Tsunami-induced topographical change recorded in documents in Japan

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Abstract. Tsunamis change topography. Examples are collected from old documents in Japan. Barrier spits, tombolos, and sandbars were often cut by overflowing tsunamis. Channels were deepened by tsunami-induced currents, and sometimes made shallow by transported sediments. An effort is made to relate the thickness of sand deposit on land to the tsunami height. Roughly speaking, a sand deposit 1 m thick is caused by a 7 m high tsunami.

1. Introduction

In addition to the massive material, "Shinshu Nihon Jishin Shiryou" (A New Compilation of the Japanese Historical Records of Earthquake), many documents were surveyed to find records of tsunami-related sand movement. Among over 160 examples found, 25 examples are selected to give a quantitative rough idea of the magnitude of topographical change in relation to the tsunami height or tsunami-induced current.

These 25 examples are from the following nine tsunamis:

1. Manju tsunami of 1026 that hit the Iwami District on the Japan Sea coast,
2. Keicho tsunami of 1605 that hit the Tokai, Nankai, and Seikai Districts on the Pacific coast,
3. Genroku tsunami of 1703 that hit the Kanto District on the Pacific coast,
4. Hoei tsunami of 1707 that hit the wide coast from Tokai to Kyushu on the Pacific coast,
5. Yaeyama tsunami of 1771 that hit Okinawa,
6. Tenpo tsunami of 1833 that hit the Dewa District on the Japan Sea coast,
7. Ansei Tokai and Ansei Nankai tsunamis of 1854 that hit the Tokai and Nankai District on the Pacific coast,
8. Showa Great Sanriku tsunami of 1933 that hit the Sanriku coast on the Pacific coast, and
9. Chilean tsunami of 1960 that hit the Pacific coast from Hokkaido to Okinawa.

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Table 1: Change of barrier spits, tombolos, and sand bars.

Location	Year	Length of opening	Water depth after tsunami	Tsunami height and velocity	Remarks
Izu Oshima	1703	110 m		10 m	Barrier spit
Imagire, Hamana	1707	90 m	∼2.1–2.4 m	3 m	Barrier spit
Takahama, Miyako	1933	90 m		2 m	Sand bar
Kiritappu, Hokkaido	1960	100 m	∼2–6 m	4.2 m ∼2.5–3 m/s	Tombolo, ∼1–2 m high

2. Erosion of Barrier Spits, Tombolos, and Sand Bars

There are several examples of cutting of sand spits, tombolos, and sandbars since olden days. An old example is found in the legion of the generation of the Habu Harbor, Izu-Oshima Island, Tokyo. The 1703 tsunami cut the sand barrier 50 m wide that had separated a fresh water lake and the sea, by the length of 100 m. Since then, the lake became a good harbor. Table 1 summarizes four similar events.

A recent example is the tombolo of Kiritappu connecting Hokkaido and Tohutu Island. Figure 1 (Yamaguchi, 1962) shows the topographical change caused by the 1960 Chilean tsunami. According to residents, the island was located off the mainland 50 years before the tsunami. Since then wave action developed a tombolo of fine sand that eventually connected the island and the mainland. The smallest width of the tombolo was about 300 m. The crest height of the tombolo was about 2 m with the lowest height of about 1 m. Solid lines were the shoreline before the tsunami.

The Chilean tsunami began with a big ebb around 3:30 a.m. The largest ebb receded to the distance of 300 m in Biwase Bay at 4:30 a.m. Then the third wave 4.2 m high overflowed the tombolo from Hamanaka Bay to Biwase Bay at 4:40 a.m. This was the highest wave. Since then, the tsunami crossed the tombolo twelve times, eight times from Hamanaka Bay to Biwase Bay and four times inversely, and a channel was built. After the highest wave, the tsunamis from Biwase Bay were stronger than those from Hamanaka Bay. The current velocity estimated by the movement of a fishing boat in the current was 2.5 to 3 m/s. When the tsunami finished, the channel was believed not large, but it grew to be 100 m wide and 2 m deep with the deepest depth of 6 m due to tidal current.

Solid lines in Fig. 1 are the original shorelines, broken lines are the inundation limit, the areas sparsely shaded by horizontal lines are the flooded areas, and densely shaded areas are the channels made by the tsunami. The black areas are the eroded areas with rich gully erosion. The eroded sand was deposited in the areas given by the dotted lines in Fig. 1.

The gullies were made by the ebb flow. A large gully was 40 to 50 m wide and more than 1 m deep, whereas a small one was 20 to 30 cm wide and 10 cm deep. Many gullies were formed on sandy beaches and some on

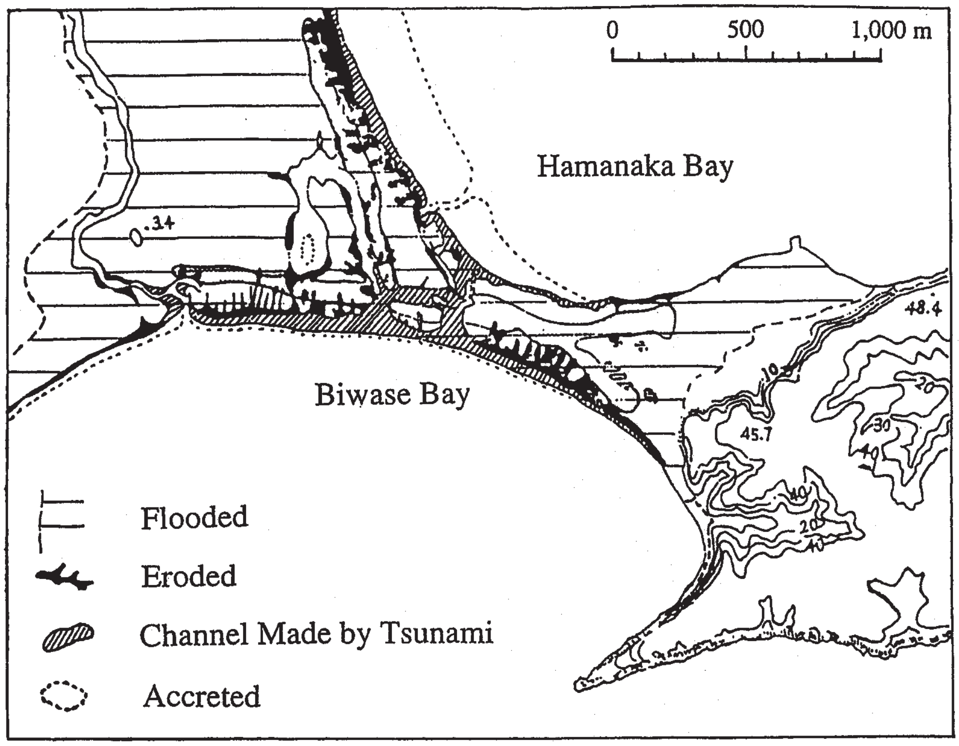

Figure 1: Kiritappu tombolo cut by the 1960 Chilean tsunami (after Yamaguchi, 1962).

pebble beaches. A beach covered by grasses showed greater resistance to erosion.

3. Depth Change of Natural and Artificial Channels

Table 2 shows eight examples for which quantitative information is available, two for the 1854 Ansei tsunami and six for the 1960 Chilean tsunami. All of them are for narrow channels. Two of them are for the case of deposition and others are for the case of erosion. For this kind of change, not the tsunami height but the tsunami-induced current is important. No measured current velocity is obtained. Witnesses estimated the current velocity in comparison with the ship movement trapped in the current or from their experiences based upon daily observation as fishermen.

3.1 Deposition of natural and artificial channels

Kushiro harbor is composed of two parts, seaport (outer port) and river port (inner port). The 1960 Chilean tsunami not only entered the harbor through the entrance between breakwaters but also overflowed the breakwaters, the crown height of which was at T.P. 2.1 m.

Table 2: Change of artificial and natural channels.

Location	Year	Erosion depth (m)	Tsunami height (m)	Current velocity	Remarks
Imagire Inlet	1854	~1.5–1.8 m	~5–6 m		Inlet to Hamana Lake
Semizo Straight	1854	–1 m (Deposition)	>2 m		Mushiake, Okayama Pref.
Kushiro River	1960	–3 m (Deposition)	2.5 m Total amp. 5 m	2 m/s	Bottom was explosed
Hachinoe Harbor	1960	>5 m	~3.6–4 m	~8–13 m/s	Along breakwaters
Kesennuma Bay	1960	9.9 m	2.8 m		Along a groin
Watanoha Inlet	1960	1 m	3.1 m Total amp. 6 m	20 km/h (5.5 m/s)	Near Ishinomaki Bottom was exposed
Ishinomaki Harbor	1960	2 m	~2.6–2.7 m		In the Kitakami River
Nakaminato Harbor	1960	~1.7–2.1 m	1.25 m Total amp. 2.12 m	7 knot (3.5 m/s)	At the river mouth

The river port was developed along the Kushiro River, the origin of distance mark of which is located at the Nusamai Bridge, in Fig. 2 (Yamaguchi, 1962). At 1 km upstream of the Nusamai Bridge, it was observed that the river bottom except for the central waterway was exposed at the time of the largest ebb, and the floods came with violent eddies and turbulence at their front. From this description, the lowest water level upstream of the Nusamai Bridge might be nearly DL-2 m (T.P. –3 m). The tsunami flooded and ebbed many times. The third wave was the highest and its water level was at T.P. 1.8 m to 2 m. Therefore, the maximum total amplitude was not larger than 5 m. The average period was about 40 minutes. The upstream end of the tsunami invasion might be 3 to 3.5 km from the river mouth, estimated by lumber and fishing boats transported by the tsunami. The flow velocity upstream of the Nusamai Bridge is estimated to be of the order of 2 m/s (JMA, 1961).

Downstream of the Nusamai Bridge, it was witnessed that the tsunami flooded through the central waterway by increasing its height, but along both sides the water did not move or flowed weakly downward. By this description, the flow velocity is not larger than that at the upstream of the Nusamai Bridge (JMA, 1961).

Figure 2 compares the topography of the river before (upper figure) and after (lower figure) the tsunami (Yamaguchi, 1962). Numerals are the water depth measured below DL that is equal to T.P. –1 m. The deepest before the tsunami (DL-6 m) was made shallow to DL-3 m after the tsunami. This deposition was the result of a tsunami that had a total amplitude of 5 m, a current velocity of 2 m/s, and a wave period of 40 minutes.

3.2 Erosion of Artificial and Natural Channels

The Chilean Tsunami at Hachinoe Harbor began with a flood of amplitude of 93 cm at 3:15 a.m., on 24 May 1960. The ebb before the second flood exposed the sea bottom at the tip of the jetty. The third wave had the amplitude of 850 cm at 5:14, the fourth wave 365 cm at 6:58, and the fifth

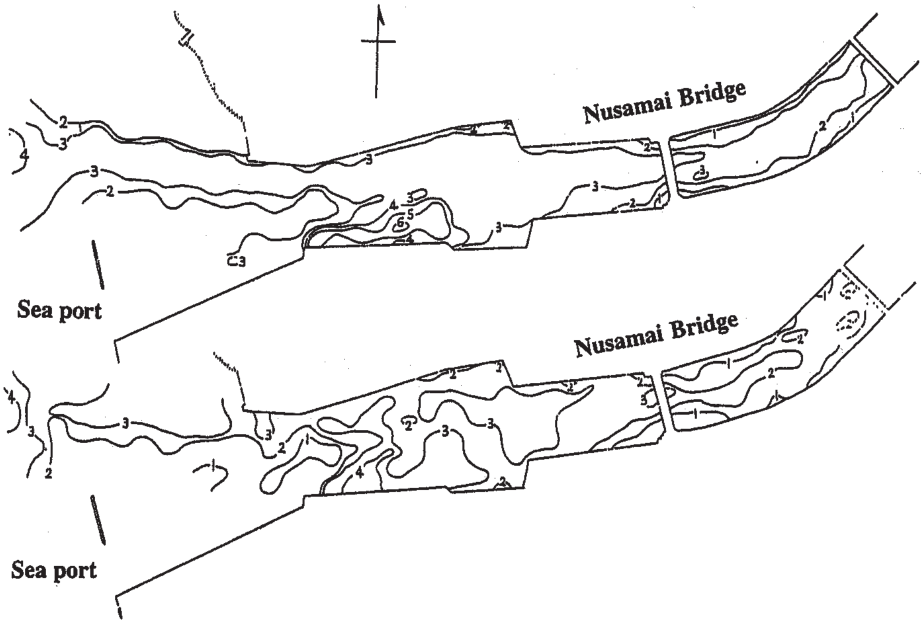

Figure 2: Water depth in the Kushiro River before (upper) and after (lower) the 1960 Chilean tsunami. Numerals are the water depth (m) below datum level (after Yamaguchi, 1962).

wave 396 cm at 6:13. Then the amplitude decreased but the tsunami and the induced turbulence continued until May 27. Wave period is estimated to be 30 to 40 minutes (JMA, 1961).

The ebbs were stronger than floods. During the ebb of the third wave from 5:14 to 5:55, the receding velocity of the tsunami front was 13 m/s at maximum, while the front came with a velocity of less than 8 m/s. At the front of the ebbs and floods, turbulent currents were observed.

Figure 3 shows the plan of the Hachinoe Harbor and the sea bottom contour along the jetty at the entrance (Hachinoe Harbor Construction Office, 1961). Sections along the line A-A′ before (dotted lines) and after (solid lines) of the tsunami are compared in Fig. 4. In the same figure, the erosion depth was given, with a maximum value of more than 5 m. This is the result of the tsunami-induced current between 8 m/s and 13 m/s.

Another example of deep erosion is found in the case of Kesennuma Bay that is composed of two parts, the inner bay 2 km long and 1 km wide and the outer bay 8 km long and 2 km wide. There is a narrow 350 m width between the two parts. Deep erosion that occurred at this narrow point is shown in Fig. 4, drawn according to Nishijo's information (1961). The maximum erosion depth is more than 7 m. The tsunami height in Kesennuma Bay was reported as high as 2.8 m. No information is available for the tsunami-induced current velocity. Kawamura and Mogi (1961) also described the sea bottom change caused by the 1960 Chilean tsunami for five harbors including Kesennuma Bay, but with no information of the current

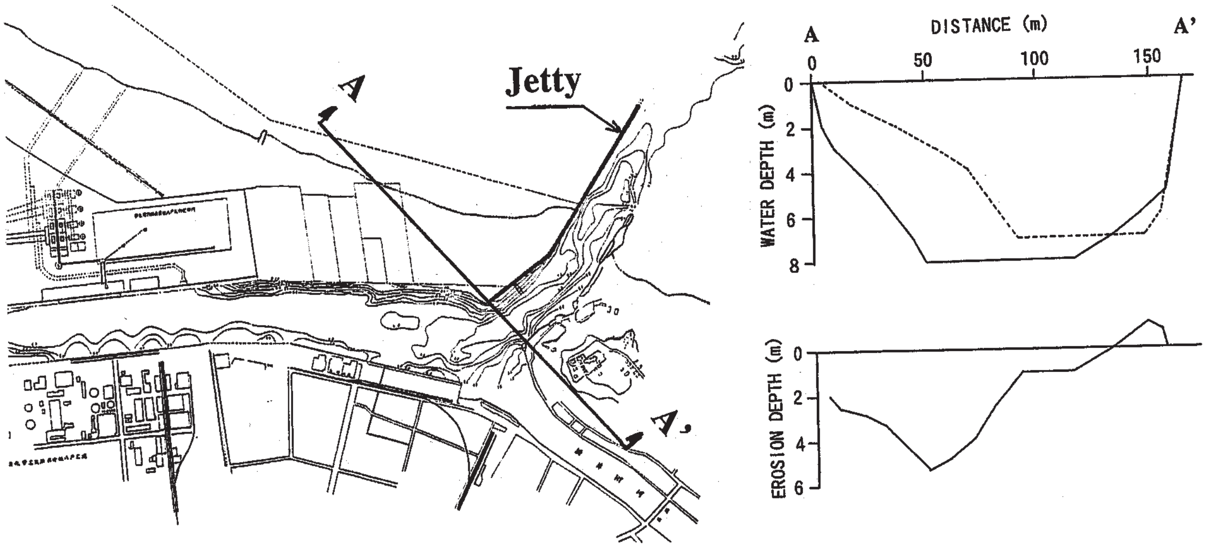

Figure 3: Plan of Hachinoe Harbor (after Hachinoe Harbor Construction Office, 1961) and the location of the section A-A′ for comparison of water depth before and after the 1960 Chilean tsunami (left figure). Water depths before (dotted line) and after (solid line) along the line A-A′ (right upper figure). Erosion depth along the A-A′ line (right lower figure).

strength. There are two efforts to simulate the erosion caused by the Chilean tsunami in Kesennuma Bay. Takahashi *et al.* (1993) obtained the maximum erosion depth of 4.6 m and Fujii *et al.* (1998) 4.7 m. Both of them are nearly half the actual erosion depth.

4. Deposition of Sand on Land

A very high sand hill was built at Iruma, Izu Peninsula in the case of the 1854 Ansei Tokai earthquake tsunami. Iruma is located near the tip of the Izu Peninsula. Figure 5a (Aida, 1986) shows the run-up height distribution

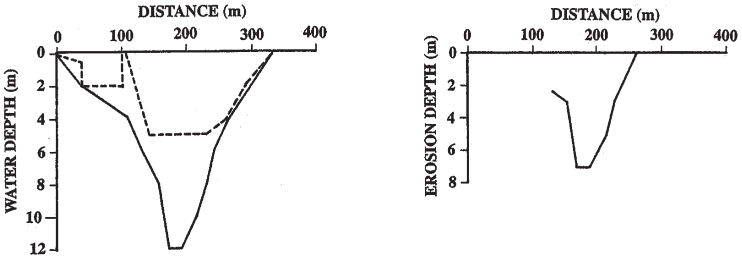

Figure 4: Section at a narrow in Kesennuma Bay before (dotted line) and after (solid line) the 1960 Chilean tsunami (left figure), and the erosion depth (right figure).

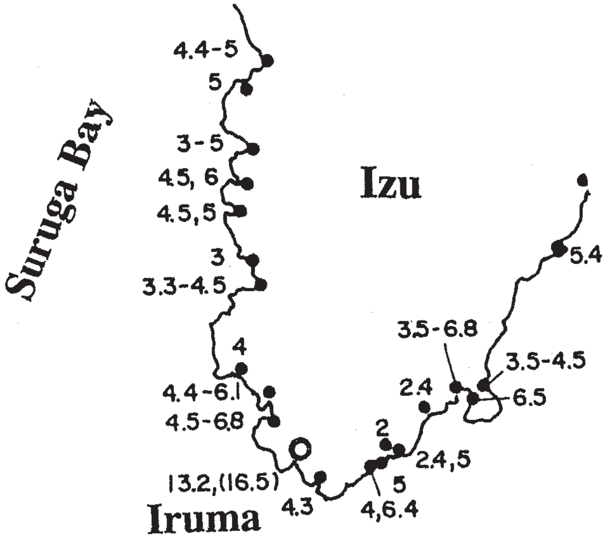

Figure 5a: Location of Iruma (white circle) and tsunami height in the neighbourhood in meters (after Aida, 1986).

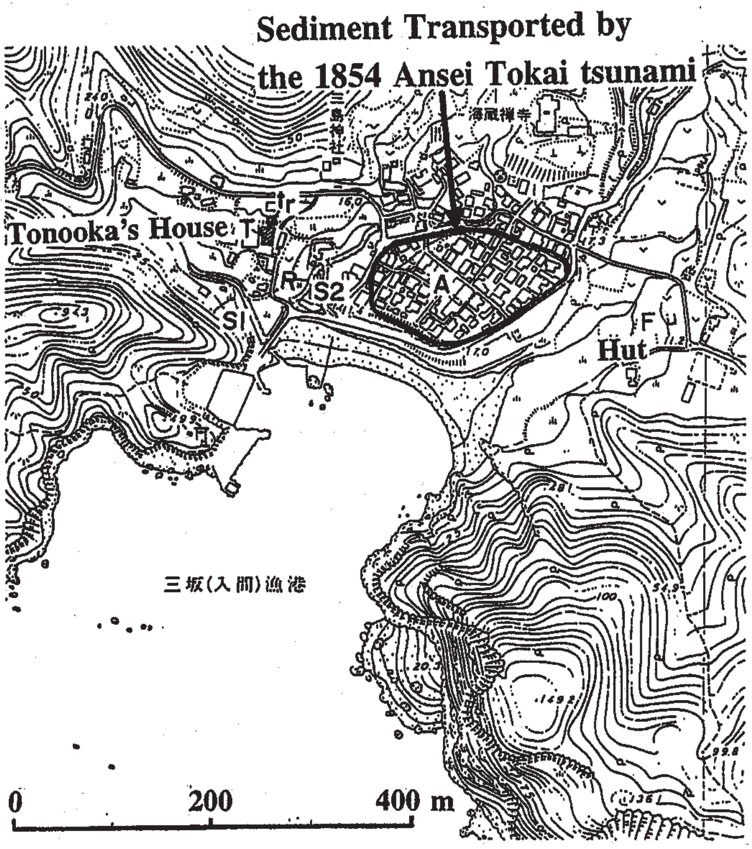

Figure 5b: A sandy hill built by the 1854 Ansei Tokai tsunami (after Asai *et al.*, 1998).

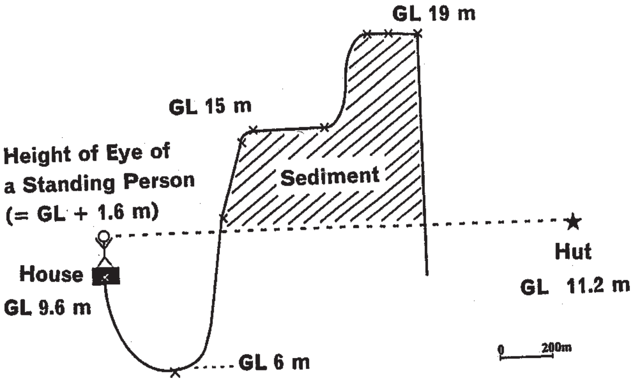

Figure 5c: Section of the hill from Tonooka's house to the hut (after Asai *et al.*, 1998).

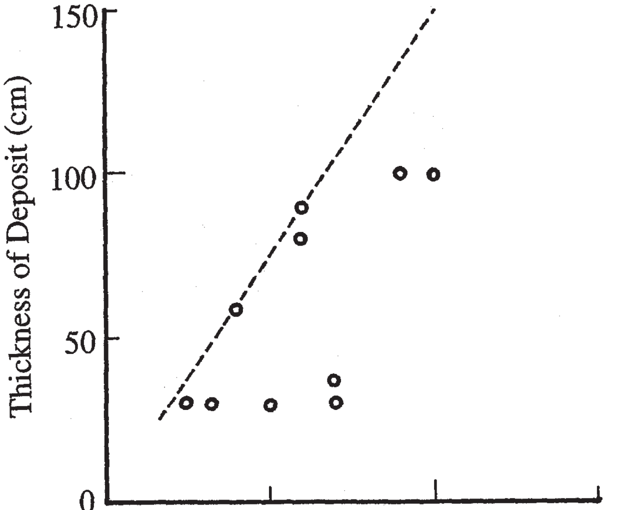

Figure 6: Relationship between thickness of tsunami deposit on land and tsunami height.

Table 3: Tsunami deposits.

Location	Year	Thickness of deposit	Tsunami height
Masuda, Shimane Pref.	1026	20–30 cm	Unknown
Shishikui, Tokushima Pref.	1605	30–45 cm	5–6 m
Misaki, Chiba Pref.	1703	60 cm	4–5 m
Ago, Mie Pref.	1707	15–30 cm	7–8 m
	1854	30–90 cm	6–10 m
Misaki, Kochi Pref.	1707	>80 cm	6–7 m
Ishigaki, Okinawa Pref.	1771	1 m	9 m
Iruma, Shizuoka Pref.	1854	>4 m	13–16 m
Niigata, Niigata Pref.	1833	1.2–1.5 m	3–4 m
Taro, Iwate Pref.	1933	25–35 cm	7 m
	1933	1 m	10 m
Minato, Miyagi Pref.	1933	8–30 cm	3.4–4.8 m
Kido, Fukushima Pref.	1933	30 cm	2.7 m

of the tsunami along the western coast of Suruga Bay. Run-up height at Iruma is exceptionally high, ∼13–16 m, compared with the run-up heights, ∼3–6 m, in the vicinity.

The Village of Iruma is located at the bottom of a tiny bay, the entrance of which is about 200 m wide. After the tsunami, a sandy hill was built and left, as is shown by the area A in Fig. 6b. The original height of this area A before the tsunami can be estimated from an old document. It is said that before the tsunami, from Mr. Tonooka's house (T in Fig. 5b), they could see his farm (F in Fig. 5b) if they stood up. After the tsunami, because of this tsunami-built hill, they could not see the farm at all. Asai *et al.* (1998) measured the height of the hill and drew the section from Mr. Tonooka's house to his farm where there is a hut now, as is shown in Fig. 5c. They decided that the original height of the hill before the tsunami was not higher than 11.2 m, from the description above. Asai *et al.* (1998) evaluated the total volume of the hill to be more than 700,000 cubic meters. They also took samples from the hill and found the sea-origin fine sands. The thickness of deposit is exceptionally large, from 4 m to 8 m. No one has yet tried to simulate this sedimentation.

Examples of deposition on land are summarized in Table 3. Tsunami heights in the table are those near the shoreline. The Niigata case in 1883 is the deposition at the upstream side of local obstacles. The Iruma case is exceptionally large, from an unknown cause. Other values might provide an idea of the possible thickness of sand deposit caused by tsunamis. Without the Iruma and Niigata cases, data are plotted in Fig. 6. The dotted line shows the upper boundary of data. Roughly speaking, the deposit 1 m thick can be caused by the tsunami height of 7 m, if there is neither exceptional concentration of tsunamis due to local topography nor existence of local obstacles to accumulate sediments, and if the amount of sand near shore is plentiful enough with no limitation.

5. Concluding Remarks

Tsunami-induced current scours, transports, and deposits bed materials. Local scouring is a cause of destruction of structures such as breakwaters, quay walls, jetties, coastal dikes, and so on. Near the toe of a jetty in the Hachinoe case, the sea bottom was scoured to the water depth of 8 m by a current velocity between 8 m/s and 13 m/s. It is an important problem to develop numerical schemes to simulate tsunami-induced current accurately, with finer grids than those in simulations of tsunami profiles.

Tsunamis not only erode but also build coastal topography. In order to solve such an exceptional case as Iruma, the dynamic law of sand deposition should be established through hydraulic experiments before a numerical simulation is tried. There are several laws for erosion and transport, but quite a few are available for deposition.

6. References

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