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Paper:

Preliminary Study on Long-Term Flooding After the Tsunami

Toshitaka Baba[*,†], **Junichi Taniguchi**[*], **Noriko Kusunoki**[*], **Manabu Miyoshi**[**], **and Hiroshi Aki**[**]

[*]Tokushima University
2-1 Minamijosanjima, Tokushima City, Tokushima 770-8506, Japan
[†]Corresponding author, E-mail: baba.toshi@tokushima-u.ac.jp
[**]Nita Consultant Co. Ltd., Tokushima, Japan

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After the Nankai earthquake in 1946, the resultant flooding lasted for a long time, because seawater remained on land after the tsunami in Kochi city. Large-scale flooding occurred in Ishinomaki city immediately after the Great East Japan Earthquake in 2011. Long-term flooding may hamper disaster responses such as rescue and recovery activities. This paper studied the risks of long-term flooding after the Nankai earthquake in Tokushima city based on a paleographical survey and numerical analysis. The paleographical survey identified statements such as "seawater sometimes flowed onto the land at the full tide," suggesting occurrences of long-term flooding after previous Nankai earthquakes. The numerical analysis separately calculated values inside and outside the levee. The tsunami waveforms outside the analysis area obtained by tsunami numerical simulation was used as the boundary condition of the inland flow modeling, that is water was introduced inside the levee when the tsunami water level exceeded the upper end of the levee. The two layers of ground surface and the drain were defined to calculate the flow, including water exchange between the two layers, and the water was drained forcefully outside the levee using a drainage pump. The possibility of long-term flooding in the analysis area is suggested when a large-scale earthquake occurs in the Nankai trough.

Keywords: long-term flooding, Nankai earthquake, paleographical survey, numerical analysis

1. Introduction

Long-term flooding is the phenomenon where seawater flows onto the land after a tsunami and remains on the land for a while. This is a complex disaster related to broad crustal movements caused by an earthquake, local subsidence due to liquefaction, and a tsunami at an alluvial lower land near a coast. It is difficult to conduct search and rescue activities and supply transportation, which involve prompt actions, immediately after a disaster in the flooding area. This exacerbates obstacles for recovery actions. Large-scale flooding inundated coastal areas such as in Ishinomaki city in 2011 off the Pacific coast during Great East Japan Earthquake [1]. Above the Nankai trough, large-scale, long-term flooding was generated in Kochi city, even during the Showa Nankai earthquake, which is relatively smaller than past Nankai earthquakes [2].

Therefore, Kochi city formulated a response policy for long-term flooding in March 2013 [3], and has been making efforts to reduce damage. However, studies on the risks of long-term flooding in other areas are rare. Long-term flooding may occur anywhere the hazards of subsidence resulting from broad crustal movements and liquefaction in lower areas are assumed. In addition, when a tsunami strikes a lower area surrounded by levees, seawater may not readily drain from the land, because of the levees. In other words, long-term flooding may occur in Kochi and other cities on alluvial land such as Osaka and Nagoya.

This study considers the case of Tokushima city as an example of long-term flooding after a tsunami. Tokushima city is assumed to subside by several 10 cm (80 cm at most), although it is relatively far from the epicenter of a Nankai trough earthquake and undergoes smaller crustal movements than Kochi city. Liquefaction can also cause local subsidence. Tokushima city is located on an alluvial lower land and includes areas below sea level, consequent to crustal movements and liquefaction. On the other hand, the city has repeatedly experienced past Nankai trough large-scale earthquakes, for which many historic documents exist. The present paper first investigates long-term flooding after past Nankai earthquakes using these historic documents. Following this, the risk of occurrence of future long-term flooding events is discussed based on a numerical simulation of the inflow, drainage, and flooding processes of a tsunami in Kawauchi district in Tokushima city.

2. Long-Term Flooding due to Past Nankai Earthquakes in Tokushima

A report created after the Showa Nankai earthquake [4] includes the amount of ground deformation in Shikoku due to the earthquake in coastal areas. This is reported as follows: −0.262 m in Kitajima town, −0.296 m in Kawauchi village, −0.2801 m in Nikenya, −0.3754 m

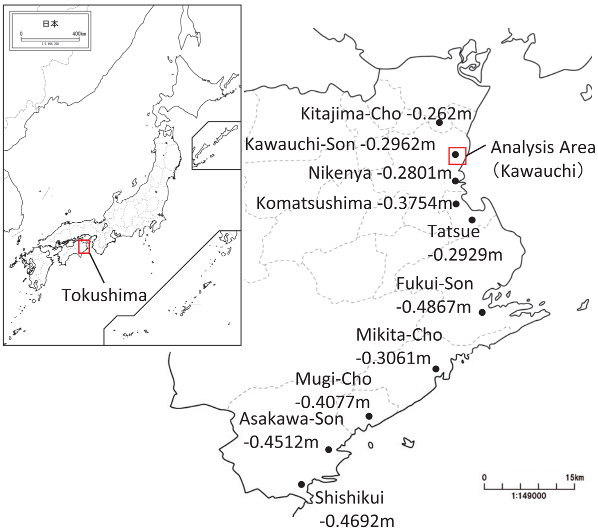

Fig. 1. Crustal deformation of the Showa Nankai earthquake (1946) [4], and area of analysis of the inflow of the tsunami, drainage, and flooding (Kawauchi).

in Komatsushima city, −0.2929 m in Tatsue, −0.4687 m in Fukui village (current Fukui village, Anan city), −0.3061 m in Mikita town (current Minami town), −0.4077 m in Mugi town, −0.4512 m in Asakawa, and −0.4692 m in Shishikui town (**Fig. 1**). The report includes pictures of accumulated seawater in coastal towns in Nikenya, Tokushima city, and Minobayashi, Komatsushima city. A tsunami or typhoon may have caused this flooding after sedimentation. Regardless, the ground height decreased to under the sea level after the Nankai earthquake.

Monuments remembering earthquake-tsunami disasters also show the effect of long-term inundation [5]. A monument dedicated to farmland recovery was erected inside the Hachiman temple grounds in Shinkai, Tachie town, Komatsushima city, which experienced ground subsidence of approximately 0.3 m after the Showa Nankai earthquake. The monument says, “80 acres of rice ponds were ruined by accumulated bad water (drainage) in Tachie town after subsidence caused by a large-scale earthquake. After the disaster, a recovery project to improve the farmlands was launched in March 1952 and completed in March 1956, at a total construction cost of 33 million yen.” In addition, other monuments were erected for drainage improvement projects responding to damage caused by salt water and rain flooding due to subsidence. These were erected on the premises of a drainage machine along the Tachie River near the Awa-akaishi station in Akaishi town, Komatsushima city, and indicate increased risks of water damage due to subsidence consequent to an earthquake.

The Ansei Nankai earthquake, which occurred in the previous earthquake cycle before the Showa Nankai earthquake, was described in “Ansei Nankai Dai-jishin Yushiki,” Nakazai’s family documents collected by the Tokushima Prefectural Archives. Based on his experience, the documents were written by Motonosuke Kondo, who lived in Omatsu village, Itano County. The documents suggest long-term flooding in Kawauchi district alongside collapsing buildings and a tsunami. In Nakagirai, all water channels filled and water did not flow. In Kagasuno, the earthquake lowered the ground level of streets, ferries, and Mise, and high tides caused monthly flooding in buildings. In Nakajimaura, seawater inundated the land during the high tide. In Okishima village, the ground level of new rice pond areas was lowered by approximately 30–90 cm, and seawater created small ponds in some areas. In Takesuga village, dykes were lowered by approximately 3 m, and the Hiraishi and Miyajima waters merged. Furthermore, dykes and pine trees were submerged in ponds. In Hiraishi village, elevated tides off the coast in the summer slowed the flow of bad water (drainage) in depressed areas, while in Yonezushindenn, new ponds were like a white sea. In addition, houses could not function, because of water inflow in a street of the Suketou Hachiman festival site on November 15 (according to the Japanese calendar – January 3, 1855, according to the western calendar).

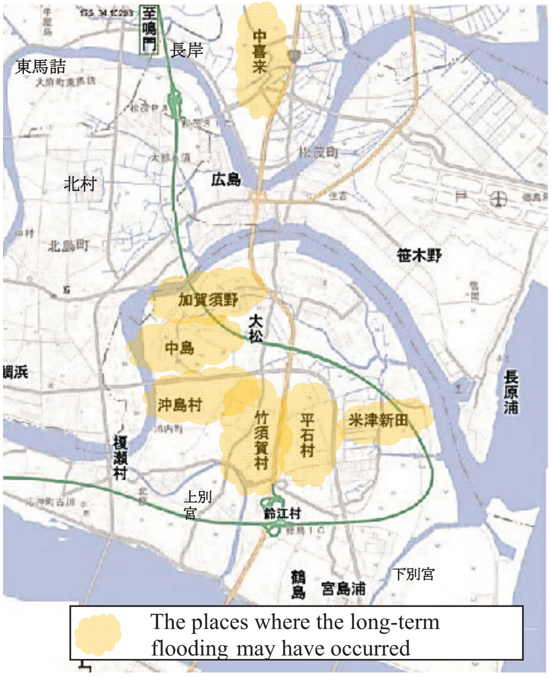

Fig. 2. Places where long-term flooding may have occurred after the Ansei Nankai earthquake (1854).

Figure 2 plots the sites of long-term flooding in Kawauchi district according to Nakazai’s family documents. The figure shows long-term flooding in the central part of Kawauchi district.

3. Calculation Method for Inflow, Drainage, and Flooding Processes of a Tsunami

3.1. Overview of the Calculation

Next, the simulation method for the inflow, drainage, and flooding processes of a tsunami is explained. Values

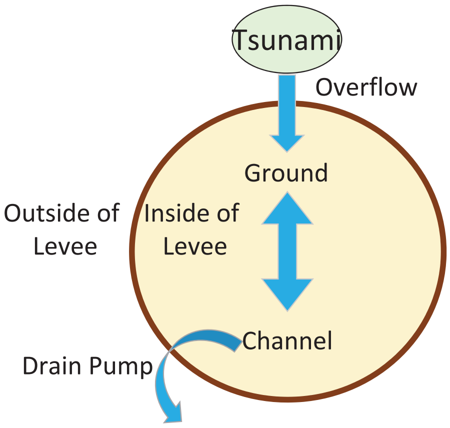

Fig. 3. Overview of the simulation.

inside and outside the levees were calculated separately. Time sequence in the water level outside the levees were recorded through a normal tsunami calculation. Based on recorded values as the limit condition, water flows inside the levees when the tsunami height exceeds the levee crown height. Inside the levees, flows on the ground surface and drainage channels are dealt with. The flow inside the levees is calculated using a calculation method equivalent to that used for the tsunami, and flow amounts are exchanged between the ground surface and drainage channels using meshes set for drainage channels. Finally, water is drained using the drainage machine on the drainage channel outside the levees. **Fig. 3** roughly illustrates the flow in the simulation.

3.2. Calculation for Areas Outside Levees (Tsunami)

The waveforms for tsunamis outside the levees were obtained by solving the following non-linear shallow water equations from the epicenter area to the target area.

$$\frac{\partial \eta}{\partial t}+\frac{\partial q_x}{\partial x}+\frac{\partial q_y}{\partial y}=0, \quad \dots\dots\dots\dots \quad (1)$$

$$\begin{cases} \dfrac{\partial q_x}{\partial t}+\dfrac{\partial}{\partial x}\left(\dfrac{q_x^2}{D}\right)+\dfrac{\partial}{\partial y}\left(\dfrac{q_x q_y}{D}\right) \\ \qquad = -gD\dfrac{\partial \eta}{\partial x}-\dfrac{gn^2}{D^{\frac{7}{3}}}q_x\sqrt{q_x^2+q_y^2}, \\ \dfrac{\partial q_y}{\partial t}+\dfrac{\partial}{\partial x}\left(\dfrac{q_x q_y}{D}\right)+\dfrac{\partial}{\partial y}\left(\dfrac{q_y^2}{D}\right) \\ \qquad = -gD\dfrac{\partial \eta}{\partial y}-\dfrac{gn^2}{D^{\frac{7}{3}}}q_y\sqrt{q_x^2+q_y^2}, \end{cases} \quad (2)$$

where, η is the change in water level from the still water surface, q_x and q_y are the flow amounts for unit width in the x or y directions respectively, D is the depth of total water, g is the acceleration of gravity, and n is the Manning roughness coefficient. The present study used the calculation code JAGURS [6], which performs this numerical calculation using the leap-frog difference method of the staggered grids.

3.3. Calculation for Areas Inside Levees

The Application of Flood Risk Evaluation (AFREL) was used to calculate water behavior inside the levees. The software is mainly used to calculate rainwater drainage. In preceding research, a reproduction calculation was conducted for heavy water caused by a typhoon and the resulting river flooding in Kamihachiman district in Tokushima prefecture, confirming that the difference between observed inundation levels at 10 points and simulation results were within 0.10 m [7]. This study simulates the flow inside the levees due to a tsunami and drainage by replacing the limit conditions for inputting normal river water level changes with tsunami waveforms.

The AFREL induces water inside the levees using the following overflow formulae when the water level exceeds the levee crown height [8, 9]:

$$\begin{cases} when\ h_2<\dfrac{2}{3}h_1, & q=\pm 0.35h_1\sqrt{gh_1}, \\ when\ h_2\geq\dfrac{2}{3}h_1, & q=\pm 0.91h_2\sqrt{g\left(h_1-h_2\right)}. \end{cases} \quad (3)$$

The water flow on the ground surface inside the levees is calculated using the above shallow water theory. The successive equation changes into the following form.

$$\frac{\partial \eta}{\partial t}+\frac{\partial q_x}{\partial x}+\frac{\partial q_y}{\partial y}=q_{CHAN}, \quad \dots\dots\dots \quad (4)$$

where, q_{CHAN} represents flow amount exchange with the drainage channel.

The drainage channel is assumed to go only in the direction of the coordinate axis and pass the mesh center. Meshes with drainage channels exchange flow amounts with the ground surface layer using the overflow formula. The calculation employs Eq. (3). Note that the flow inside the drainage channels neglects the advection term in Eq. (2) to increase numerical stability. Successive equations employ Eq. (4).

The drainage pump was modeled by shifting the flow amount by the drainage capacity from set meshes to designated meshes.

4. Analysis Target Area and Calculation Conditions

Detailed calculations were conducted for Kawauchi district, which is located north of Tokushima city. Many descriptions on long-term flooding in the district emerged in the historic documents. Kawauchi district is surrounded by levees, because it is located at a low altitude nearby a river and the sea. Currently, the levee crown height on the south of Yoshino River is approximately 5 m in T.P., while others are approximately 2 m high (**Fig. 4**). When large-scale tsunamis strike the area, flooding is expected to occur first on the west of Kawauchi district, which is characterized by a lower levee crown height. This area has 13 drainage machine sites to drain rainwater (**Fig. 5**). In addition, Kawauchi district has only drainage

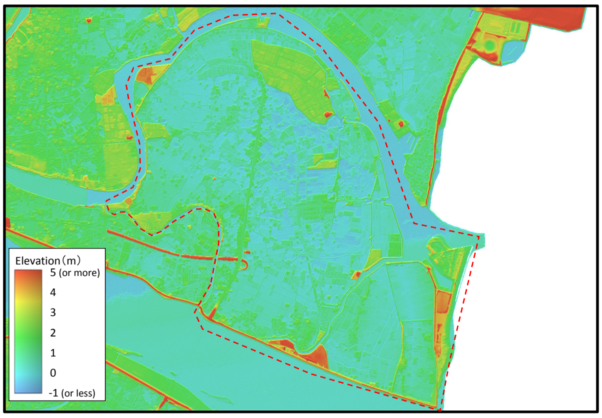

Fig. 4. Elevation of current Kawauchi area (surrounded by the red dashed line): Formulated using numerical map information provided by the Geospatial Information Authority of Japan.

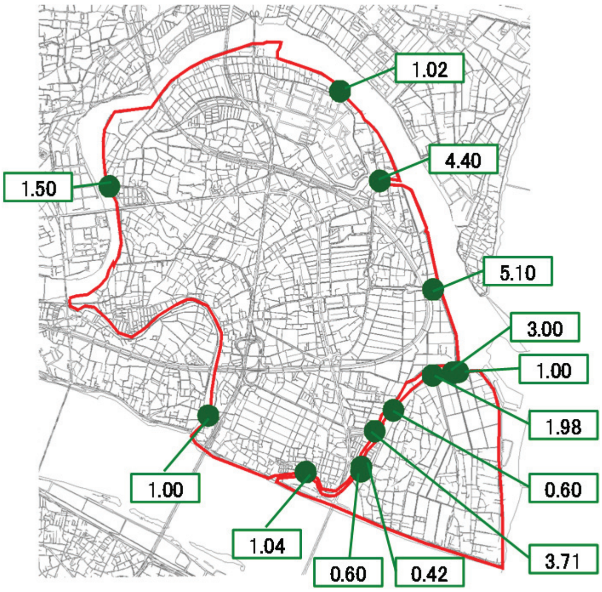

Fig. 5. Drain pumps and capacity (m^3/sec) in the Kawauchi area.

channels (open water channels) and no sewerage systems. Using the above method, inundation, drainage, and flooding processes in Kawauchi district due to two tsunamis caused by the Ansei Nankai earthquake in 1854 [10] and Case 3 assumed by the Cabinet Office (M9) [11] were analyzed.

In the tsunami calculation, fault parameters [10] were used to calculate the initial water level of the tsunami consequent to the Ansei Nankai earthquake in 1854. The vertical components of crustal deformation obtained using the semi-infinite uniform elastic model [12] were assigned to the sea surface with a rise time of 60 sec. The initial water level data considering fracture propagation for each 10 sec were used for Case 3, which was assumed by the Cabinet Office. The spatial resolution was gradually increased from the large area, including the wave source, to the target area using the nesting method. The differential grid interval in and around the Kawauchi district was set at 10 m. Tsunami waveforms at 15 points surrounding Kawauchi district were obtained with a time step width of 0.2 sec by calculating the tsunami for 12 hours after its occurrence.

Subsidence of approximately 0.18 m and 0.74 m due to crustal displacements in the 1854 Ansei Nankai earthquake and Cabinet Office's assumption model was considered for the calculation for inside the levees. Subsidence by liquefaction was neglected for convenience, and the levees and 10 drainage machines in the target area were assumed sound. The tidal level was set as a constant at syzygy mean high tide for the past five years (T.P. +0.92 m). The tsunami flowed inside the levees based on the overflow formula of Eq. (3), which moves on the principle of gravity and forces drainage by the drainage machines, while disregarding natural evaporation and ground infiltration. The horizontal resolution of differential grids was 25 m, and the time step was 0.01 sec. Tsunami input was for 12 hours, because it rarely exceeds the levee height 12 hours after the earthquake occurs. The simulation for inside the levees was conducted for 72 hours.

5. Analysis Results

Figure 6 shows the waveforms for the tsunami water level outside the levees alongside the crown levee height. The tsunami water level was below the crown height for the 1854 Ansei Nankai earthquake. The maximum tsunami water level in the northwestern areas exceeds the crown height for Case 3.

Figure 7 shows temporal and spatial changes in the inundation depth within the target area. In the 1854 Ansei Nankai earthquake (**Fig. 7**, top), inundation occurred in the area behind through west water channels approximately one hour after the earthquake occurred, although the tsunami did not exceed the levees. Following this, water moved through the underpass of the banked Tokushima Expressway to low-altitude central areas. Drainage through the drainage machines was almost complete approximately 12 hours after the earthquake. On the other hand, in Case 3, inundation occurs from the northwestern broad areas approximately one hour after the earthquake occurs, spreading to central areas. The maximum flooding depth is slightly more than 1 m. Flooding remains at the 72-hour mark, when the analysis was completed.

6. Discussion and Future Challenges

Many descriptions of long-term flooding emerged in the paleographical survey for the Kawauchi area in the case of the 1854 Ansei Nankai earthquake. In the simulation of inflow, drainage, and flooding processes of the 1854 Ansei Nankai earthquake as the wave source, drainage was completed 12 hours after the earthquake

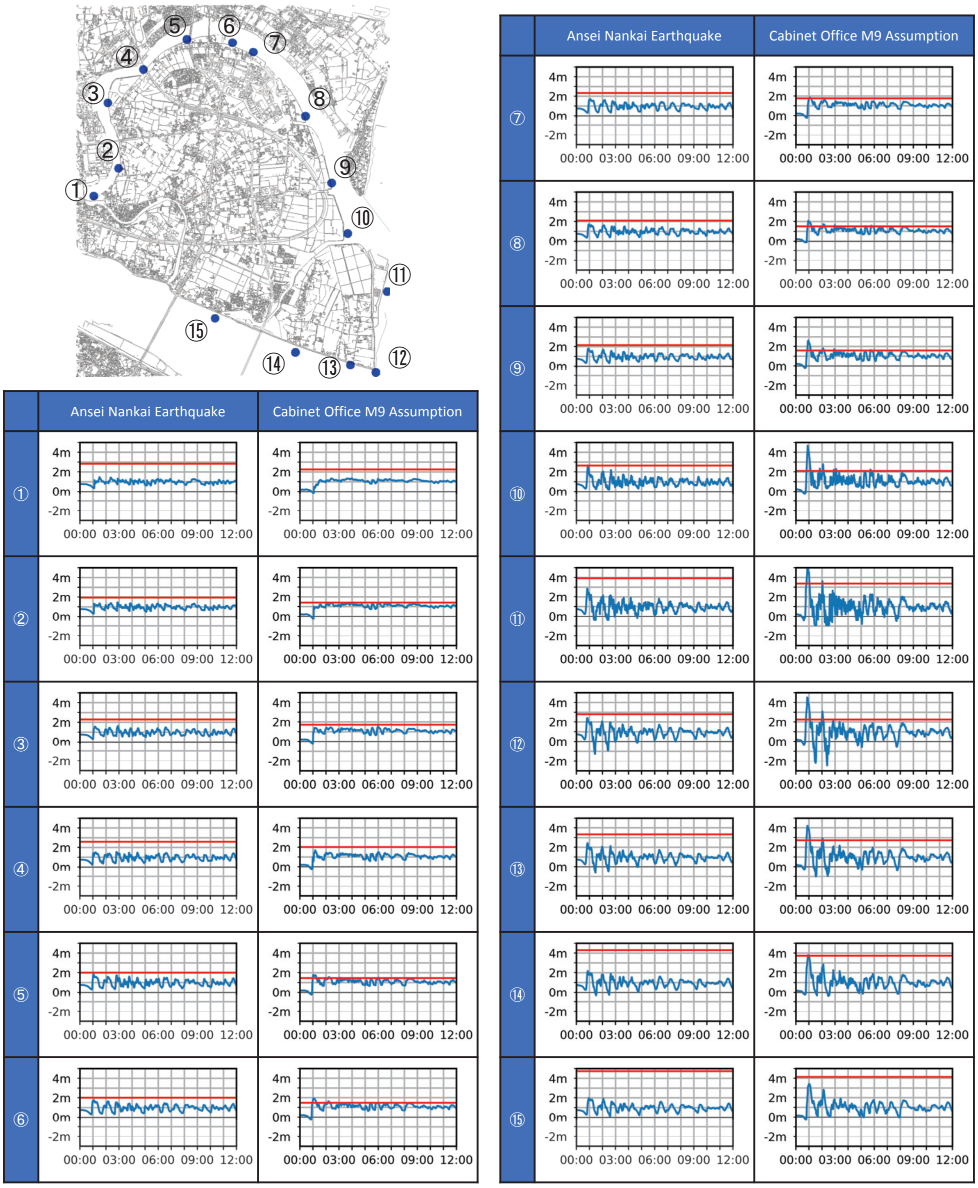

Fig. 6. Tsunami waveform around the target area calculated by the Ansei Nankai Earthquake Model (1954) and Cabinet Office M9 Assumption Case 3 Model (blue lines). The red lines represent the levee heights.

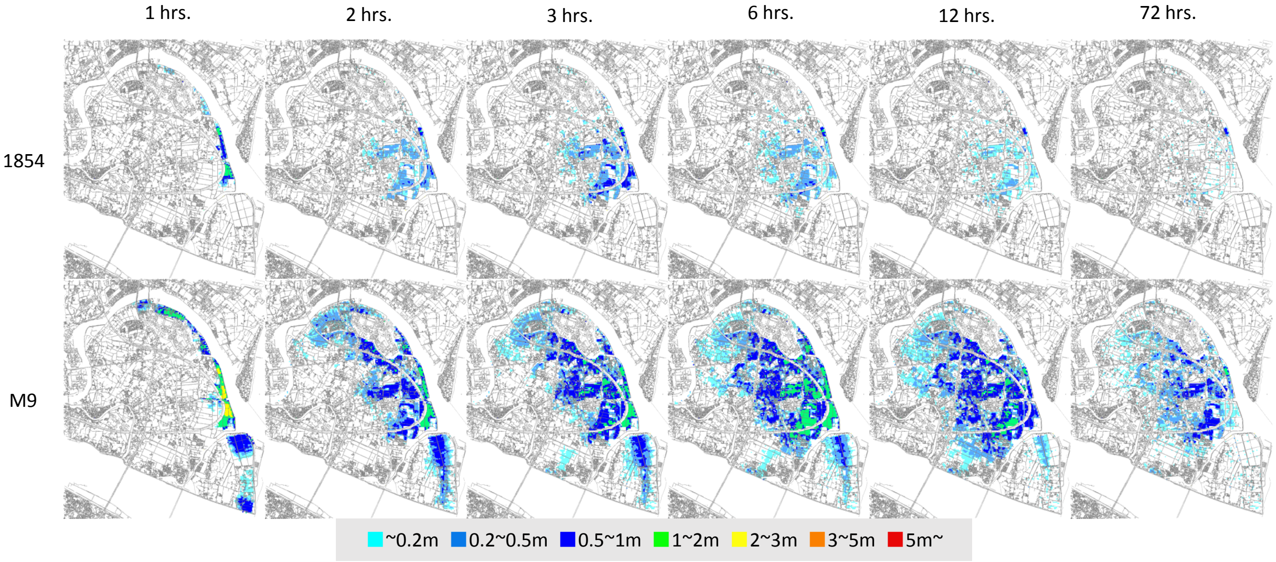

Fig. 7. Time change of flooding depth at the target area calculated by the Ansei Nankai Earthquake Model (1854) (upper) and Cabinet Office M9 Assumption Model (lower).

occurred. In this study, we haven't attempt to accurately reproduce the 1854 earthquake because the levees and drainage machines were assumed in the current landforms. It may suggest that the difference can be attributed to the disaster reduction effects of the levees and drainage machine sites. However, the imperfect characteristics of the analysis model, including that it does not consider ground subsidence due to liquefaction, is also influential.

In the analysis for Case 3, assumed by the Cabinet as being larger than the 1854 Ansei Nankai earthquake, huge tsunami flows onto the land and long-term flooding may occur, because of a large volume of subsidence due to crustal deformations. The final flooding areas (**Fig. 7**, right bottom corner) roughly coincide with the areas where long-term flooding occurred in 1854 based on the paleographical survey in **Fig. 1**. This suggests that the central area of Kawauchi district has remained the same depressed area as that in 1854, while coastal landforms have significantly changed because of the levees constructed.

The analysis model in this paper can be used to consider measures for long-term flooding. For example, when addressing the management of a drainage machine site as a hardware measure, the drainage capacity and facility's height limit such as that of the control panel can be determined. In addition, preparing sufficient stockpiles can be a software measure. In the present study, water remained in some areas three days after the earthquake occurred if the drainage machines operate as in Case 3, which was assumed by the Cabinet Office in Kawauchi district. Therefore, food and medical supplies must be stored in case of isolation for more than three days.

However, the obtained results are for preliminary purposes only. As such, the analysis model includes items that need to be modified. For example, ground subsidence due to liquefaction is not considered. Furthermore, the levees and drainage machines become useless during actual shakings and tsunamis [13]. Also not considered is the blocking of drainage channels due to collapsed buildings and floating debris. In addition, the tidal height was set as a constant at the full tide in the current study. Prediction of a levee breach due to shakings and tsunamis and blockage of water channels are especially difficult to predict. However, seawater will flow into areas that have subsided below the seawater level consequent to only crustal movements even without tsunamis if the levee height is uniformly lowered by 75% as used in the tsunami predictions by the government. Probabilistic representation of long-term flooding hazards would be needed by creating multiple scenarios that randomly determine levee breach points with the Monte Carlo simulations.

7. Conclusion

Long-term flooding risks after a tsunami in Kawauchi district, Tokushima city were studied based on a paleographical survey and numerical simulation. Kawauchi district is located on soft ground at a lower altitude and surrounded by a river and sea. Seawater flowing as a tsunami may accumulate and flow onto land lower than the sea level during the high tide, because the ground subsides through broad crustal movements and liquefaction resulting from an earthquake. However, the present numerical simulation is for preliminary purposes, and must be improved for accurate prediction.

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References:

[1] The Touhoku Regional Development Bureau, "92% of drainage caused by tsunami disappeared ∼ Emergency drainage measures go to final stage," http://www.thr.mlit.go.jp/Bumon/kisya/saigai/images/34655_1.pdf, 2011 [accessed May 26, 2016]

[2] A. Mikami and N. Tsujino, "Damage to Levee Embankments in Kochi City Area during the 1946 Showa-Nankai Earthquake," Historical Earthquake, Vol.27, pp. 27-39, 2012.

[3] Kochi Prefecture, "Results of the Nankai earthquake long-term flood countermeasure investigation," 2013, http://www.pref.kochi.lg.jp/soshiki/010201/files/2015041500011/2013040300465_www_pref_kochi_lg_jp_uploaded_life_84591_289930_misc.pdf [accessed Jan. 6, 2017]

[4] Shikoku Region Development Council, "Final report of survey on ground change in Shikoku region – entity of Shikoku regional ground change occurred at the time of the Nankai earthquake (December 21, 1947) and thereafter," 1956.

[5] Tokushima Prefecture, "Knowing the Nankai Earthquake, monuments of earthquakes and tsunamis in Tokushima," 2008, http://www.jishin.go.jp/main/bosai/kyoiku-shien/13tokushima/material/tksm_22_3.pdf [accessed Jan. 6, 2017]

[6] Baba, T., N. Takahashi, Y. Kaneda, K. Ando, D. Matsuoka, and T. Kato, "Parallel implementation of dispersive tsunami wave modeling with a nesting algorithm for the 2011 Tohoku tsunami," Pure appl. Geophys., Vol.172, pp. 3455-3472, doi:10.1007/s00024-015-1049-2, 2015.

[7] M. Miyoshi, T. Tamura, H. Ali, and M. Fujita, "The Relationship between Rainfall and Flood Damage Caused by Inner Water Flooding in Hachiman, Tokushima," Civil Engineering Society Shikoku Branch Heisei 25 Natural Disaster Forum Proc., pp. 69-77, 2013.

[8] J. Honma, "Discharge coefficient for trapezoidal weir [1]," J. of Civil Engineering Society, Vol.26, No.9, pp. 849-862, 1940.

[9] J. Honma, "Discharge coefficient for trapezoidal weir [2]," J. of Civil Engineering Society, Vol.26, No.6, pp. 635-645, 1940.

[10] I. Aida, "Numerical Experiments for the Tsunamis Generated off the Coast of the Nankaido District," Bulletin of the Earthquake Research Institute, Vol.56, pp. 713-730, 1981.

[11] The Japanese Cabinet Office, "Study Meeting of the Giant Earthquake Model of Nankai Trough," 2012, http://www.bousai.go.jp/jishin/nankai/mode [accessed March 26, 2016]

[12] Y. Okada, "Surface deformation due to shear and tensile faults In a half-space," Bulletin of the Seismological Society of America, Vol.75, pp. 1135-1154, 1985.

[13] K. Sugawara, Y. Sugisawa, and Y. Karino, "Rapid Reconstruction of Pumps for Regional Drainage Destroyed by Tsunami in the Great East Japan Earthquake," J. of the Japanese Society of Irrigation, Drainage and Rural Engineering, Vol.80, pp. 903-906, 2012.

Name:
Toshitaka Baba

Affiliation:
Professor, Tokushima University

Address:
2-1 Minamijosanjima, Tokushima City, Tokushima 770-8506, Japan

Brief Career:
1999 Joined JAMSTEC
2015 Joined Tokushima University as a Professor

Academic Societies & Scientific Organizations:
- Seismological Society of Japan (SSJ)
- Japan Geoscience Union (JpGU)
- American Geophysical Union (AGU)

Name:
Junichi Taniguchi

Affiliation:
Tokushima University

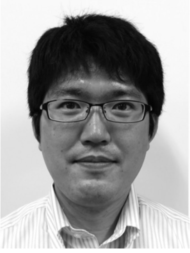
Address:
2-1 Minamijosanjima, Tokushima City, Tokushima 770-8506, Japan

Academic Societies & Scientific Organizations:
- Japan Society of Civil Engineers (JSCE)

Name:
Noriko Kusunoki

Affiliation:
Tokushima University

Address:
2-1 Minamijosanjima, Tokushima City, Tokushima 770-8506, Japan



Name:
Manabu Miyoshi

Affiliation:
Nita Consultant Co., Ltd.

Address:
38-2 Suzuenishi, Kawauchi, Tokushima City, Tokushima 771-0122, Japan

Academic Societies & Scientific Organizations:
- Japan Society of Civil Engineers (JSCE)

Name:
Hiroshi Aki

Affiliation:
Nita Consultant Co., Ltd.

Address:
38-2 Suzuenishi, Kawauchi, Tokushima City, Tokushima 771-0122, Japan

Academic Societies & Scientific Organizations:
- Japan Society of Civil Engineers (JSCE)