Study of an empirical model to evaluate tsunami inundation area

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Introduction

Many lives became victims of tsunami in Tohoku Earthquake. Although damaged areas due to tsunami had been anticipated before the earthquake, they are based on numerical simulations seeking tsunami height, inundated areas and inundation depth in case of specific scenario earthquake occurring. While these numerical simulations are elaborate study, it requires large amount of efforts to model geography and structures along coastlines, and sequential calculations in general. Also, it is not easy to apply constructed model configuration to various other scenario.

This study is motivated to put tsunami phenomena to a simple empirical model as a heuristic for future disaster reduction. The model is a regression model to predict inundation areas with three explanatory variables, tsunami height at coastline, distance from coast line and ground level of an objective point. Data are collected by Tohoku Earthquake Joint Survey Group[1]. The model is validated by comparing predicted inundation areas to actual inundated area in Tohoku Earthquake and simulation results of Nankai-trough earthquake model by Cabinet Office, Government of Japan published in summer 2012.

Model

1. Regression Model

Given tsunami surge is losing its energy due to frictions and air resistance with being transformed to potential energy, the model can be expressed by the function in (1) where potential energy and loss energy are assumed to be a function of ground level and distance from coastline, respectively. In inundation areas, lower bound of z – h is zero.

$$z = H + \alpha h + \beta L \qquad (1)$$

where, z : run-up height (m)
H : tsunami height at coastline (m)
h : ground level (m)
L : distance from coastline (m)
α, β : regression coefficient

2. Data

Run-up height, z, and distance from coastline, L, are collected data, ranked A or B in data confidence, by Tohoku Earthquake Joint Survey Group ranging from coastal area of Rokkasyo Village, Aomori Prefecture to Shirako Town, Chiba Prefecture. Ground level, h, is set to be equal to z by assuming ground level is equal to run-up height.

By assuming inundation height at measuring points located within 50m from coastline approximately equal to tsunami height at coastline, Tsunami heights along coastline are set continuously by linear-interpolation of those data.

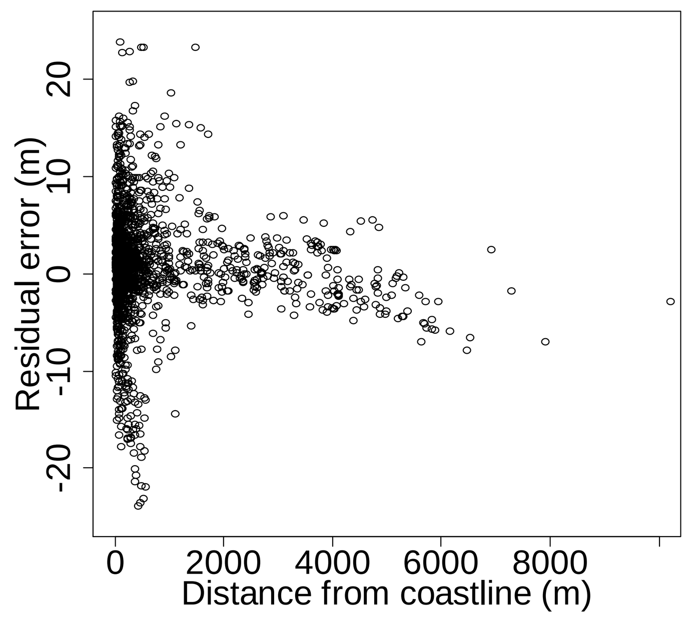


Fig.1 Distance from coastline and residuals

3. Regression Analysis

Regression analysis yields following model in (2)

$$z = H + 0.2359h - 0.001604L \qquad (2)$$

Residual standard deviation is estimated by 5.39m, which is extremely large at points near coastline. However, it becomes smaller with increasing distance from coastline. (See Fig.1)

Verification

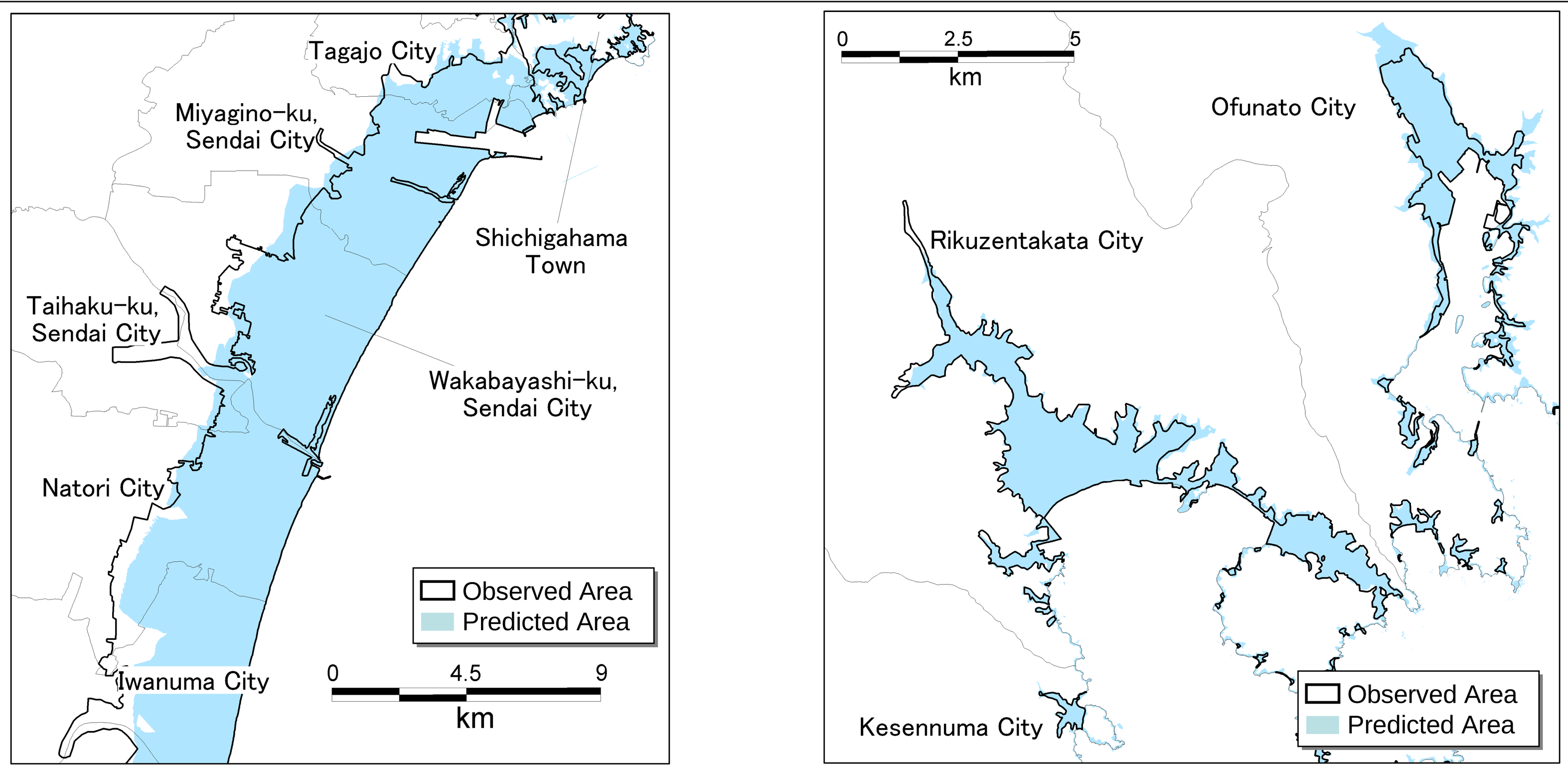
Predicted inundation areas by the model are compared with inundated areas in Tohoku Earthquake and simulation results of Nankai-trough earthquake model (M9.0).

1. The 2011 off the Pacific coast Tohoku Earthquake and Tsunami

Table.1 shows comparison of actual inundated area with predicted inundation area by municipal administration unit. Fig.2 shows actual and predicted inundated area in Sendai Plain, Rikuzentakada City and Ofunato City.

Table.1 Comparison with the actual inundation area and predicted area in Tohoku Earthquake.

	observed (km^2)	predicted (km^2)	ratio		observed (km^2)	predicted (km^2)	ratio		observed (km^2)	predicted (km^2)	ratio
Aomori Pref.				**Miyagi Pref.**				**Fukushima Pref.**			
Rokkasho Village	5	18	3.60	Shiogama City	6	3	0.50	Okuma Town	2	5	2.50
Oirase Town	3	4	1.33	Shichigahama Town	5	6	1.20	Tomioka City	1	5	5.00
Misawa City	6	20	3.33	Tagajo City	6	6	1.00	Naraha Town	3	5	1.67
Hachinohe City	9	15	1.67	Miyagino-Ku, Sendai City	20	22	1.10	Hirono Town	2	3	1.50
Hashikami Town	0.5	0.5	1.00	Wakabayashi-Ku, Sendai City	29	30	1.03	Iwaki City	15	32	2.13
Iwate Pref.				Taihaku-Ku, Sendai City	2	3	1.50	**Ibaragi Pref.**			
Hirono Town	1	2	2.00	Natori City	27	25	0.93	Kita-Ibaragi City	3	5	1.67
Kuji City	4	8	2.00	Iwanuma City	29	26	0.90	Takahagi City	1	2	2.00
Noda Village	2	5	2.50	Watari Town	35	28	0.80	Hitachi City	4	3	0.75
Fudai Village	1	3	3.00	Yamamoto Town	24	23	0.96	Tokai Village	3	4	1.33
Tanohata Village	1	3	3.00	**Fukushima Pref.**				Hitachinaka City	3	2	0.67
Iwaizumi Touwn	1	7	7.00	Shinchi Town	11	10	0.91	Oarai Town	2	2	1.00
Miyako City	10	27	2.70	Soma City	29	28	0.97	Hokota City	2	2	1.00
Yamada Town	5	8	1.60	Minami-Soma City	39	35	0.90	Kashima City	3	8	2.67
Otsuchi Town	4	7	1.75	Namie Town	6	10	1.67	Kamisu City	3	18	6.00
Kamaishi City	7	13	1.86	Futaba Town	3	7	2.33	**Chiba Pref.**			
Ofunato City	8	16	2.00	Okuma Town	2	5	2.50	Choshi City	1	2	2.00
Rikuzentakata City	13	15	1.15	Tomioka City	1	5	5.00	Asahi City	3	9	3.00
Miyagi Pref.				Naraha Town	3	5	1.67	Sosa City	1	11	11.00
Kesennuma City	18	32	1.78	Hirono Town	2	3	1.50	Yokoshiba-Hikari Town	1	5	5.00
Minami-Sanriku Town	10	14	1.40	Iwaki City	15	32	2.13	Sammu City	6	12	2.00
Onagawa Town	3	5	1.67	Shinchi Town	11	10	0.91	Kujukuri Town	2	9	4.50
Ishinomaki City	73	50	0.68	Soma City	29	28	0.97	Oamishirasato Town	0.5	5	10.00
Higashi-matsushima City	37	36	0.97	Minami-Soma City	39	35	0.90	Shirako Town	1	8	8.00
Matsushima Town	2	1	0.50	Namie Town	6	10	1.67				
Rifu Town	0.5	0.5	1.00	Futaba Town	3	7	2.33	**total**	668.5	869.0	1.30



(a) Sendai Plain (b) Rikuzentakata City, Ofunato City

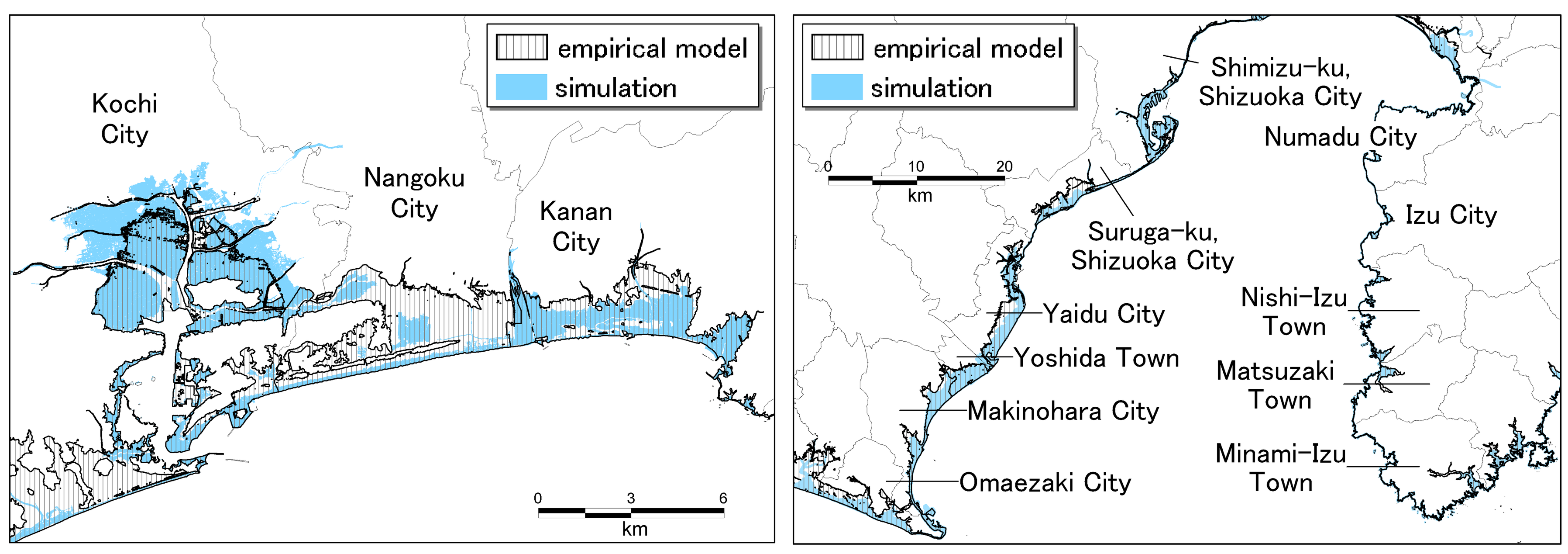
Fig.2 Comparison inundation area of predicted area with observed area

2. Nankai-trough earthquake model by Cabinet Office, Government of Japan (2012)

Table.2 shows comparison of inundation areas by the model with those of the government study by the Cabinet Office in 2012 for coastal areas in Shizuoka, Aichi, Mie, Wakayama, Tokushima and Kochi. There are 11 cases of inundation area in Government study, among which Case 1 is chosen. Also, the condition that bank revetment is broken 3 minutes after earthquake, is selected for comparison.

Table.2 Comparison the inundation area of the empirical model with the simulation model by the Cabinet Office in 2012 (unit : km^2)

※ The government study by Cabinet Office (2012)	simulation※	empirical model	ratio		simulation※	empirical model	ratio		simulation※	empirical model	ratio
Shizuoka Pref.				**Aichi Pref.**				**Wakayama Pref.**			
Atami City	0.5	0.8	1.64	Minami-Chita Town	4.6	6.5	1.41	Minabe Town	1.8	4.0	2.28
Ito City	0.8	1.5	1.84	Tokoname City	6.2	12.9	2.07	Inami Town	1.5	2.6	1.75
Higashi-Izu Town	0.7	0.9	1.18	Chita City	0.7	3.4	5.09	Gobo City	4.6	9.0	1.93
Kawadu Town	0.8	1.3	1.68	Tokai City	3.0	7.6	2.57	Mihama Town	2.5	5.9	2.33
Shimoda City	5.0	7.8	1.57	Midori-ku, Nagoya City	1.9	0.4	0.23	Hidaka Town	1.1	2.9	2.67
Minami-Izu Town	3.5	5.4	1.53	Minato-ku, Nagoya City	28.9	31.4	1.09	Yura Town	1.7	2.0	1.15
Matsuzaki Town	1.9	3.1	1.62	Minami=ku, Nagoya City	10.7	6.0	0.56	Hirokawa Town	1.8	2.1	1.14
Nishi-Izu Town	2.7	3.1	1.17	Atsuta-ku, Nagoya City	3.7	0.6	0.15	Yuasa Town	1.2	1.6	1.32
Izu City	1.3	1.4	1.13	Nakagawa-ku, Nagoya City	14.4	0.7	0.05	Arita City	2.2	3.6	1.66
Numadu City	8.1	21.9	2.71	Tobishima Village	2.6	11.1	4.19	Kainan City	4.8	6.0	1.25
Fuji City	3.5	15.6	4.50	Yatomi City	4.7	9.6	2.06	Wakayama City	19.9	19.3	0.97
Shimizu-ku, Shizuoka City	13.7	17.5	1.28	Mizuho-ku, Nagoya City	1.1	0.0	0.00	**Tokushima Pref.**			
Suruga-ku, Shizuoka City	4.7	12.8	2.70	Nakamura-ku, Nagoya City	0.6	0.0	0.00	Naruto City	16.1	14.3	0.89
Yaidu City	14.3	21.4	1.49	Kanie Town	5.2	0.0	0.00	Matsushige Town	9.1	4.8	0.53
Yoshida Town	7.3	8.6	1.18	**Mie Pref.**				Tokushima City	32.0	19.1	0.60
Makinohara City	11.2	16.7	1.50	Kisosaki Town	1.5	4.2	2.86	Komatsujima City	18.8	14.9	0.79
Omaezaki City	9.9	19.0	1.92	Kuwana City	3.3	7.2	2.22	Anan City	25.8	28.5	1.10
Kakegawa City	6.1	26.4	4.33	Kawagoe Town	2.1	6.2	3.02	Minami Town	2.1	3.4	1.59
Fukuroi City	2.0	20.6	10.55	Yokkaichi City	16.3	23.9	1.46	Mugi Town	1.2	1.8	1.51
Iwata City	17.4	44.9	2.57	Suzuka City	7.0	14.7	2.10	Kaiyo Town	3.3	5.8	1.73
Minami-ku, Hamamatsu City	23.9	42.9	1.79	Tsu City	36.8	38.1	1.04	**Kochi Pref.**			
Higashi-ku, Hamamatsu City	0.0	1.4	－	Matsuzaka City	38.3	34.3	0.89	Toyo Town	1.6	2.8	1.72
Naka-ku, Hamamatsu City	3.4	11.3	3.32	Meiwa City	13.0	14.5	1.12	Muroto City	3.4	5.5	1.64
Nishi-ku, Hamamatsu City	19.1	18.3	0.96	Ise City	39.4	28.0	0.71	Nahari Town	1.3	1.8	1.36
Kita-ku, Hamamatsu City	0.9	0.9	1.01	Toba City	8.5	11.7	1.38	Tano Town	1.0	1.3	1.27
Kosai City	8.0	7.2	0.90	Shima City	22.5	28.1	1.25	Yasuda Town	0.8	2.0	2.60
Aichi Pref.				Minami-Ise Town	12.5	16.6	1.32	Aki City	5.7	9.3	1.65
Tahara City	33.2	44.2	1.33	Taiki Town	0.7	1.2	1.60	Geisei Village	0.4	2.1	5.61
Toyohashi City	25.7	27.9	1.09	Kihoku Town	10.0	11.7	1.17	Konan City	7.5	10.9	1.46
Toyokawa City	2.7	3.9	1.48	Owase City	5.9	6.8	1.16	Nangoku City	3.4	13.3	3.93
Gamagori City	3.3	5.8	1.77	Kumano City	2.2	5.6	2.53	Kochi City	26.8	35.5	1.32
Hazu Town	1.0	1.7	1.69	Mihama Town	2.4	6.3	2.62	Tosa City	3.5	5.7	1.64
Kira Town	7.9	9.1	1.15	Kiho Town	2.3	3.3	1.48	Susaki City	11.2	12.2	1.08
Isshiki Town	15.3	14.6	0.95	**Wakayama Pref.**				Naka-Tosa Town	3.6	4.9	1.38
Hekinan City	7.7	9.6	1.25	Shingu City	1.7	4.9	2.96	Shimanto Town	2.4	3.1	1.29
Takahama City	1.4	2.3	1.67	Nachi-Katsuura Town	6.2	7.7	1.26	Kuroshio Town	8.9	11.1	1.24
Kariya City	2.9	1.3	0.46	Taiji Town	1.0	1.4	1.36	Shimanto City	6.0	12.5	2.06
Higashiura Town	5.1	3.7	0.73	Kushimoto Town	8.4	10.4	1.24	Tosashimizu City	10.5	11.9	1.14
Handa Town	5.5	9.5	1.73	Susami Town	2.1	2.9	1.33	Otsuki Town	1.7	2.7	1.54
Taketoyo Town	1.5	4.0	2.69	Shirahama Town	5.3	9.5	1.79	Sukumo City	10.6	10.9	1.03
Mihama Town	1.9	5.2	2.76	Tanabe City	5.2	6.7	1.28	**Total**	890.0	1182.3	1.33



(a) Around Kochi City (b) Around Shizuoka City

Fig.3 Comparison inundation area of the empirical model with the simulation model by the Cabinet Office in 2012

Conclusion

1. Empirical model to predict Tsunami inundation area is developed by using data of Tohoku Earthquake Joint Survey Group.
2. In a comparison with actual inundated areas in Tohoku Earthquake, the model generally replicates inundated area where Tsunami surge linearly from the origin while in particular geography there are gaps between predicted and actual inundated area.
3. In a comparison with Nankai-trough earthquake model (M9.0) by Cabinet Office, Government of Japan, targeting Pacific coastal area from Shizuoka to Kochi, the model predicts larger inundation areas to a certain extent than those of government study. Nonetheless, the model is still deemed to generally replicate inundation area except for areas of particular geography as gaps are laid within 0.5 to 2 times of predicted area.

Reference 1) The 2011 Tohoku Earthquake Tsunami Joint Survey Group : http://www.coastal.jp/tsunami2011/