Tsunami flood risk prediction using a neural network

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Abstract

The 2011 earthquake off the Pacific coast of Tohoku (known as the "Sendai Earthquake") occurred on March 11, 2011 and severely damaged the Tohoku coastal area facing the Pacific Ocean. The number of casualties in the Sendai earthquake, as of August 9, 2013, included 15,883 deaths, with 2656 people still missing. The cause of death for nearly 90% of those killed was drowning because many people were swept away by the resulting tsunami. Focusing on the area inundated by the current induced by the tsunami, even in adjacent areas, a difference was apparent in the inundation distances from the coastline. Clarification of the reason for this difference is necessary for city planning when considering disaster reduction in the future.

In this study, we first clarify the factors that promote inundation in the Sendai area, excluding the effects from small ground undulations, by using a neural network that has been used to solve a complex relationship with each of the factors. Based on the results of the factors that promote inundation, we have selected Iwata City in the Shizuoka Prefecture as a study area because its region is similar to the Sendai area that has flat level ground and also it is likely to be struck by a tsunami generated from any Tokai, Tounankai, and Nankai type earthquake. In our risk prediction, we estimate the risk for tsunami damage in Iwata City and propose measures to reduce this damage.
Keywords: tsunami, neural network, "inundation factors", risk analysis.

1 Introduction

The Great East Japan Earthquake occurred on March 11, 2011, and the coastal zones along the Pacific Ocean in the Tohoku area were inundated by the current induced by the resulting tsunami. There was extensive damage and loss of life in

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an instant; however, a difference was seen in the inundation area away from the coastline. In cases of extreme inundation in the Sendai plain, inland areas 5 km from the coastline were flooded. Although it is assumed that objects along the coastline, including houses, roads, rivers, cultivated land and coastal forestation inhibited the tsunami-induced current, the effect of these objects on inhibiting this current has yet to be clarified.

In this study, based on the damage after the Great East Japan Earthquake, the factors that inhibit or promote inundation from tsunami-induced currents were investigated using a neural network. From the results, we estimate the potential damage caused by a tsunami from the Tokai earthquake, which is predicted to occur in the near future.

2 Damage from tsunami due to the Great East Japan Earthquake

The Tohoku area along the coast facing the Pacific Ocean was severely damaged by the tsunami caused by the Great East Japan Earthquake. The wave height of the tsunami was reported to be between 2 and 21 m based on field investigations by numerous researchers [2]. Moreover, as shown in Figure 1, the value of the maximum run-up height was reported to reach nearly 40 m [2]. Approximately 90% of the casualties from the Great East Japan Earthquake were a result of the tsunami [3]. Figure 2 shows examples of damage caused by the tsunami.

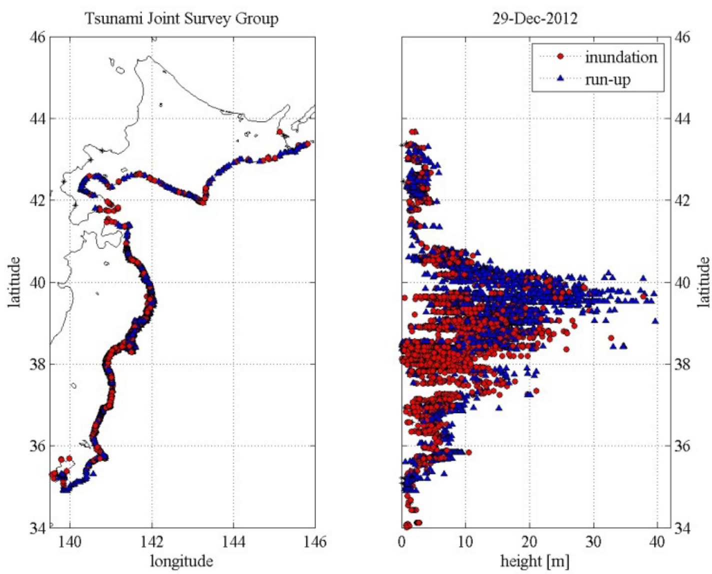


Figure 1: Tsunami wave height and run-up height measured by the 2011 Tohoku Earthquake Tsunami Joint Survey (TTJS) Group [3].

(a) Damaged building in Onagawa City

(b) Flotsam in Ishinomaki City

(c) Damaged hotel in Taro City

(d) Collapsed dike in Taro City

Figure 2: Examples of damage caused by the tsunami.

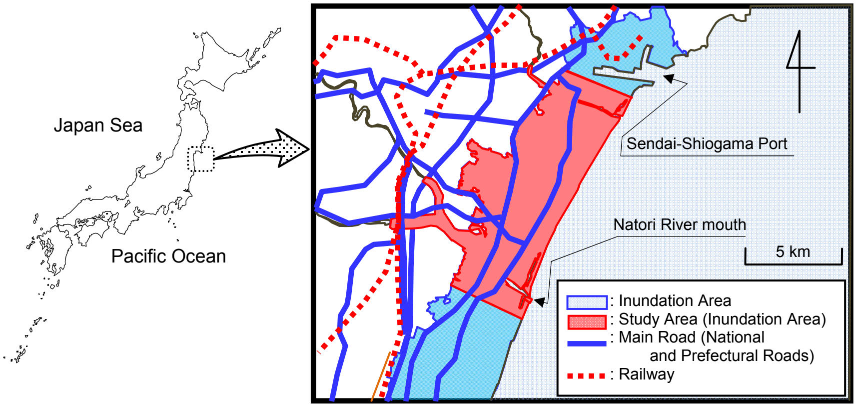


Figure 3: Map of the study area (Sendai plain).

Figure 3 shows the area in the Sendai plain inundated by the tsunami-induced current. The maximum distance of the inundation area from the coastline was reported to be approximately 5 km. However, as shown in Figure 3, there is a difference in the distances of the inundation area from the coastline, even if the area is primarily flat. It is assumed that the inundation area is affected by objects on the ground (predictor variables).

3 Methodology

3.1 Estimation of factors that promote inundation

To investigate the effect of predictor variables, we selected a flat area of land – the Sendai plain. As shown in Figure 4, 60 survey lines perpendicular to the coastline were set up at 200 m intervals. Along each survey line, the width of the beach, the width of coastal forestation, the width of fields including the ground (e.g., cultivated land), roads and parks, the width of big buildings such as factories and warehouses, the width of residential areas, the width of rivers perpendicular to the coastline, the width of rivers parallel to the coastline, the width of lakes and ponds, and the wave height were selected as predictor

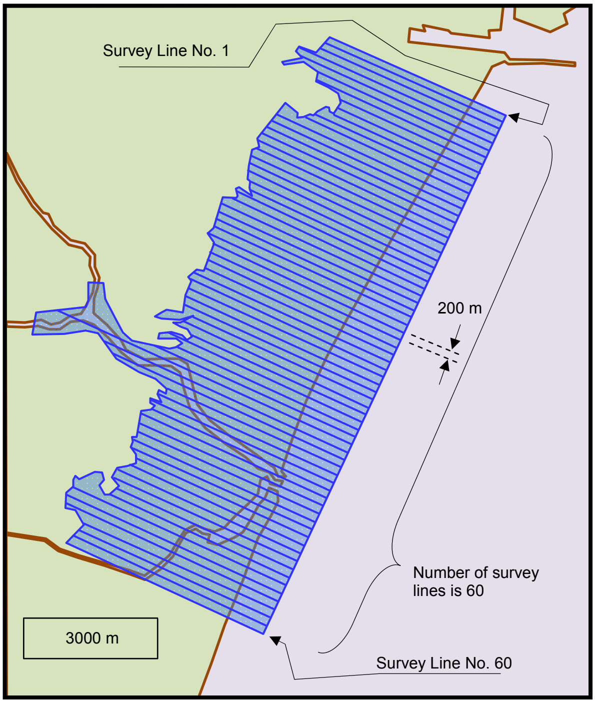


Figure 4: Survey lines in study area.

(a) Beach

(b) Coastal forestation

(c) Field (cultivated land)

(d) Big building

(e) Residential area

(f) River (canal)

Figure 5: Examples of predictor variables.

variables to perform the analysis using a neural network. Figure 5 shows examples of these objects. As shown in Figure 6, "the rivers perpendicular to the coastline" were defined as ranging from 0 to 45° from the survey line, and "the rivers parallel to the coastline" were defined as ranging from 46 to 90° from the survey line. The values of the predictor variables were measured as length across the survey line, and the values of the objective variable were equal to the inundation distance from the coastline along the survey line, as shown in Figure 7. The degrees of importance of the predictor variables (the factors that promote inundation) against the objective variable were estimated a using neural network. A neural network is a computational model based on the structure and functions of biological neural networks. Information that flows through the network affects the structure of the neural network because it changes, or learns, based on inputs and outputs. Neural networks are considered nonlinear statistical data modeling tools where the complex relationships between inputs and outputs are modeled or patterns are found. Here, we used an IBM software package, SPSS Neural Networks V 20, to create the hierarchical neural network.

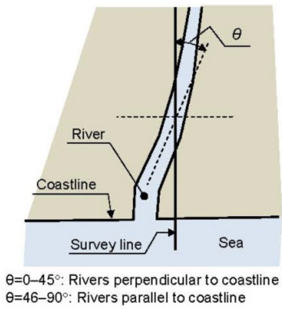
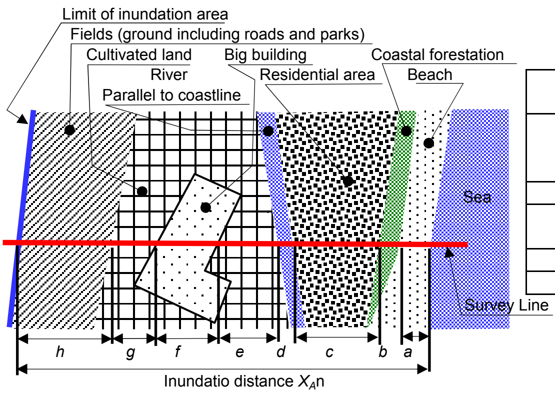


Figure 6: Definition of rivers perpendicular or parallel to the coastline.



Predictor variables	Measured distance (m)
Fields (grounds including roads and parks)	*h*
Cultivated land	*e*+*g*
River parallel to coastline	*d*
Big buildings	*f*
Coastal forestation	*b*

Figure 7: Example of method for measuring predictor variables.

3.2 Risk analysis for future tsunami

We conducted a risk analysis on the inundation for a future tsunami caused by the Tokai, Tounankai, and Nankai type earthquake. We selected the coast of Iwata City in Shizuoka Prefecture facing the Pacific Ocean as the study area, as shown in Figure 8. A broad plain stretches out from coastline to inland, similar to the Sendai plain. It is estimated that a large earthquake will strike this area in the future, and the resulting tsunami will likely inundate towns along the coast. We divided this area into nine regions, each 3000 m long by 500 m wide, as shown in Figure 8. The component ratio of land use was surveyed using aerial photographs and a field survey. We then assessed the degree of risk for each region.

Figure 8: Test sites for tsunami risk analysis (Iwata City in Shizuoka Prefecture).

4 Results of analysis

4.1 Factors that promote inundation

The objective variable and predictor variables were measured using aerial photographs and survey results of the inundation area [4]. Table 1 shows the data (predictor variables) input into the neural network. Figure 9 shows the calculated values using the neural network compared with the actual values (i.e. teaching data) X_A on the inundation distance from the coastline. As shown in Figure 9, the calculated values X_E are almost equal to the actual values, within ±3% error. The neural network estimated the inundation distance very well. Figure 10 shows the degree of importance of the predictor variables against the objective variable (inundation distance) based on the calculations using the neural network. As shown in Figure 10, the inundation was promoted by the ground (including cultivated land), roads, parks and rivers perpendicular to the coastline. On the other hand, the inundation was inhibited by rivers parallel to the coastline, lakes and ponds, coastal forestation and beaches. In addition, although it is considered that the inundation distance strongly depends on wave height, it had a low degree of importance in our network because we considered that there was little difference in wave height along the survey lines.

4.2 Risk analysis for a future tsunami

Table 2 shows the component ratio of land use in the nine selected regions. Table 3 shows the results of risk analysis based on Figure 10. As shown in Table 3, the degree of tsunami risk differs among neighboring regions. Measures to reduce the damage caused by a tsunami could include management of coastal forestation, creation of embankments, and construction of rivers (or canals) parallel to the coastline for irrigation of fields for common use. We also recommend that the foundations of arterial roads parallel to the coastline be made higher.

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Table 1: Measured values for predictor variables.

Survey line No.	Beach (m)	Coastal forestation (m)	Field (m)	Cultiv-ated land (m)	Reside-ntial area (m)	Big buildings (m)	Rivers parallel to coastline (m)	Rivers perpend-icular to coast line (m)	Lakes and ponds (m)	Wave height (m)
1	65	305	2816	0	0	696	0	0	0	9.0
2	150	70	2144	0	110	1050	0	0	369	8.8
3	169	0	2693	0	300	426	0	0	387	8.6
4	262	0	2367	150	655	512	0	0	93	8.4
5	258	0	2006	25	1339	281	0	0	122	8.8
6	63	0	1008	0	1878	90	0	1465	0	8.7
7	185	225	1475	0	0	0	0	3117	0	8.6
8	185	220	169	2032	835	231	46	0	0	8.8
9	153	254	192	2029	884	105	38	0	0	12.6
10	166	197	672	1253	321	198	37	0	0	7.1
11	157	353	185	2152	0	0	43	0	0	10
12	147	436	182	1704	339	0	56	0	0	7.5
13	170	311	319	2245	155	0	46	0	0	7.3
14	174	285	300	2518	203	0	26	0	0	9.0
15	163	386	271	2376	769	45	29	0	0	10.2
16	174	664	106	2939	174	0	26	0	0	12.1
17	176	670	214	3035	0	0	24	0	0	13.8
18	163	574	0	3115	0	0	22	0	228	14.3
19	176	594	0	3204	120	0	22	0	0	11.5
20	156	540	0	3271	0	0	23	0	0	5.4
21	177	587	0	3132	0	0	23	0	145	5.4
22	165	709	159	2462	0	238	23	0	287	6.1
23	152	548	380	2589	76	120	21	0	0	6.1

Table 1: Continued.

Survey line No.	Beach (m)	Coastal forestation (m)	Field (m)	Cultiv-ated land (m)	Reside-ntial area (m)	Big buildings (m)	Rivers parallel to coastline (m)	Rivers perpend-icular to coast line (m)	Lakes and ponds (m)	Wave height (m)
24	160	559	155	2503	304	0	20	0	0	5.7
25	175	665	0	2790	0	0	27	0	0	5.3
26	241	297	368	2475	93	0	53	0	0	4.8
27	248	51	222	2685	503	111	27	33	0	5.3
28	206	63	66	100	1197	0	30	0	0	12.2
29	197	87	163	2934	674	0	30	0	0	11.2
30	200	488	154	2866	317	0	27	0	0	9.2
31	127	422	0	3029	337	0	33	0	0	7.2
32	114	614	0	2867	358	0	326	0	0	5.9
33	97	599	120	2485	374	0	30	0	0	5.8
34	100	603	0	2956	0	0	29	0	0	5.6
35	89	253	289	2058	0	0	0	951	0	5.3
36	82	641	110	2440	281	0	46	0	0	5.0
37	64	637	295	2283	425	0	44	0	0	4.9
38	58	661	136	2725	229	0	40	0	0	5.0
39	62	615	0	2997	0	0	44	0	0	5.2
40	49	622	127	2417	410	0	46	0	0	5.1
41	42	600	289	2432	184	0	46	0	0	5.3
42	42	613	109	2108	296	0	43	0	0	6.3
43	57	470	245	2292	141	0	91	0	0	16.1
44	57	344	176	2089	346	0	48	0	189	11.9
45	59	319	274	2777	72	0	30	0	185	8.0
46	55	331	191	1831	670	0	225	0	0	4.6

Table 1: Continued.

Survey line No.	Beach (m)	Coastal forestation (m)	Field (m)	Cultiv-ated land (m)	Reside-ntial area (m)	Big buildings (m)	Rivers parallel to coastline (m)	Rivers perpend-icular to coast line (m)	Lakes and ponds (m)	Wave height (m)
47	78	285	272	2618	486	0	238	0	0	3.8
48	75	307	222	3509	187	0	241	1338	0	4.1
49	101	439	398	2265	0	0	237	117	0	4.3
50	118	145	314	3112	0	0	303	256	0	4.5
51	106	50	442	1808	556	0	344	278	0	4.7
52	120	55	765	916	294	0	400	839	0	5.1
53	184	0	0	1348	0	0	402	1238	0	5.6
54	298	0	310	1383	0	74	0	1283	0	6.8
55	0	0	0	1956	1020	0	0	776	0	8.5
56	0	0	168	1986	1041	0	34	0	755	9.3
57	0	50	222	2171	754	0	43	0	180	8.4
58	287	0	273	2441	624	0	36	0	187	7.5
59	226	87	342	1977	715	91	33	0	218	10.2
60	203	121	0	2433	338	0	48	0	276	8.3

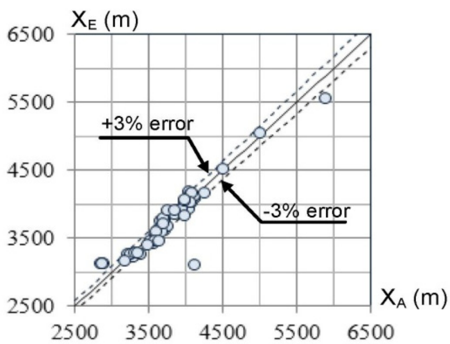

Figure 9: Comparison of estimated and actual values.

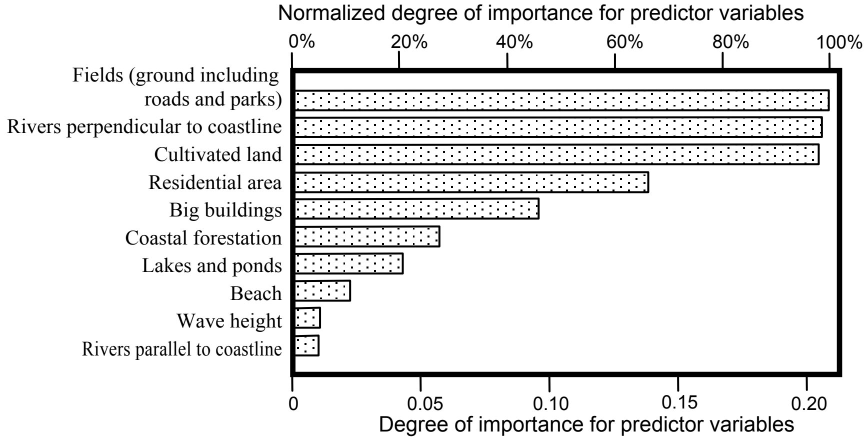

Figure 10: Factors affecting inundation area.

Table 2: Component ratios of land use in selected regions.

Predictor variables	Survey Area (%)								
	A	B	C	D	E	F	G	H	I
Beach	5.8	3.5	5.7	8.6	5.4	-	3.0	3.5	7.9
Coastal forestation	8.0	13.2	17.5	10.8	1.8	5.5	20.0	14.1	6.4
Fields (ground including roads and parks) /Cultivated land	54.7	53.7	52.1	56.6	68.5	75.9	57.4	52.3	33.2
Residential area	28.4	12.2	9.3	23.2	8.8	7.6	8.0	12.6	46.0
Big buildings	3.6	4.9	4.7	0.8	3.3	11.0	-	5.6	3.6
Rivers parallel to coastline	-	-	-	-	-	-	2.1	1.5	2.9
Rivers perpendicular to coastline	-	12.5	10.6	-	12.1	-	4.3	10.4	-
Lakes and ponds	-	-	-	-	-	-	5.2	-	-

5 Conclusion

In the present study, we attempted to clarify the factors that promoted (predictor variables) inundation in coastal regions from the tsunami after the Great East Japan Earthquake on March 11, 2011. Using risk analysis of these factors, we also estimated the degree of risk for tsunami in Iwata City, Shizuoka Prefecture, and we proposed measures to reduce potential damage from a tsunami. The main results are summarized as follows:

- Using a neural network for the analysis, the predictor variables to reduce the inundation distance are rivers parallel to the coastline, lakes or ponds, coastal forestation, large buildings such as factories and warehouses, and beaches. Moreover, the risk analysis for tsunami in the case of Iwata City in Shizuoka Prefecture was performed using the factors that inhibit inundation, and the judgments on safety were made.

- For areas where earthquakes may occur in the future, we propose managing coastal forestation, creating embankments, and constructing rivers (or canals) parallel to the coastline as measures to reduce tsunami damage.

Table 3: Result of risk analysis for Iwata City in Shizuoka Prefecture.

Predictor variables	Survey Area								
	A	B	C	D	E	F	G	H	I
Fields (ground including roads and parks)/ Cultivated land	IV	IV	IV	IV	V	V	IV	IV	IV
Rivers perpendicular to coastline		III	III		III		III	III	
Big buildings						II			
Coastal forestation		II	II	II			II	II	
Lakes and ponds							I		
Beach	II		II	II	II				II
Rivers parallel to coastline							I	I	I
Residential area	Exist (near coastline)	Exist (near coastline)		Exist (near coastline)				Exist (far from coastline)	Exist (near coastline)
Judgment on Safety	×	×	○	×	Δ	○	○	Δ	×

I: It can be expected to reduce damage greatly.
II: It can be expected to reduce damage.
III: Not exceeding 30% land use is not expected to reduce damage.
IV: 30–60% land use is not expected to reduce damage.
V: Exceeding 60% land use is not expected to reduce damage.
: The area has large risk for loss of life due to tsunami-induced current.
: The area has low risk for loss of life, although there is inundation by the tsunami.
: The area has little risk for loss of life because of reduced inundation.

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