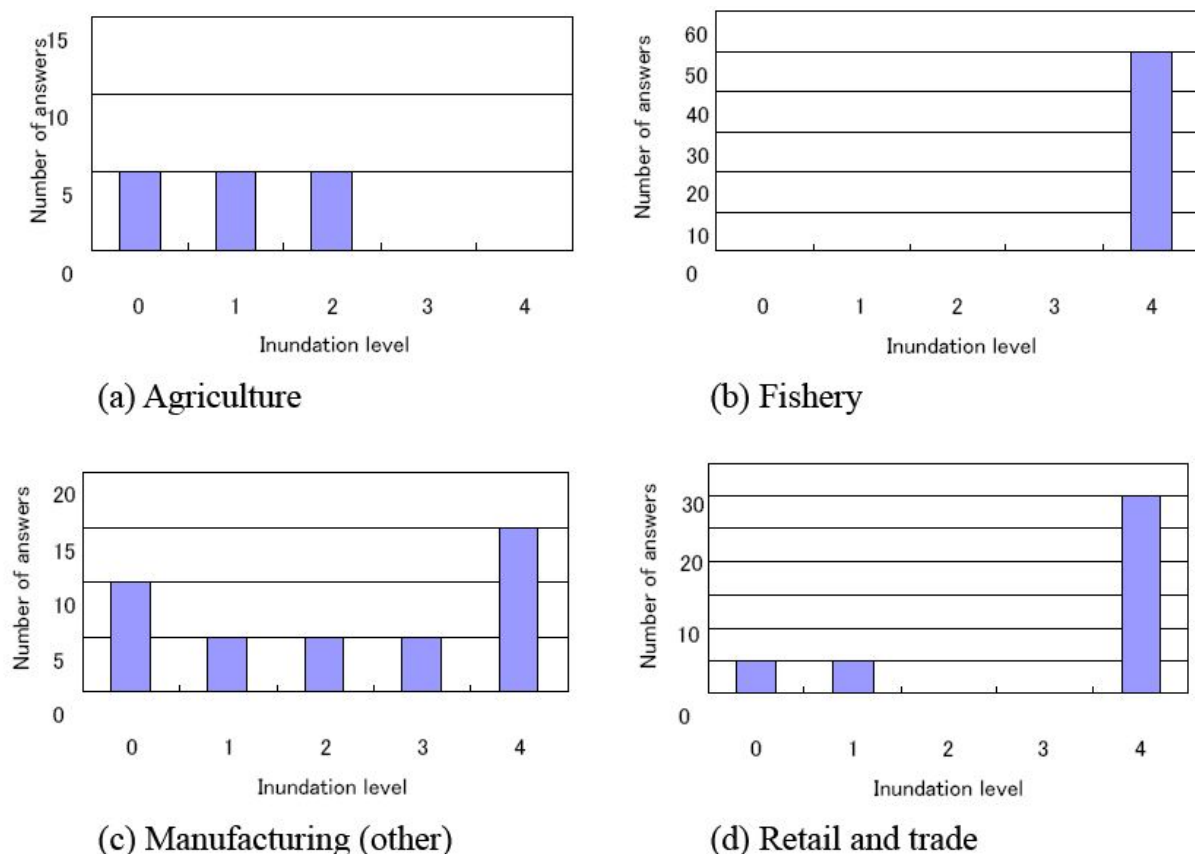
former Netherlands force in 17th century, was also impacted by tsunami, but there was no overflowing flood because the structural foundation height was more than 10m. However, the Galle bus terminal, situated much closer than the fort, was heavily damaged by strong tsunami waves, situated at a low level and crowded when tsunami struck.

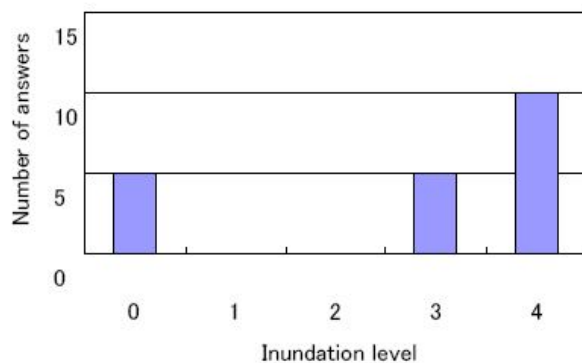
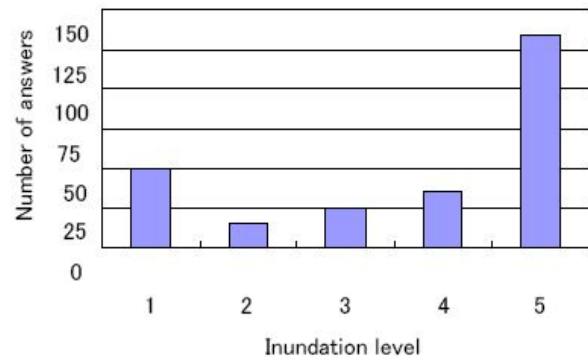
The industries are classified and analyzed using the tsunami inundation level that categorized in the range of tsunami inundation height as shown in Table 2. Figure 2 shows the number of the answers corresponding to each inundation level in various industries. The numbers counted at each inundation water level are different for each type of industry. As can be seen, the fishery industries (Figure 2b) on the coast have been severely damaged by the tsunami where the inundation height was more than 3m. Agricultural farms (Figure 2a) have not been hit by the high water front because most of them were situated far from the coastline. Some tourist hotels close to the shore did not get damaged because building being built on small hills.

**Table 2** Tsunami inundation levels.

Tsunami inundation level	Tsunami inundation height (m)
0	$h = 0$
1	$0 < h < 1$
2	$1 < h < 2$
3	$2 < h < 3$
4	$h > 3$

**Figure 2.** Tsunami inundation height.



**Figure 2.** *Cont.***(e) Financial Industry****(f) Whole industries**

### 2.3.2. Damage to the Institutions

This section describes the damage to the institutions caused by the tsunami. The damage of institutions is comprised of two main parts: building and facilities (industrial facilities, heavy machinery and light machinery). The answers about damage are categorized among five phases based on the percentage of damage ranging by 0, 25, 50, 75, and 100%.

#### *(a) Damage to Building Structures*

Figure 3 shows the total building damage percentage of each industry. Most of the buildings in this local area were made of bricks or reinforced concrete. However, in case of buildings located near the coastal area, not only infill walls but also concrete frames were washed away by the tsunami severely.

As regards the fact that most of the concrete frames were damaged and or washed away, it is difficult to recognize the places of reinforcing rods. In addition, most of the buildings in manufacturing industries and retail trade had 100% damage. On the other hand, the finance business and lifeline companies had little damage.

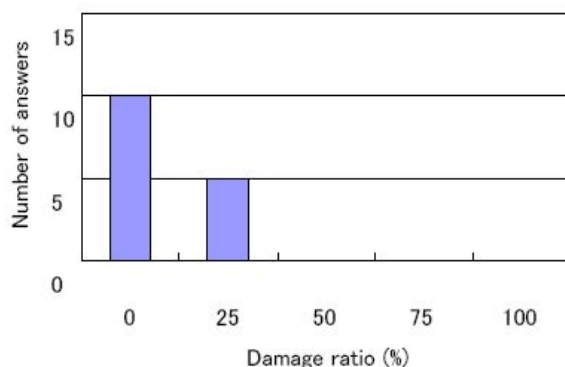
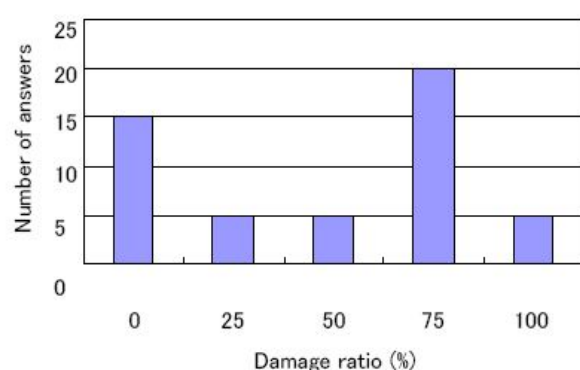
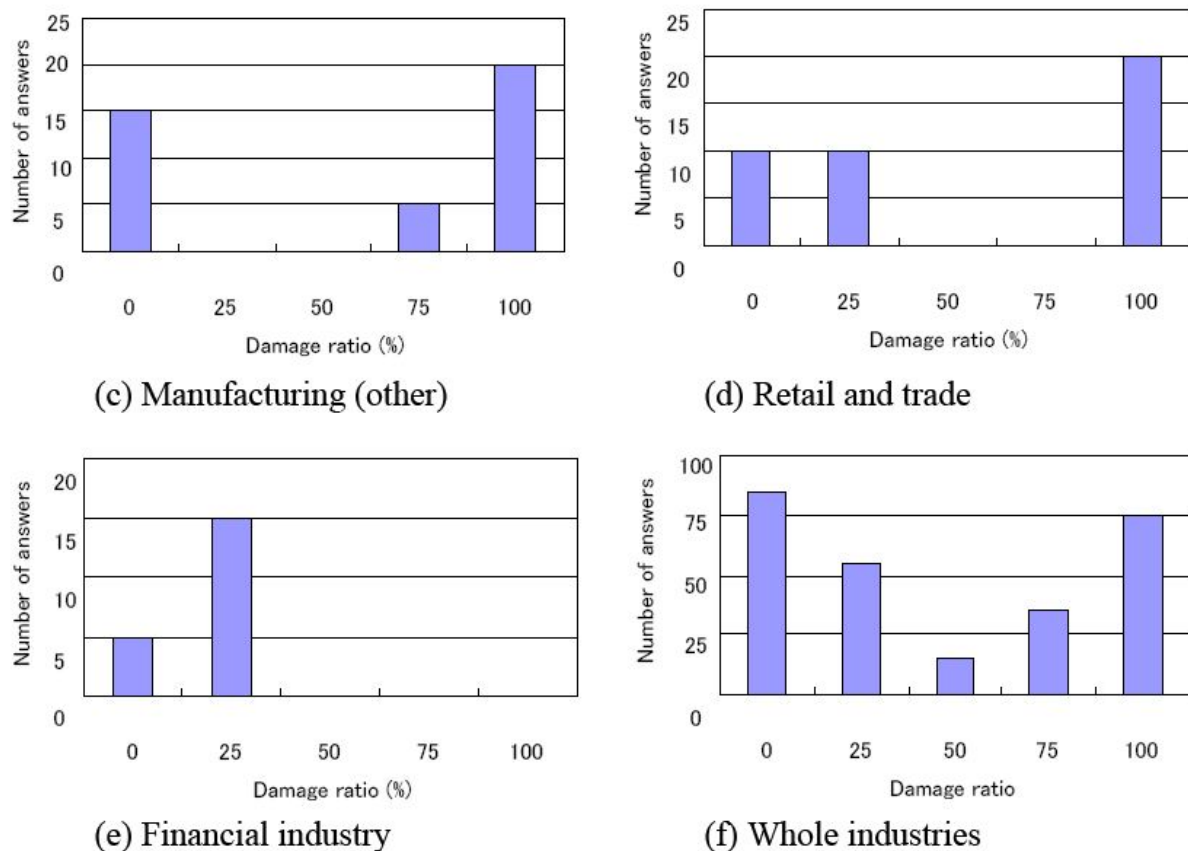
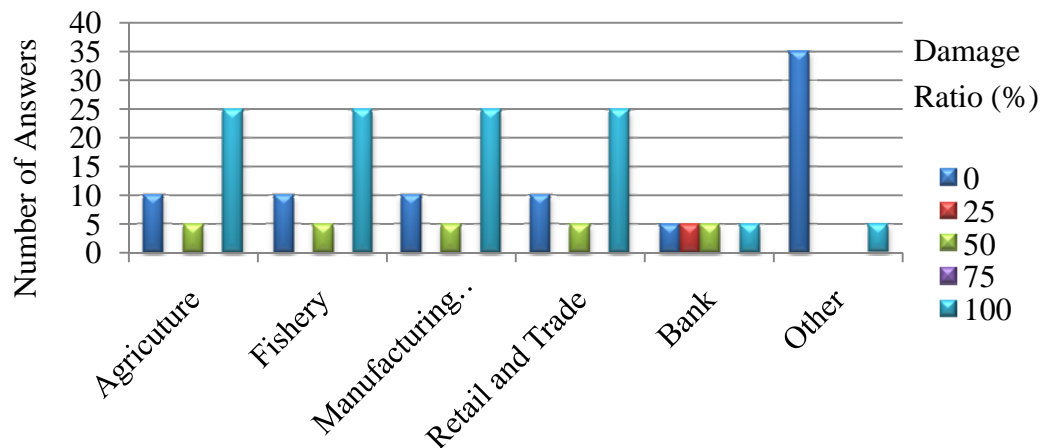
**Figure 3.** Damage to building facilities.**(a) Agriculture****(b) Fishery**

Figure 3. Cont.

*(b) Damage to Business's Facilities*

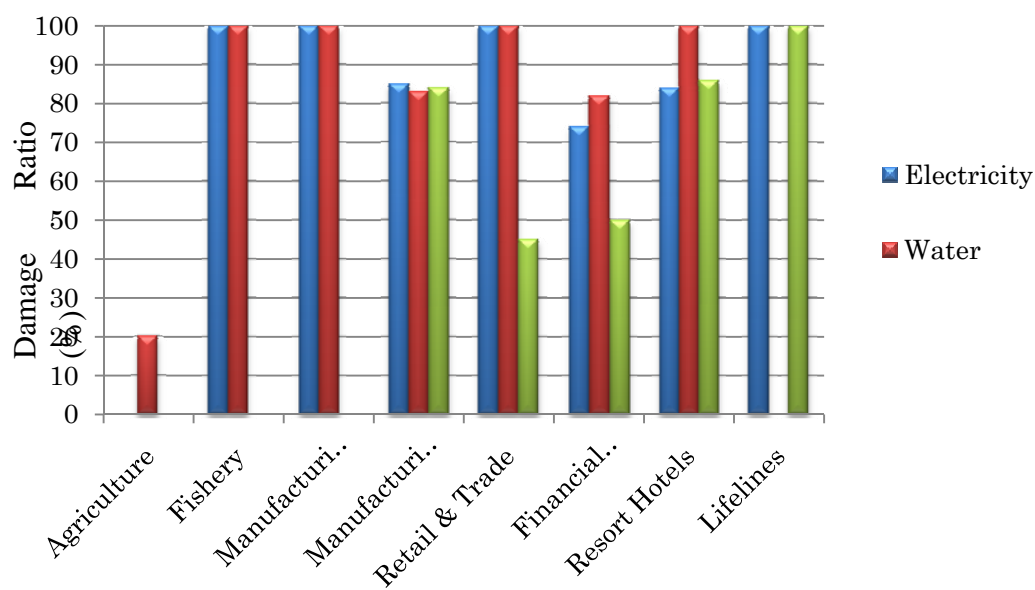
The damage to the industrial facilities is shown in Figure 4. The types of facilities are different in each company, except financial (banks) and lifeline companies, in which the percentage of damage concentrates from 0% to 100% and becomes a concave distribution. From the individual answers of the investigation, the facilities inside the buildings were buoyed with the flood current, including debris. In many places, electric facilities soaked in seawater did not report massive damage to the outside of facilities, but their internal electricity systems tended to break down. The facilities of an ice making company were heavily damaged including equipment such as electric generators and other ice plant devices.



**Figure 4.** Damage to industrial facilities.

*(c) Damage to the Lifelines (Power, Water and Telecommunication)*

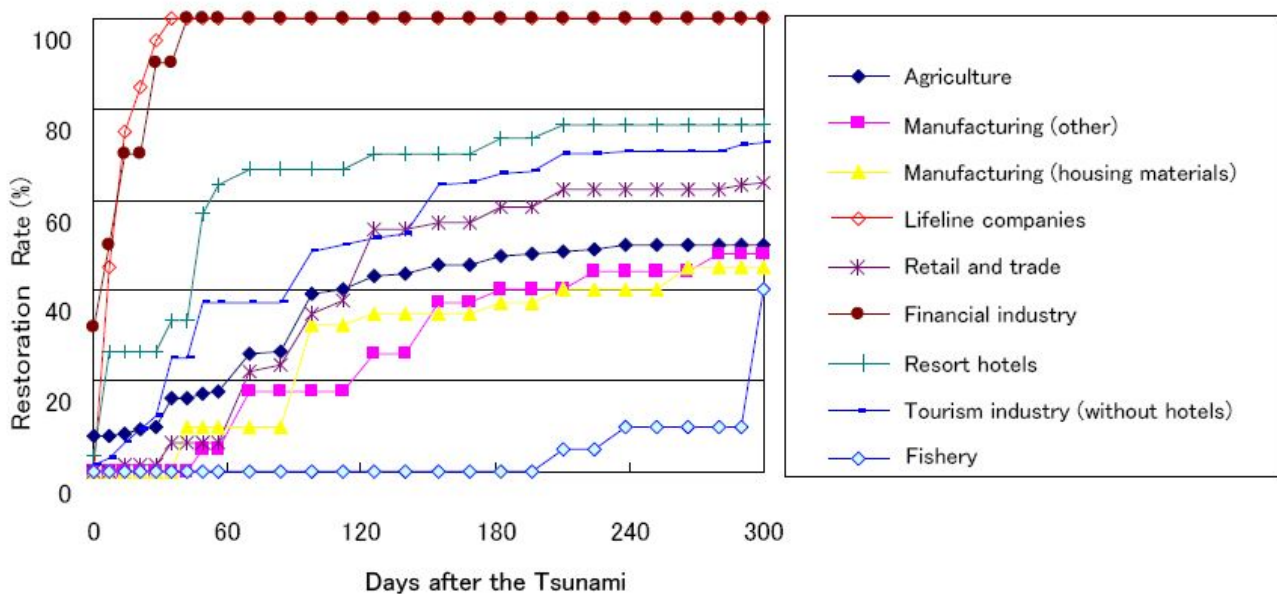
Moreover, the three lifelines of electricity, water supply and telecommunication have been investigated. Because the study area had not a gas pipeline but LP (Liquid Petroleum) gas cylinders, the gas lifeline was removed from this analysis. In terms of water supply, most of the families in the countryside usually use well water. However, in this study, we were concerned with the damage related to piped water. Figure 5 shows the supply situation of lifelines according to each type of industry. In case of agriculture, they were located far from the coastline, thus protecting them from the tsunami damage in Galle. Comparing three lifeline systems, on average 84% of the electricity system and 75% of the water supply system were out of service after the tsunami. However, the telecommunication system had less damage compared with other lifelines. The people already use mobile telephones, and therefore the influence of blackout was small for fixed lines.

**Figure 5.** Damage condition of lifeline.

### 2.3.3. Restoration Process of the Tsunami Affected Industries

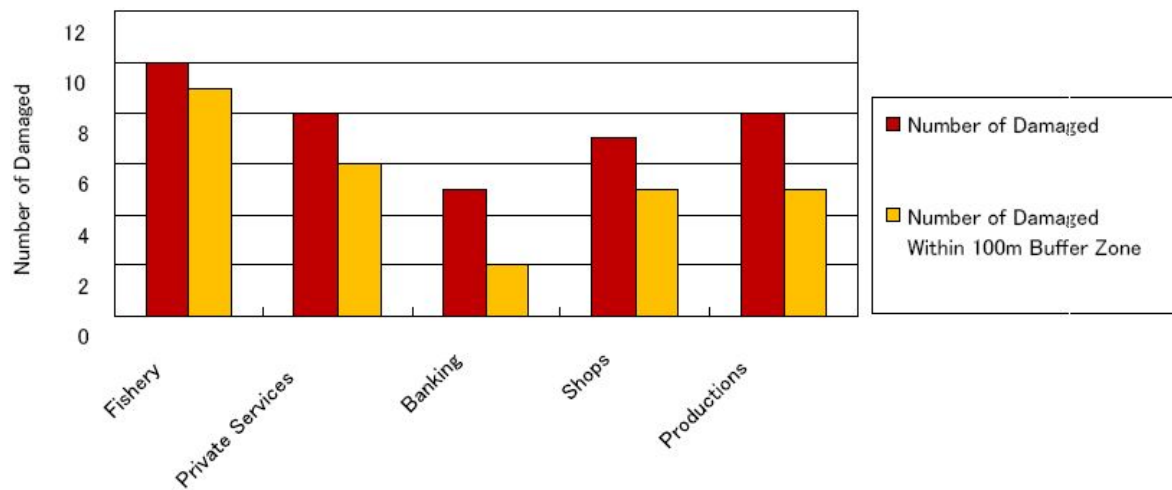
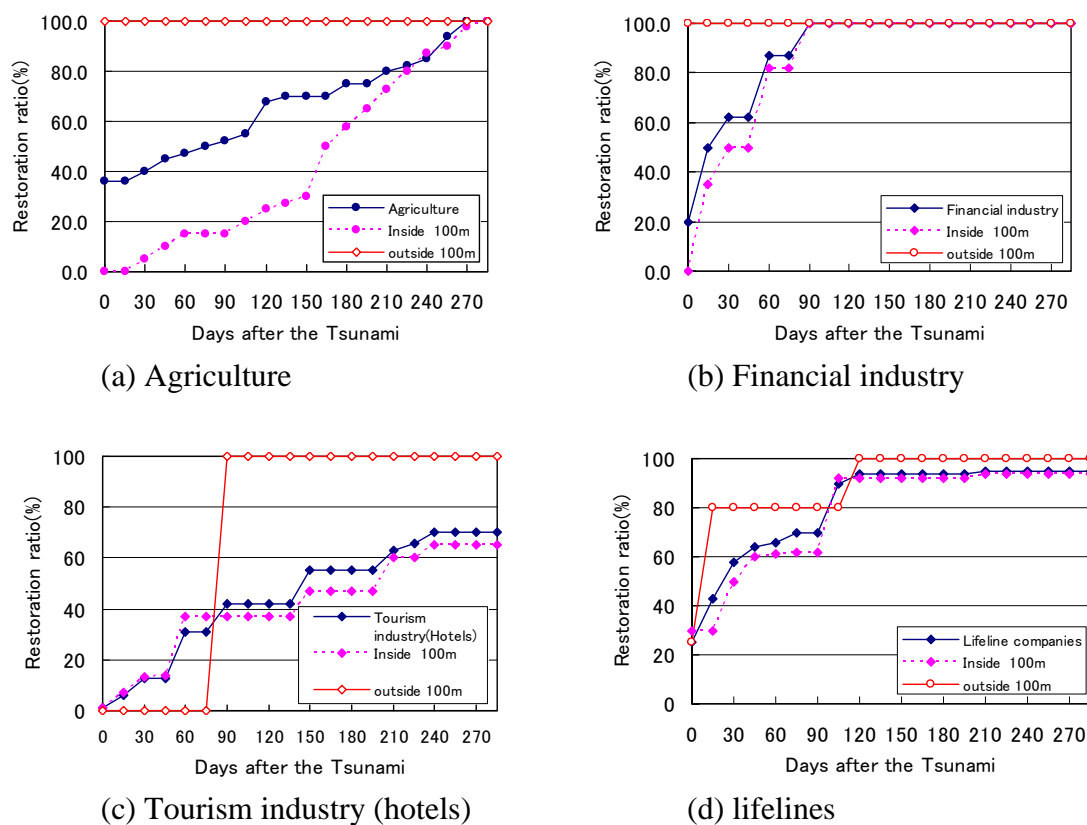
Figure 6 shows the average restoration process by tsunami affected industries. The financial industry recovered faster than other industries. They provided their service for customers using mobile phone networks connected with main branches, though the other communication networks were out of service. The restoration of the lifeline companies are also fast because their building facilities had less damage from the tsunami and got immediate external support for recovery from other prefectures. The agriculture industry suffered by salt water and took around 6–12 months for recovery. The most severely affected industry by the tsunami was the fishery. Fishing communities lost most of their equipment and did not have enough insurance for recovery. Most of the fishermen and their family members lost their lives. The tourism industry was also affected heavily. Still the foreign and local tourists are infrequent in their visits.

**Figure 6.** Restoration process in Industries.



### 2.3.4. 100 m Affected Buffer Zone

This section describes how the distance from the shoreline affects the restoration process. The Government of Sri Lanka has announced a 100 m buffer zone from the shoreline, where construction and rebuilding is prohibited. Therefore, hotels that were originally at the coastline cannot be reconstructed. Figure 7 compares the restoration process of the industry located within a 100 m buffer zone from coastline. It is clear that the restoration of the industries in buffer zone was later than ones located outside of the buffer zone. Restoration of hotels within the 100 m buffer zone recovered quicker. Figure 8 shows the restoration process of industries according to the distance from the shoreline.

**Figure 7.** Damage inside and outside the 100 m buffer zone.**Figure 8.** Restoration process of industries by the distance from the shoreline.

### 3. Proposed Model for Industrial Restoration

From the viewpoint of business continuity management, it is very important to continue the business or to restart in a short period time, even if there is interruption by a disaster. In other words, it is primarily necessary to grasp the damages in terms of both lifeline and industrial facilities. In order to analyze the post-disaster activities and affects, a restoration process for lifeline and industrial facilities subject to natural disaster should be considered. In this section, a model for the restoration process is constructed considering the business interruption due to the damages caused by the tsunami.

The proposed model is applied to industries restoration process in southern Sri Lanka after the tsunami.

### 3.1. Proposed Model of Restoration for Industries

#### 3.1.1. Concept of the Model

In order to study the business interruption damages to building and facilities of each business and corresponding restoration process have been studied. Restoration of industrial facilities after the tsunami could to be evaluated considering a damage level (damage degree). The completeness of restoration of all industrial facilities is defined as they reach to the normal state before tsunami effect. In this study, we divided the damage state,  $DS$ , into five states and restoration process for every damage state is evaluated. The restoration rate,  $R_{Fn}(t | x)$ , that depends on time,  $t$ , related to the facility  $Fn$  with tsunami intensity level,  $x$ , has given the occurrence probability  $P_{Fn}(DS | x)$  of damage state,  $DS$ , in the tsunami intensity level  $x$ , and conditional restoration rate of business facilities,  $R_{Fn}(t | DS)$ , according to damage state,  $DS$ , depending on time is as follows.

$$R_{Fn}(t | x) = \sum_{DS=1}^5 R_{Fn}(t | DS) P_{Fn}(DS | x) \quad (1)$$

The external force of the tsunami wave is mainly occurred by dynamic drag force of wave, which is proportional to the product of the square of wave speed and the projected area. Wave velocity is proportional to the water depth, then it can be said that the wave force is proportional to square of whole depth of the water. Shuto [7] defines the value of squared inundation height from the past tsunami damage as the tsunami intensity and classified the damage situation from the past tsunami damage based on its index. In this study, we have not classified the square value of inundation height considering the implicational local inundation situation. We set the tsunami intensity level for five states due to the inundation levels. The five states are non-inundation, less than 1m, less than 2 m, less than 3 m and above 3 m as shown in Table 2.

#### 3.1.2. Occurrence Probability of Institution Damage

The damage state is a disintegration value, which is divided into five phases from A to E. Damage state A means the high damage level and damage state E is presented as the low damage level (no damage), damage rate  $y$  ( $0 \leq y \leq 100\%$ ). In addition, each damage state has a representative figure  $k_{DS}$  given the damage state  $DS$  shown in Table 3. Therefore, occurrence probability,  $P_{Fn}(DS | x)$ , of industrial damage condition according to the tsunami intensity level is expressed by section integral calculus of distribution's lowest damage rate  $y_1$  to highest damage rate when given the damage rate  $y_2$  distribution  $f(y | x)$ .

$$P(DS | x) = \int_{y_1}^{y_2} f(y | x) dy \quad (2)$$

**Table 3.** Definition of damage state  $DS$ .

Damage state $DS$	Damage state $k_{DS}$	Range of damage rate $y(\%)$
A	100	$87.5 \leq y \leq 100$
B	75	$62.5 \leq y \leq 87.5$
C	50	$37.5 \leq y \leq 62.5$
D	25	$12.5 \leq y \leq 37.5$
E	0	$0 \leq y \leq 12.5$

Damage rate distribution function  $f$  under condition of tsunami intensity level  $x$ , is given by beta distribution as a continuous function with range from 0 to 100. The beta distribution function of damage rate is as follows,

$$f(y|x) = \frac{1}{B(q,r)} \cdot \frac{y^{q-1}(100-y)^{r-1}}{100^{q+r-1}} \quad 0 \leq y \leq 100 \quad (3)$$

Here  $q$  and  $r$  are parameters that express the distribution shape. In addition, the beta function  $B(q, r)$  is expressed as,

$$B(q, r) = \frac{\Gamma(q)\Gamma(r)}{\Gamma(q+r)} \quad (4)$$

Average of the distribution function,  $\mu_y$ , and variance,  $\sigma_y^2$ , are as follows,

$$\mu_y = 100q/(q+r) \quad (5)$$

$$\sigma_y^2 = \frac{qr}{(q+r)^2(q+r+1)} \cdot 100^2 \quad (6)$$

The parameters  $q$  and  $r$  are estimated by solving equations that equivalent to Equation (5), (6) provided from questionnaire average and variance of damage rate by the method of moment.

### 3.1.3. Restoration of Institution with Damage State

Here, the proposed model of restoration rate,  $R_{Fn}(t|DS)$  is explained. The restoration rate can be calculated using the accumulated value of the restoration density distribution,  $r_{Fn}(t|DS)$ , of each damage state  $DS$  and representative figure  $k_{DS}$  of damage state  $DS$ .

$$R_{Fn}(t|DS) = 1 - k_{DS} + k_{DS} \int_0^t r_{Fn}(\tau|DS) d\tau \quad (7)$$

The ratio of the restoration rate is given by damage state  $DS$  and representative figure  $k_{DS}$  reduced by 1. The restoration rate is depending on representative figure  $k_{DS}$  and time  $t$ . The parameters of gamma distribution  $k$  and  $v$  is given as,

$$r_{Fn}(t|DS) = \frac{v(vt)^{k-1} e^{-vt}}{\Gamma(k)} \quad t \geq 0 \quad (8)$$

$$R_{Fn}(t | DS) = \int_0^t r_T(\tau | DS) d\tau \quad (9)$$

in which, the average of this distribution function  $\mu_t$ , and variance  $\sigma_t^2$  are as follows,

$$\mu_t = k / \nu \quad (10)$$

$$\sigma_t^2 = k / \nu^2 \quad (11)$$

For estimation of the parameters of distribution functions, the moment method is employed. Thus, the occurrence probability,  $P_{Fn}(DS | x)$  of damage state  $DS$  in certain tsunami intensity level  $x$ , and the restoration rate,  $R_{Fn}(t | DS)$  could be estimated.

### 3.2. Proposed Model of Restoration for Lifeline Facilities

The electricity, water supply and telecommunication are considered as the most important lifeline for business and industries. Since lifeline is a system, for damage analysis of lifeline, not only physical damage but also functional damages should be considered. ATC-13 has presented the method for evaluation of lifeline systems restoration based on the supply levels of them. The evaluation method presented in ATC-13 would be recommended for the restoration process based on the lifeline network data, risk assessment of the network and facilities and earthquake ground shaking, if there is enough data for them. By the way, restoration time reported by lifeline company is on main system basis. From customers' point of view, the restoration time is much longer than that. We employed database obtained from responders. The proposed model of restoration rate for lifeline is performed by a method that evaluates with product sum of the state restoration rate and the occurrence of the damage state of the industries. Here, the damage state of lifeline systems is categorized into two states so that the restoration function of a lifeline could be expressed as,

$$R_{Ln}(t | x) = \sum_{i=1}^2 R_{Ln}(t | DS) P_{Ln}(DS | x) \quad (12)$$

The damage state has two results, whether the lifeline is functioning or not functioning. When the lifeline system is functional, the representative figure  $k_{DS}$  of damage state  $DS$  becomes 0, and the state of restoration rate  $R_{Ln}(t | DS, DS = \text{functional})$  becomes 1. In contrast, when the lifeline is not functional, the representative figure  $k_{DS}$  of damage state  $DS$  becomes 1, and the state restoration rate  $R_{Ln}(t | DS, DS = \text{not functional})$  gives accumulated value of the conditional restoration density distribution.

In this study, we have used the lifeline damage data collected from the questionnaire answers, without theoretical modeling of the occurrence probability of the damage state. It is necessary to build model based on detailed data. However there is not enough data to analyze the relation between lifeline and the spatial inundation characteristic of the tsunami to analyze. The conditional restoration rate is estimated by the given gamma function.



### 3.3. Application of Proposed Restoration Model

#### Estimation of Institution Restoration

The proposed restoration model was employed in order to estimate the restoration curves according to the tsunami intensity, based on the collected data in southern Sri Lanka. First of all, damage state parameters and restoration rate parameters were calculated based on the equations presented in Section 3.1. The restoration process and resistance to tsunami force are different by the type of buildings, conditions of the facilities and so on. However, in the present study, we do not have enough numbers of answers to analyze these factors separately. Therefore, all the buildings for different industries are assumed to have the same resistance and arranged without distinguishing industrial classification. The fishery industry, which was dependent on fishing boats was different from others and was subsequently removed from this analysis.

Tables 4 and 5 show the data for number of answers, beta distribution parameters, and average and variance of the damage ratio,  $y(\%)$ , of the building and facilities, for the different levels of tsunami intensities. If the tsunami level is 0 (there was no inundation), it can be concluded that there was no physical damage to the building and facilities. In addition, as the number of answers of tsunami intensity levels 2 and 3 are limited, their answers were influenced by answers of previous and next industry level. For example of tsunami intensity level 2 in Table 4, the counter of origin level 2 is 4. The level 1 and 3 were adjusted due to level 2 and average and variance were calculated. As the result of Tables 4 and 5, the damage rate increases according to tsunami intensity level and the variance of level 2 and 3 show high values. Thus, as it can be seen in the increment of 0% to 100%, the damage rate distribution curve has two peaks.

**Table 4.** Parameter of building damage rate,  $y(\%)$ , due to the tsunami intensity level.

Tsunami intensity	Number of	Average	Variance	Beta distribution parameter	
level $x$	answers $N$	$E(y)$	$Var(y)$	$q$	$r$
1	65	3.84	88.14	0.13	3.07
2	25	60	2062.5	0.1	0.07
3	36	53.57	922.6	0.91	0.78
4	130	63.46	1561.54	0.31	0.18

**Table 5.** Parameter of facilities damage rate,  $y(\%)$ , due to the tsunami intensity level.

Tsunami intensity	Number of	Average	Variance	Beta distribution parameter	
level $x$	answers $N$	$E(y)$	$Var(y)$	$q$	$r$
1	69	6.25	468.75	0.02	0.23
2	23	62.5	2291.67	0.02	0.01
3	92	46.25	1072.92	0.51	0.74
4	76	55.77	849.36	1.06	0.84

Furthermore, Tables 6 and 7. show the results of occurrence probability of buildings and facilities, using the beta distribution's parameters. For the damage states A and B, the occurrence probability increases as the tsunami intensity level becomes large.

**Table 6.** Occurrence probability of building damage.

DS	Tsunami intensity level x (inundation height h (m))				
	0	1	2	3	4
	H = 0	0 < h ≤ 1	1 < h ≤ 2	2 < h ≤ 3	H > 3
A	0%	0%	36%	44%	67%
B	0%	1%	15%	18%	9%
C	0%	9%	11%	13%	6%
D	0%	41%	14%	13%	7%
E	100%	49%	24%	12%	11%

**Table 7.** Occurrence probability of facility damage.

DS	Tsunami intensity level x (inundation height h (m))				
	0	1	2	3	4
	H = 0	0 < h ≤ 1	1 < h ≤ 2	2 < h ≤ 3	h > 3
A	0%	6%	54%	64%	80%
B	0%	6%	2%	11%	12%
C	0%	6%	1%	7%	5%
D	0%	10%	2%	8%	3%
E	100%	71%	42%	11%	1%

The parameters of the restoration density function were then estimated at every damage state of the institution. Even if it was past nine months since the first investigation since the tsunami (at the end of September 2005), most fishery industries were still being restored or had not restored yet. Thus, answers from the fishery industries were removed from the analyses as mentioned above. Five of 29 answers (building/facilities or both) had not been restored by the time of the survey. The government announced that the area within a 100 m buffer zone from the shore would not be supported. This regulation would also hamper quick restoration. Here, the restoration completion of the above building/facilities is considered to have taken 360 days.

In the Tables 8 and 9, the parameters of the restoration density function of each damage state for buildings and facilities are presented respectively using the gamma distribution. The damage state D of Table 9. is estimated from relations with restoration days of other damage states. As the damage becomes more severe, average of the restoration days would get longer.

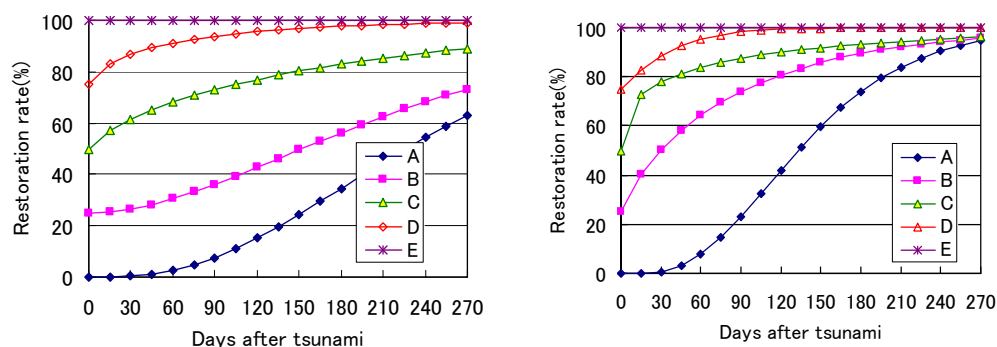
**Table 8.** Parameters of the restoration density function of damage states for buildings.

Tsunami intensity	Number of	Average	Variance	Gamma distribution parameter	
level DS	answers N	$E(t)$	$Var(t)$	k	$\nu$
A	14	222.4	10435.8	3.493	0.014
B	3	240.7	25665.2	2.212	0.009
C	2	142.2	26480.8	0.711	0.004
D	11	55.6	5005.2	0.589	0.009

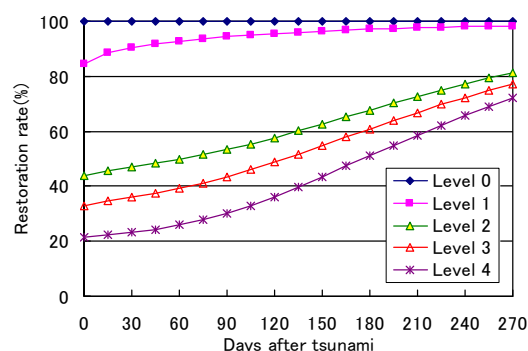
**Table 9.** Parameters of the restoration density function of damage states for facilities.

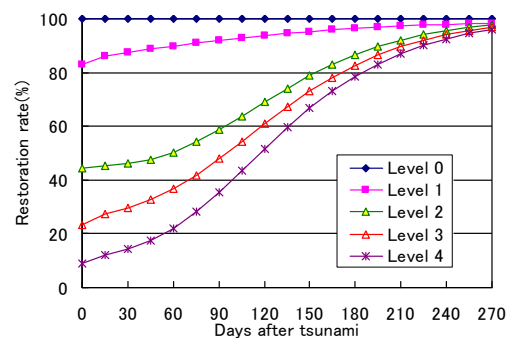
Tsunami intensity	Number of	Average	Variance	Gamma distribution parameter	
Level DS	answers $N$	$E(t)$	$Var(t)$	$k$	$\nu$
A	19	168.3	7765.2	4.321	0.03
B	4	114.6	15966.1	0.796	0.009
C	5	77.8	15606.3	0.311	0.004
D	3	55.6	5005.2	1.196	0.033

Furthermore, the conditional restoration curves of each damage state according to equation (7) are shown in Figures 9 and 10. If the building is in damage state A or B, it dramatically slows down the restoration curve; on the other hand, the restoration curve becomes convex if it is in another damage state. This means that if the industrial building and facilities were completely destroyed or washed away by tsunami wave, they needed more time for restoration because of the cost and different construction method of restoration. Moreover, the damage state A of the facilities draws a concave restoration process, but other damage states show fast restoration.

**Figure 9.** Restoration process of buildings. **Figure 10.** Restoration process of facilities.

The restoration of buildings and facilities due to the tsunami intensity level, which is calculated from the occurrence probability of the damage state, are presented in Figures 11 and 12. Concerning the restoration of buildings, there is a gap between the tsunami intensity less than level 1 and more than 2. If the tsunami intensity level is more than level 2, the occurrence probability of damage state A becomes higher. Therefore, the restoration process decreases.

**Figure 11.** Restoration rate of buildings according to tsunami intensity levels.

**Figure 12.** Restoration rate of facilities according to tsunami intensity levels.

#### 4. Other Factors Affecting the Restoration

In Sections 2 and 3, the restoration process in business companies in terms of facilities and lifelines after the tsunami was theoretically studied using the statistical analyses of distribution functions. We found that the actual restoration rate was almost less than the restoration rate calculated by estimation. In this section, we discuss about other possible factors that may affect the restoration process.

##### 4.1. Financial Support

At the time of tsunami, most of the industries that were subsequently damaged had financial problems. Many of the industries were not covered by insurance for tsunami or floods. As this was the first of such incidents in Sri Lanka, industries were surprised and not expecting a tsunami event. Due to the priority given to the human live saving and health-care facilities, the government was unable to provide financial support to the industrial restoration. Some Non-Governmental Organizations (NGO) and foreign governments provided some help to industries such as the fisheries. However, due to the modern nature of the some facilities, traditional fishermen could not cope with the operational state. For example, the fishery boats provided by European Union countries were not suitable for the rough seas around Sri Lanka.

##### 4.2. Qualified Employees

After the tsunami, most employees were affected and had to be moved to shelters and relief camps. Some employees were killed and injured by the tsunami event. Company workers were in a dire mental status and the companies were shut down.

##### 4.3. Transportation and delivery

The Galle main road, which is located parallel to the shoreline, was completely damaged by the tsunami. This took a couple of weeks to reconnect Galle to other areas, specially the capital of Colombo. The port of Galle and Hambantota also had heavy damage. The railway was damaged running parallel to the highway. One operational train was hit by the waves killing more than 1,000 people. There were several main bridges of highway and railway destroyed by the event, disconnecting the south from the capital Colombo. The coastal region of the Ampara district also faced severe damages with the tsunami tide hitting 4.5 km into the country. The rescue teams and workers reached

the site through optional ways taking more time to rescue and to do reconstruction works. The manufacturing and transportation of fishery products to other areas were completely shut down due to the consequences. Damage to the transportation facility heavily affected the cement industry, industrial facilities and fishing communities. The Galle port, which is the most important port of Southern Sri Lanka, was suffered considerable damage due to subsidence. The loss of the port facility prevented relief supplies and facilities such as equipment from reaching by ships and transport industrial products. Other small ports on the south coast of Sri Lanka, such as the dock at Hambantota, were also damaged yet still able to accommodate small ships.

#### *4.4. Drainage System*

The storm drainage system covering entire Galle district consists of several long channels that were made many years ago during the Spanish colonial period. This drainage system suffered extensively from the tsunami strike as the slabs covering the channels were broken, lifted and dislocated. The mud and debris then filled the channels, preventing drainage of the flood water and debris.

#### *4.5. Water Supply From Wells*

Most places use the water pumped out from wells in Ampara and Galle districts although several urban parts, including the industrial area, used a pipeline water supply through the Bope-Poddala water supply system (WSS). The distribution pipelines supplying water to many parts of the Ampara and Galle districts were also damaged due to the collapse in bridges holding pipelines, collapse caused by the intensity of tsunami waves and impact by debris and large objects such as boats.

#### *4.6. Effect on Structures*

The industrial structures struck by the tsunami wave impacted with a run-up height of 1 m to maximum of 5 m. The tsunami waves applied force on structures can be considered in several forms including hydrodynamic pressure, buoyancy, uplift, scour and impact by debris carried by water. Engineered and non-engineered structures of industries in the tsunami affected areas of East and Southern Sri Lanka may be classified into three general categories based on their observed performance. These categories are as follows.

##### *4.6.1. Industries with Wood Houses with Tile or Corrugated Steel Sheet Roof*

In our survey, we found 15 of 52 buildings in industrial were classified into typical low cost and affordable building in the damaged area. The buildings were constructed with a timber frames made up of columns and beams supporting wood joists. The roof is covered with clay tile or thin corrugated steel sheets or coconut leaves. These buildings were completely disintegrated when swept by the tsunami. The construction material was broken down to small pieces of debris easily and it affected the instruments such as machines inside of the industries.

#### 4.6.2. Non-Engineered Concrete Construction

Non-engineered concrete frame building structures with masonry infill are common in Sri Lanka. The columns of these building are substandard in construction sections are lightly reinforced with plain bars. These columns were suffered significant damage from the tsunami waves. Their flexural capacity is significantly below the applied bending forces due to tsunami wave run-up. Flexural failure half way up the column height occurred due to the deficient column section capacity especially in the building that were close to the ashore. The thin clay brick or block masonry walls are about 60 mm thick [2], these walls were suffered out of-plane punching shear failure due to the tsunami. Many of these buildings were severely damaged or collapsed. Once the walls failed, the tsunami waves washed away all the contents of the building.

#### 4.6.3. Engineered Reinforced Concrete Construction

The engineered and the well-constructed reinforced concrete frame structures could survive the tsunami with minor damage in southern Sri Lanka and survived height tsunami run-up levels close to the shore. Damage to these buildings was limited to some cracks in their walls. Though in terms of the contents of the buildings all inside facilities and equipment including stores covered by water wave, there were everything on the first floor was swept away or damaged. However, in the Eastern side we found many concrete structures footprints that completely damaged and washed away by the waves. There for it shows a lower recovery process in Ampara area than Galle.

#### 4.7. 100 Meter Buffer Zone Restriction

The Sri Lankan government prohibited new construction within a 100 m distance from the shoreline. The overwhelming majority of more than 500,000 people displaced lived in 100 m of the coast when the tsunami struck [2]. While privately owned land within the 100 m buffer zone rule is permanently prevented. This means hundreds of small industries such as fishing communities and others who lived and worked on or near the shore are finding it difficult to recover. Hotels, retail and other businesses related to tourism were not supported by the government or any other organizations. Not only did the lifeline systems not recover for the industries in 100 m buffer zone, but there was also no financial support. Seafood prices decreased because of fears that fish may have fed on thousands of human corpses washed into the sea by the tsunami.

#### 4.8. Tourists Fear For Visiting

Tourism industries, manufacturing industries and retail trade did not completely restore at the time of the survey, nine months after the tsunami. Most of them were showing the restoration rate around 60%–70%. Hotels and restaurants have started operating in the 100 m buffer zone too. However, there were still few foreign tourists, but employees expect it to recover soon when the tourist season starts at the end of the year. Even if the industry does not have physical damage by tsunami, sales dropped at a large scale, when the number of tourists decreased.



#### 4.9. Customers

Fishery industries were the most affected industries by the tsunami. Some fishermen communities and their families lost their lives and their houses, adding to that the damages to their fishing boats and equipment. Furthermore, fishing boats or nets were not renewed by government or NGO groups. In addition, there were severe decreases in fish consumption forcing them to stop catching fish for several months. Some fishermen were also engaged in marine capture fishing and possessed smaller boats.

#### 4.10. Effect of Salty Water

Agricultural lands were completely damaged across all estuaries, leading up to 4–5 km away from the shoreline. Many farmers who own rice fields and fishponds faced damages, affecting their dual source of income. Most of the Agriculture firms in the coastal region have been affected by salty water. The south part of Sri Lanka is famous for rice, cinnamon, coconuts and other vegetable cultivation. Most agricultural sectors have been washed away from the 100 m coastal zone, except the coconuts. Coconuts trees have not been damaged but have been indirectly affected by salty water from the tsunami. The damages to the agriculture sector were mainly confined to the destruction of standing crops in paddy and other crop fields and home gardens along the entire coastal belt, and the washing away of parts of cashew and betel cultivations along the south coast. Entry of seawater into productive fields has induced high levels of soil salinity. Consequently, farmers will not be able to grow crops in those soils for about 3–4 years till the salinity is naturally flushed away by seasonal monsoon rains. Agricultural infrastructures including a large number of store buildings were also damaged.

The restoration process of the business affects the residual function of societies in varying degree. The ATC-13 (1985) provides the methodology for evaluation of the impact of lifeline failures on loss of function of particular facilities, and also it establishes an index called the importance factor. The important factors are based on experts' judgment and prescribed for the conditions in California, United States only. Kajitani [8] *et al.* (2005) proposed the residual factor from the questionnaire survey to Japanese business companies for the residual degree of business due to lifeline interruption. These factors vary depending on the area, industry and disaster type. The importance factors of lifeline systems are examined based on the result of survey in Sri Lanka, referring to the methodology of ATC-13 by Kuwata [9] *et al.* (2006). It is very important to identify of the importance factors to estimate the real recovery process.

Damage assessment and prevention studies were carried out by Liu *et al* [10] and the results stressed the importance of education on disaster management. Goff *et al* [11] also analyzed tsunami run-up height, inundation distance, morphological changes, and sedimentary characteristics of deposits along the south west and east cost of Sri Lanka. Moreover tsunami impact in Maldives and cyclone storm in Myanmar were investigated by Fritz *et al* [12,13] through field surveys.

### 5. Conclusions

The 26 December 2004 Sumatra Earthquake-Tsunami event has provided a unique and valuable opportunity to evaluate the performance of various building, facilities and lifeline systems during the

tsunami wave strike. There are essential and meaningful observations to be made concerning the response of buildings due to the tsunami forces. This will help prepare a wide area of research to develop and improve the mitigation procedure. The restoration process of business in terms of buildings, facilities and lifelines, on the other hand, have shown to be especially critical areas of research interest. In this study, we investigated a method to evaluate the functionality of the business companies after the tsunami disaster. This method has several modules, such as damage estimation of business bases (building, facilities and lifeline) caused by tsunami intensity, restoration ratio-to-time model for business base, and the functionality of the business introduced to facility restoration and its influence on the business. The tsunami impact on industries and its subsequent restoration process are studied based on an interview survey in southern Sri Lanka after the tsunami, and the survey results are applied to the proposed model. The results of this study can be summarized as follows;

- (1) From the actual data of the field survey, it has turned out that electricity and water supply were almost completely stopped, at the time of the tsunami, except agriculture, which is located far from the shoreline.
- (2) In terms of damage and the restoration rate, because of lack of financial support, the fishery industries had the most severe damages and have not recovered completely, even nine months after the tsunami to the date the survey was being held.
- (3) In terms of extensive damage to buildings and equipment, their restoration rate grows slower in the first few months.
- (4) The business restoration under the tsunami inundation height of 2 m depends mostly on the business facilities restoration than the lifeline restoration.
- (5) The lifeline interruption affects the business continuity more than compared with previous studies. It can be concluded that because of the increasing interrelation of business base its importance factor has become great. The Ceylon Electricity Board (CEB) made immediate repairs to restore power supply to the affected areas. No restoration of damaged power supplies is being carried out within the buffer zone.

The restoration curve and importance factor obtained in this study is based on the limited number of responses; however, the applicability of parameters is required to be examined further.

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## Conflict of Interest

The authors declare no conflict of interest.

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