

# Chapter 2

## Tsunami Damage: What Is Unexpected?

Koji Ichii

### 2.1 Introduction

The 2011 Great East Japan Earthquake was a nightmare. The trust that society had for engineers turned into disappointment. More than 15,000 people died in the earthquake and the failure of the nuclear power plant forced society to face the invisible hazard of radiation.

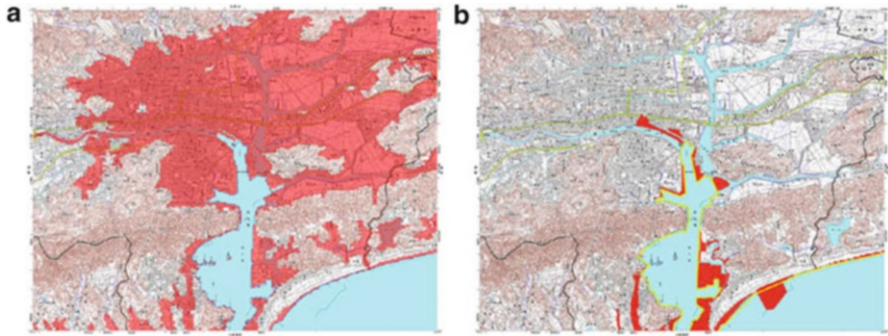
The main reason for the disaster was the large scale of the earthquake and tsunami. A 9.0-magnitude (Mw) earthquake was unexpected. However, the presidents of the Japanese Society of Civil Engineers (JSCE) and other societies jointly appeal that engineers should not use the word “unexpected” as an excuse. This appeal might be correct. The author believes the event was really unexpected, and our unawareness of the event made the scale of the disaster larger. In addition, engineers should carefully check what was unexpected and discuss why this was so.

This chapter is written to start the discussion. It focuses on the unexpected issues related to tsunamis and geotechnical structures. First, brief outlines of our conventional effort for tsunami hazard mitigation and real phenomena in the 2011 Great East Japan Earthquake are introduced. Then, unexpected issues are discussed. Finally, a proposal for the safety and relief of society is presented.

This chapter was written in September 2011. The detail of the damage caused by the 2011 Great East Japan Earthquake is still under investigation by numerous researchers and engineers. In this sense, the report of the earthquake is not fixed. It will take years to establish and share common understandings of what happened in the earthquake. However, the discussion needs to start immediately, even if there is only limited information.

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**Fig. 2.1** An example of published tsunami hazard maps (Kochi Prefecture). (Note that this map is not the latest version). (a) The case when embankments and floodgates work well. (b) The case when embankments and floodgates do not work

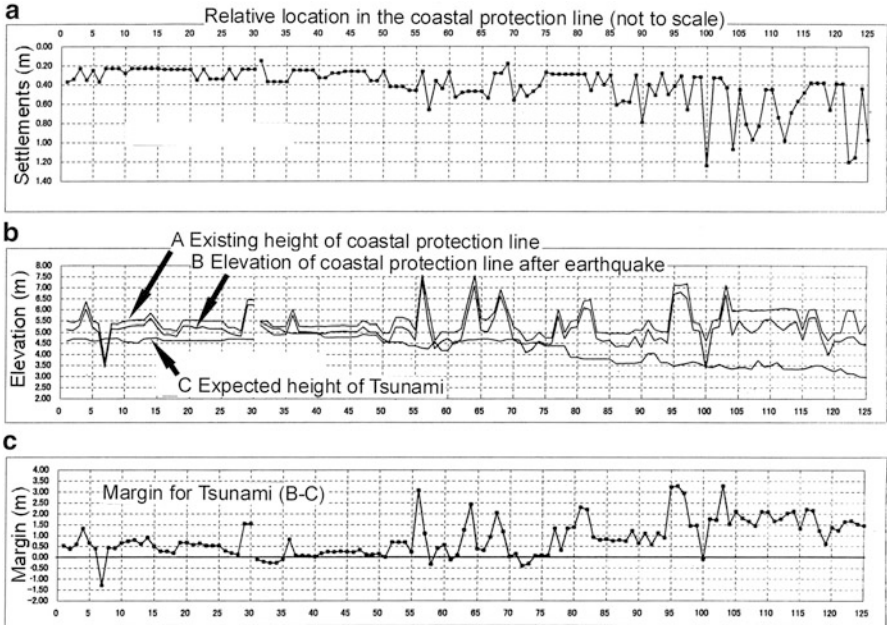
## 2.2 Efforts for Tsunami Hazard Mitigation

It is true that scientists have been working hard to prepare for future earthquakes and tsunamis. First it is necessary to summarize the conventional efforts to mitigate tsunami disaster.

One of the problems in the tsunami hazard evaluation was that the seismic resistance of coastal protection structures was not appropriately evaluated. This is mainly because of a budget shortage. It was reported that seismic performance evaluations were not conducted for almost 60 % of Japanese coastal structures in 2006. Apparently, in most cases unless an earthquake occurs far away, strong ground motion attacks structures before tsunamis. These strong ground motions sometimes trigger liquefaction in structural foundations, and coastal structures such as embankments and floodgates are damaged. The damage to these structures magnifies the tsunami disaster.

Figure 2.1 shows an example of tsunami hazard maps. This is not the latest version of the maps, but was made public by the Kochi Prefecture several years ago. The maps were prepared for two circumstances: one in which embankments, floodgates, or other coastal protection structures do not work, and the other in which these structures work well. These were the best- and worst-case scenarios. They prepared these two types of hazard maps because they did not know the seismic performance of coastal structures. Another reason was that the real situation was close to the worst case (shown on the left-hand side of Fig. 2.1). If more attention is paid to seismic performance evaluation and improvement, the situation could improve (closer to the best case shown in the right-hand side). In other words, the left side of the figure was the anticipated situation to realize the necessity of the countermeasures, and the right side was the target to be accomplished by engineers.

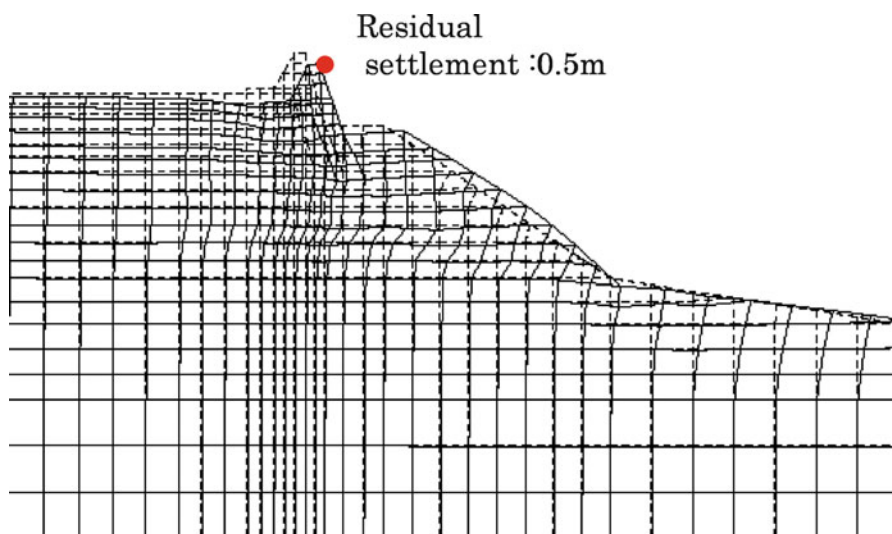
Based on this idea, seismic performance evaluation was performed with enthusiasm. Figure 2.2 shows an example of seismic performance evaluation of seaside



**Fig. 2.2** An example of seismic performance evaluation along a coastline (Osaka Prefecture). (a) Settlements of coastal structures. (b) Elevations of coastal protection lines before and after earthquakes and the expected height of a tsunami. (c) Margin of a tsunami

structures along a coastline of the Osaka Prefecture. In this area, 125 total types of structures are located on the 70-km coastline. For each structure, settlement induced by the anticipated ground motion was evaluated (Fig. 2.2a). Then subtracting the evaluated settlement from the height of the structure (A in Fig. 2.2b), the residual height of the coastal structure could be evaluated (B in Fig. 2.2b). The margin for tsunamis (Fig. 2.2c) could be evaluated by comparing the residual height (B in Fig. 2.2b) and the anticipated tsunami height announced by the Japanese government (C in Fig. 2.2b). In the case shown in Fig. 2.2, there was no margin at approximately seven parts, and further detailed investigations or countermeasures were necessary.

The evaluation of the settlement shown in Fig. 2.2 was performed by referring the summary of finite element method (FEM) parametric studies. An example of FEM analysis is shown in Fig. 2.3. Not only the deformation pattern, but also the settlement at the crest can be evaluated. The applicability of FEM analysis for coastal structures has been widely published (i.e., Iai et al. 1998). However, it was not cost effective to build a FEM model for each site. Therefore, a simple but cost-effective system to evaluate the settlement of coastal structures by referring the summary of FEM parametric studies was proposed, and it was applied to obtain the result shown in Fig. 2.2. The author was a member of the project that proposed the system.



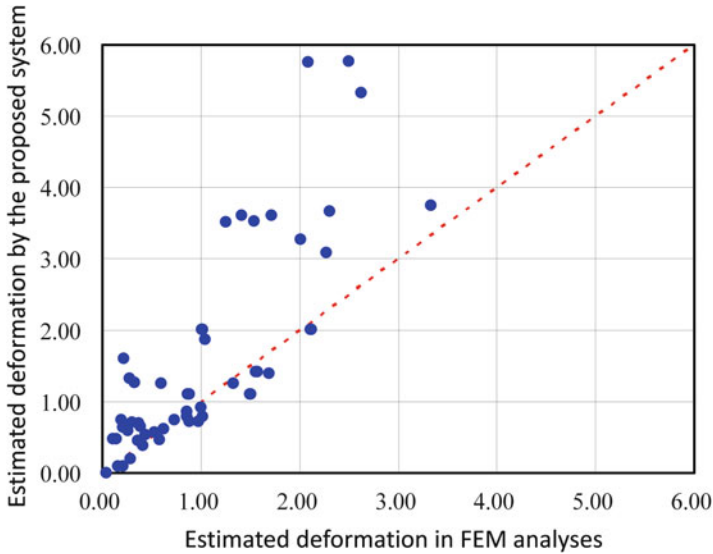
**Fig. 2.3** An example of finite element method analysis of a seawall

Although the details of the system were not published in English, the essential concept (without the data used in the final system) can be found in a paper by Ichii and Donahue (2005).

Numerous parametric studies were performed to establish the system; then the effects of the differences in the conditions (e.g., thickness of rubble slope, slope inclination) were summarized. In the application of the system to a target site, the case most similar to the target site is picked up. Based on the differences between the pick-up case and the target site, the calculated settlement of the case is corrected for the site. The summary of the parametric study is used to evaluate the amount of correction in this procedure.

Appropriate evaluation of the possible settlement is usually difficult. However, the proposed system is dedicated to be used only for the purpose of screening (i.e., selection of relatively weak sites). This clear definition of the purpose made it easy to establish the system. In other words, the system was designed to answer the safer side estimation. Figure 2.4 shows a comparison between the estimation by the proposed system and the FEM results. For half of the cases, the estimations agree well; but for the other half, the simple proposed system gives safer side values.

It should be emphasized that engineers pursue the safer side if there are unclear elements. Figure 2.1a is a worst-case scenario in which no embankment or flood-gate works. In other words, because usually not all embankments or floodgates are broken, one can expect the real situation to be better than that represented in Fig. 2.1a. Figure 2.2 shows a discussion of the tsunami hazard based on the anticipated tsunami height. This anticipated height is usually calculated from the worst-case scenario. Figure 2.4 shows the accuracy of the seismic performance evaluation. This result also indicates the existence of a safety margin related to the



**Fig. 2.4** Comparison of the results of detailed analyses (FEM) and of a simple (but safer side) system

method used in practice. Thus, we believe that there are usually many safety margins in the practice to consider uncertainties.

An example of countermeasures should be noted here. For the Kuji, Kamaishi, and Ofunato ports, breakwaters were constructed both at the gate of the port and the harbors. Figure 2.5 shows the Kamaishi Port Gate Breakwaters, which were constructed to mitigate the impact of tsunamis.

The construction of structures as a countermeasure is usually a large project that benefits the civil engineering industry. Appropriate (or exaggerated?) estimation of future disasters is necessary to realize the project. In this sense, not only the engineers but also almost all the people related to the civil engineering industry are familiar with the concept of safety margin.

In a sense, almost no one tends to cut the safety margin. Engineers have believed that they should point out the risks and hazards of earthquakes and tsunamis, and should make progress in seismic assessments and countermeasures. These efforts create a safer society, and the knowledge of these efforts gratifies engineers.

## 2.3 What Happened in the 2011 Great East Japan Earthquake

The 2011 Great East Japan Earthquake ( $M_w = 9.0$ ) was a huge-scale event. Figure 2.6 shows the estimated slippage at the fault. Both the area of moved fault and amount of slippage were quite large. This large movement under the sea bottom induced an extensive tsunami. The detailed mechanism of the tsunami is still under

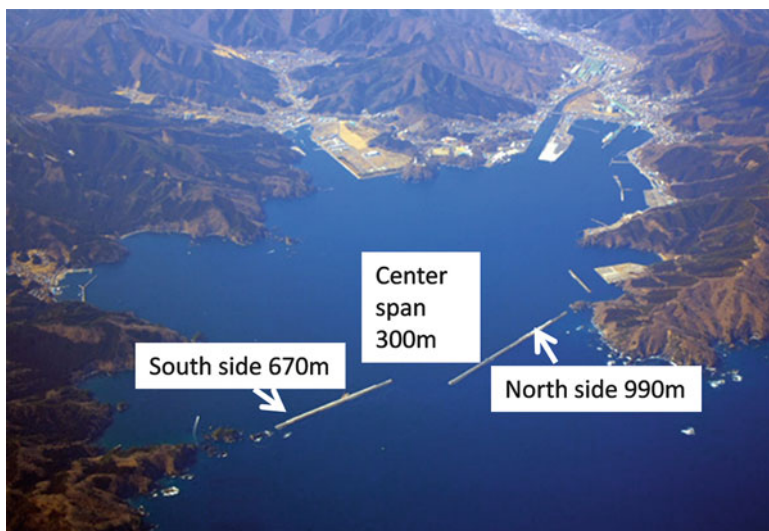


Fig. 2.5 Kamaishi Port Gate breakwaters (Kamaishi Port Office)

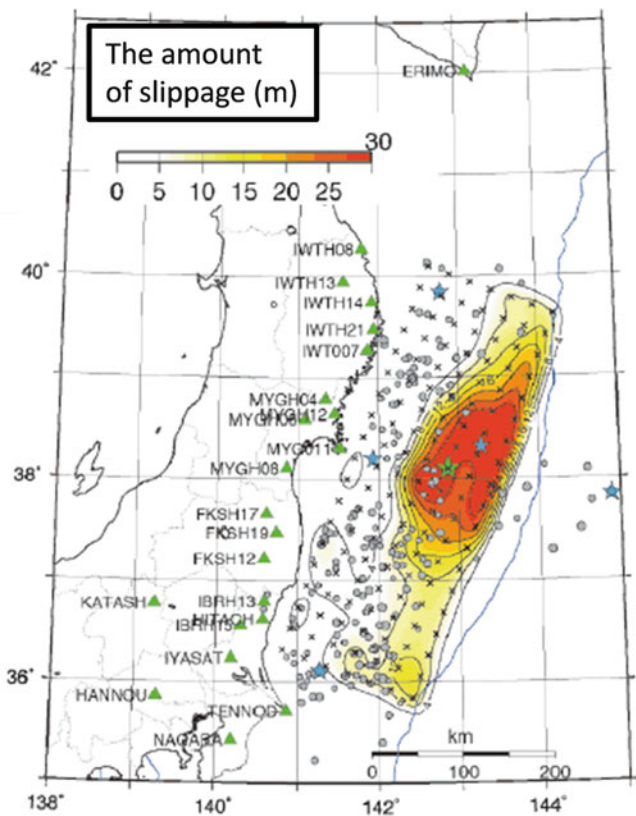
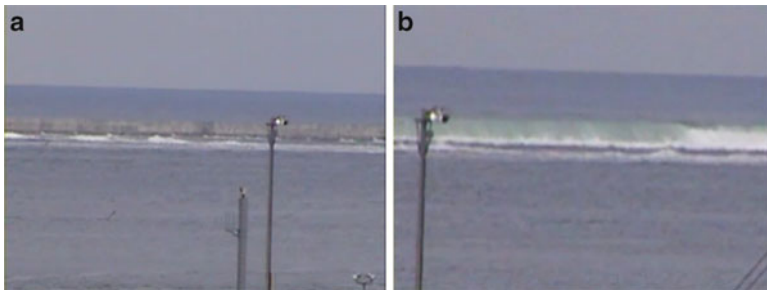


Fig. 2.6 Contours of the estimated slippage (Cabinet Office, Government of Japan)





**Fig. 2.7** Snapshots of the moment of tsunami (anonymous official). (a) The moment of tsunami. (b) Tsunami covered everything

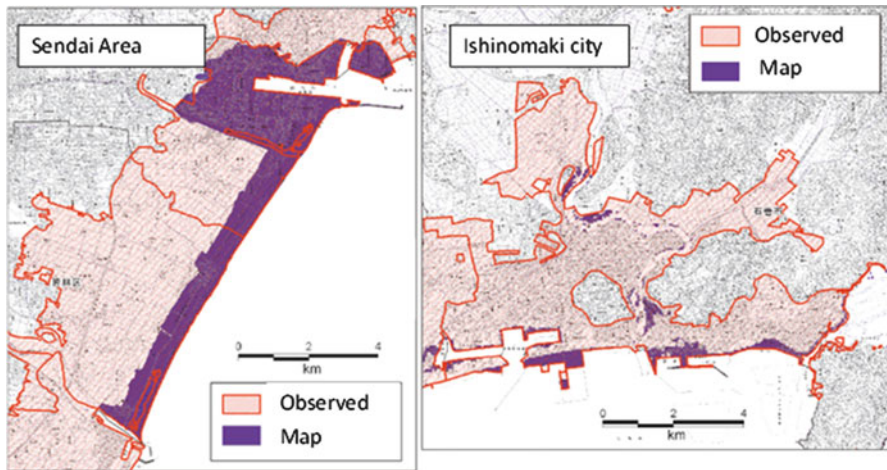


**Fig. 2.8** Snapshots of the Kamaishi Port Gate Breakwater (anonymous official). (a) Bubbles behind the caisson walls. (b) Overflowed tsunami

investigation, but the fact is that the significant height of the tsunami was observed on the eastern coast of Japan.

Figure 2.7 shows snapshots from the video recorded by a government official. He evacuated to the roof terrace of a building and recorded the entire event from the terrace. The tsunami height shown on the left side of Fig. 2.7a was almost as high as a two-story house, and the houses shown in the figure were swept away. The entire city was covered by the tsunami, as shown in the right side of Fig. 2.7b. These scenes were recorded at the Kamaishi Port, where breakwaters were installed as shown in Fig. 2.5.

The observed tsunami height was larger than expected in the design of breakwaters. The real performance and effect of breakwaters for the mitigation of tsunami impact were still under investigation and discussion. The situation at the first tsunami wave at the breakwater site was recorded by the official mentioned in the preceding. Figure 2.8 shows the tsunami at the breakwaters. In the beginning, white bubbles were observed behind the caissons of breakwaters (Fig. 2.8a). The reason of this phenomenon might be the difference of the water level between the front (tsunami) and back (port) sides. But there is a discussion that this was caused by the water flow between caissons or upward flow from rubble foundations owing to the high permeability in the foundations. Nevertheless, a few moments later, the tsunami overflowed as shown in the right side of Fig. 2.8b.



**Fig. 2.9** Tsunami inundation areas observed in reality and shown in the hazard maps (Cabinet Office, Government of Japan)

As a result of the unexpected height of the tsunami, the observed inundation was far beyond the area earlier imagined. Figure 2.9 shows the comparison between the tsunami inundation areas shown in the hazard maps and those observed in reality. The reality was much more severe than imagined.

Many people died as a result of the discrepancy between projected inundation and the reality. In addition to the people who *could not* evacuate, some people *did not* evacuate. The reason why they did not evacuate might be as follows.

“I did not imagine the tsunami would come to my place, which is far from the coast.”

“I believed the breakwaters and seawalls made us safe.”

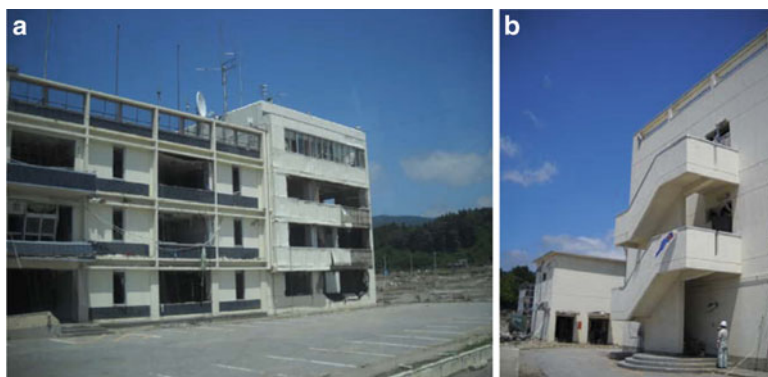
These comments are fictitious as the author did not actually conduct interviews. But similar comments were heard several times from interviews on broadcast television with people who were actually in danger. Similar comments also can be found in discussions related to the failure of the Fukushima nuclear power plant. Note that because of the limited information opened for public discussion, the debate related to the nuclear power plant failure is skipped in this chapter. However, as a philosophical issue, it might suggest similar problems.

## 2.4 From a Field Survey

The author joined the field survey team of the JSCE and visited the damaged area in July 2011. The following are more realistic reports.

Figure 2.10 shows the damage to the Rikuzentakata City Office. About one third of city officers died in the earthquake (more than 80 people out of approximately





**Fig. 2.10** Photos of Rikuzentakata City Office. (a) The damaged Rikuzentakata city office. (b) Emergency stairs of the office

300 people). The height of the tsunami was unbelievable, reaching the third floor, as shown in Fig. 2.10a. A tsunami of such a height was a completely unexpected event.

What was disappointing was the fact that the emergency stairs did not reach to the roof terrace, as shown in Fig. 2.10b. Actually, some people on the roof terrace survived. (The video of evacuated people on the terrace was recorded and broadcast throughout the Internet.) Therefore, there may have been another way to evacuate to the roof terrace, which was effective. But if the emergency stairs had reached the roof, more people could have been evacuated.

It might be impossible for us to imagine that such a high tsunami would attack the office. Otherwise, more efforts would have been made. Obviously, even for such a high tsunami, more effort could have been expended to mitigate the disaster, such as extension of the stairs to the roof, preparation of a rubber boat on the roof, and so on. The point is that it is unlikely to imagine such an unbelievably high tsunami in advance, and accept the budget required for evacuation efforts that would usually be needless.

Figure 2.11 shows damaged sea walls at Ofunato city. Emergency repairs were ongoing at the time of the survey, as shown in Fig. 2.11a. The side part of the seawall survived, and the cross-section of the wall can be observed as shown in Fig. 2.11b. An old small sea wall was recognized at the cross-section, and it was obvious that the seawalls were improved before the tsunami.

Here, the improvement of sea walls means the increase of the wall height and width. Although the details (e.g., the time of improvement) are unknown, efforts were made to ensure stronger coastal protection. Unfortunately, the tsunami height was greater than expected, and the disaster could not be prevented. The problem is that how high seawalls need to be is not known.

If there were a physical limitation to the possible height of tsunamis, the problem would be easy. For example, there might be a physical upper limit in the level of the possible strong motion because the strong motions propagate through the ground, and strong shear forces caused by strong ground motions require large shear strain in the ground. Usually, the ground has strong nonlinear characteristics, and large shear strain



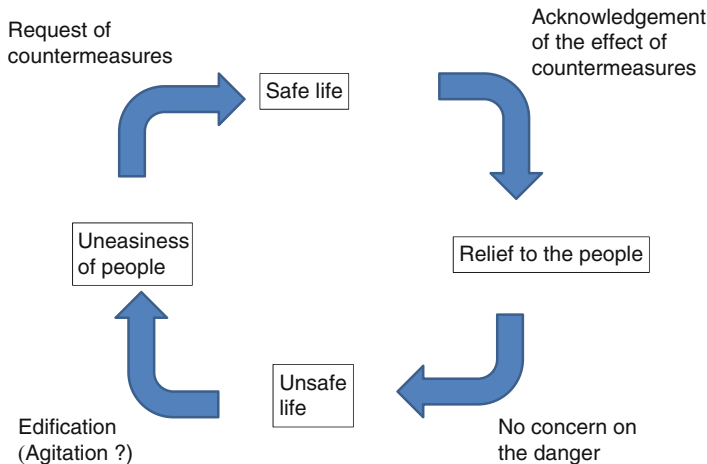
**Fig. 2.11** Photos of seawalls with improvements prior to the tsunami. (a) Damaged sea walls in Ofunato City. (b) Evidence of improvements

decreases the shear stiffness. Thus, strong motions cannot be transmitted without losing the features of motions. However, a tsunami is the movement of a water mass. It looks like the larger movement of sea bottom ground could induce larger water mass movement. Furthermore, not only earthquakes, but also any types of sea bottom movement, such as landslides, can create tsunami. Therefore, it appears that there is no upper limit to tsunami height. This implies that completely sufficient countermeasures are impossible. The level of safety or relief can be increased; however, the possibility of an unexpected event and disaster always remains.

## 2.5 Safety and Relief

The expectation for civil engineers is to build a safe society and offer reassurance to the people. However, the facts observed in the 2011 Great East Japan Earthquake disaster remind us that it is almost impossible to build a safe and reassured society. From the previous discussion, the following has been learned.

- (a) Although engineers tend to choose safer options, in reality the hazard can be far beyond the expectation.
- (b) Publication of hazard maps or construction of breakwaters as countermeasures was believed to be effective to mitigate tsunami disaster. However, these efforts not only give the society a false feeling of relief, but also restrain people from evacuating. Therefore, once the real hazard becomes more severe than the expectation, the damage could be magnified.
- (c) Even for the magnificently high tsunami observed after the earthquake, something could have been done to mitigate the disaster; for example, the extension of emergency stairs and preparation of rubber boats.
- (d) Efforts to improve coastal structures have been carried out and may contribute to more safety. However, the tsunami height was greater than expected. This fact confirms the fact that nobody can identify enough improvements to ensure complete safety.



**Fig. 2.12** The relationship between “safety” and “relief”

The author thinks that these lessons are related to the relationship between safety and relief. Lately, safety and relief have been buzz words in Japanese public administration and civil engineering. Many politicians try to guarantee the safety and relief of society. Many projects have been put into practice to build a safe society and give relief to the people.

The relationship between safety and relief can be schematically illustrated as shown in Fig. 2.12. Safety can be established by the preparation of countermeasures, and relief can be realized by the acknowledgment of the effect of countermeasures. However, once the people obtain relief, they lose the concern about the danger. A situation that does not have a consciousness of danger is a truly unsafe condition. Therefore, engineers should work hard to educate the people. In a sense, this edification is a kind of agitation to make the people request countermeasures. As a result of education, they may feel unease and request countermeasures. Thus, civil engineering projects to provide a safe society can be conducted at the request of the people. This is an endless cycle, and will not ensure safety for all.

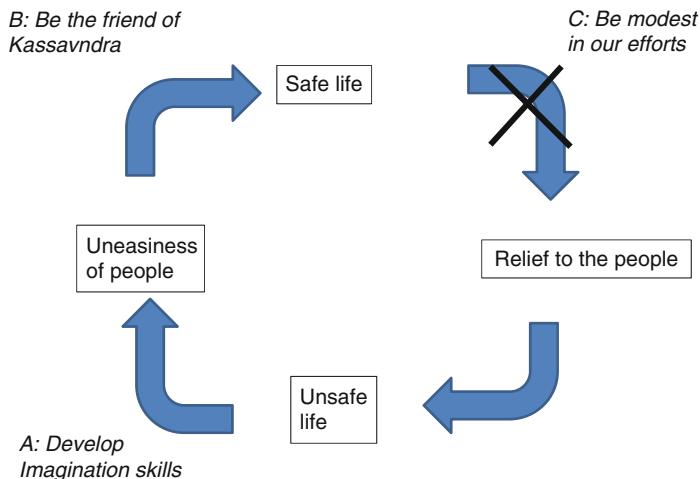
Considering the cycle shown in Fig. 2.12, what we should learn from the experience to stop the cycle is summarized in Fig. 2.13. There are three main lessons.

(a) *Develop imagination skills*

The development of more imagination is needed. In a sense, it was not recognized before the earthquake that the people were too reassured and were therefore unsafe. Engineers were also too reassured considering that they tend to choose safe practices. This was actually because of the shortage of imagination. Not only the tsunami phenomenon itself, but also the limited collective imagination was unexpected in this disaster.

(b) *Be a friend of Kassavndra*

Kassavndra was a female prophet in Troy. Her prediction was right, but nobody believed her. It is not clear whether there was a person who pointed out the possibility of such a great disaster in advance. However, people would not



**Fig. 2.13** What should be done to stop the endless cycle

believe it until it really happened. Therefore, even if somebody foretold the event, the extension of the emergency stairs at the city office would not have been done. The calamitous story is often ignored, and the person who tells it is regarded as a kind of Kassavndra because it is not expected. We must become a friend of Kassavndra and learn how to adapt to the story.

(c) *Be modest in our efforts*

Engineers often pride themselves on their efforts for society, especially those efforts to build a safe society, which contribute to the relief of people. However, in a sense, these efforts were overrated by the people, and their relief made the disaster worse. This was truly an unexpected situation. Engineers should be more modest. This is an especially severe issue in the discussion related to the failure of the nuclear power plant.

## 2.6 Conclusions

As mentioned earlier, it will need years to establish and share common understandings of what really happened in the earthquake. This chapter is written to start the discussion of the unexpected issues related to tsunamis and geotechnical structures. The event was truly unexpected, and this ignorance of the possibility of such an event enlarged the disaster. What and why was unexpected must be carefully reviewed and discussed.

As a result, some unexpected factors in the relationship between safety and relief have been pointed out. Shortage of imagination, avoiding unhappy stories, and overestimation of the effort for countermeasures could have been improved. These kinds of unexpected matters should be carefully checked to avoid future failures.



**Fig. 2.14** Decoration for a festival at the temporary office

In addition to these unexpected matters that amplified the disaster, some unexpected benefits were also observed. For example, Fig. 2.14 shows a decoration at the temporary office of Rikuzentakata City. This decoration encouraged the people, especially the children of the city. The mutual cooperation and undefeated attitude of the people in the damaged area were also admirable. Human virtues beyond expectation were demonstrated.

## References

- Anonymous Official (2011) The video tape recorded on the roof terrace of Kamaishi port Office, Anonymous government official in Kamaishi Port who recoded the video
- Cabinet Office (2011) White paper on disaster management 2011, Government of Japan (In Japanese with English executive summary on the website, <http://www.bousai.go.jp/hakusho/h23/index.htm>, downloaded on September, 2011)
- Iai S, Ichii K, Liu H, Morita T (1998) 'Effective stress analyses of port structures', Special issue of soils and foundations. Jpn Geotech Soc 29:97–114
- Ichii K, Donahue MJ (2005) Evaluation of sea dike settlement due to seismic shaking prior to tsunami attack. In: Solutions to coastal disasters 2005, ASCE, Charleston, pp 616–629
- Kamaishi Port Office. The outline of Kamaishi Port Gate breakwaters, [http://www.pa.thr.mlit.go.jp/kamaishi/bousai/b01\\_03.html](http://www.pa.thr.mlit.go.jp/kamaishi/bousai/b01_03.html) in Japanese, downloaded on September, 2011
- Kochi Prefecture: Website of Kochi prefecture in a past time (downloaded on September 1, 2007) (The latest version can be found at: <http://www.pref.kochi.lg.jp/soshiki/010201/tunamisin-suiyosoku.html>) (in Japanese)
- Osaka Prefecture: Non-published information related to the committee of disaster prevention along the coastal line, the committee was organized from 2005 to 2006

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