GEO-HAZARDS DURING EARTHQUAKES AND MITIGATION MEASURES

-LESSONS AND RECOMMENDATIONS FROM THE 2011 GREAT EAST JAPAN EARTHQUAKE-

The Japanese Geotechnical Society

July 2011
The Japanese Geotechnical Society
2011 Committee for Geo-hazards during Earthquakes and Mitigation Measures
4-38-2, Sengoku, Bunkyo-ku, Tokyo
TEL: 03-3946-8677 FAX: 03-3946-8678 jgs@jiban.or.jp
http://www.jiban.or.jp

Actions taken after the Earthquake

When the largest earthquake in Japan's modern history, the 2011 Great East Japan Earthquake of Mw9.0, struck on 11th March, members of the Geo-disaster Committee of the Japanese Geotechnical Society (the JGS) immediately began an initial survey of the damage. The JGS decided on the following action plans to the disaster one week after the Earthquake:

(1) Confirmation of safety of the members, and message from the President

(2) Support for the disaster areas: collection of donations, and responses to requests for surveys, restoration and reconstruction

(3) Surveys: initial survey, dispatch of primary and secondary survey groups

(4) Research:

(5) Reporting and disseminating information: primary, secondary, tertiary, and final survey reports

(6) Recommendations: preliminary and final reports on lessons and recommendations

(7) Establishment and implementation of business continuity planning (BCP) for the functions of the JGS

In accordance with the above action plans, in the last four months since the outbreak if this earthquake, The JGS website was renewed and a special corner on the March 11 Earthquake was created (18th March), the first survey report meeting was organized (11th April), a professional volunteer system was established and registration started (1st April), a special session on the Earthquake was organized at the Asian Regional Conference of the International Society of Soil Mechanics and Geotechnical Engineering (24th May), publication of the survey reports in the JGS's monthly journal has begun (from June edition), a draft of the preliminary recommendations was released (1st July), a report on the disaster was presented at the Japan-Korea Geotechnical Engineering Workshop (6th July), and disaster reports and draft recommendations were presented and discussed at an Annual Conference of the Japan Geotechnical Society (7th July). We are currently preparing to donate copies of a reprint of the book "Ground in Kanto Region" to the affected local governments while identifying research issues, dispatching specialists to central and local governments, and taking commissions for investigations, etc. As to the future, we are preparing for a Japan-India Workshop in December and also considering the possible submission of an appeal to the United Nations regarding the importance of geo-disaster prevention (via the International Society of Soil Mechanics and Geotechnical Engineering).

Issues Raised by the 2011 Great East Japan Earthquake

(a) Significance of subduction zone earthquakes

Unlike earthquakes caused by inland active faults, such as the 1995 Great Hanshin-Awaji Earthquake, this was an earthquake along the subduction zone of large moment magnitude of Mw=9.0 whose seismic motions continued for a long time. Damage from this earthquake and its many aftershocks occurred in many locations over a very wide area, causing restoration and recovery to be delayed. The ground subsidence associated with crustal movements exceeded the normal engineering response level. Further, the unprecedented scale of the problems was overwhelming, with the immediate damage compounded by the tsunami, ground contamination, salinity of farmland, and the need to dispose of the waste generated.

(b) The difference in structural safety of public and private assets

On the one hand, damage to many public assets such as social infrastructures that had been designed in accordance with the latest technical standards was little or none, which has proven effectiveness of the current seismic technologies, but on the other hand there was an evident lack of safety in private assets including reclaimed residential land and private houses, etc..

(c) The importance of business continuity planning (BCP) and of preventing damage to system functionality

It was revealed that even in cases where there was no damage to the main structures of railways and industrial facilities, etc., the functionality of systems as a whole did not work due to damages to the ancillary facilities. This confirms the importance of system safety and BCP.

(d) The need for integrated and comprehensive measures for restoration and reconstruction as well as strengthening expertise in local governments

Many government departments are involved in recovery from disaster and action against radiation damage, including the Ministry of Land, Infrastructure, Transport and Tourism, the Ministry of Agriculture, Forestry and Fisheries, the Ministry of Economy, Trade and Industry, the Ministry of the Environment, the Ministry of Education, Culture, Sports, Science & Technology, the Ministry of Health, Labor and Welfare. There have been many reported problems caused by the vertically segmented government organization arising from differences at the national, prefectural, city, town, and village levels. These difficulties led directly to passage of the Basic Act on Recovery from the 2011 Great East Japan Earthquake was enacted on 20th June; going forward, vigorous efforts are needed to implement integrated and comprehensive restoration and recovery measures. On the other hand, local governments are short of the necessary personnel and technical expertise, and there is great concern that this is delaying recovery. Looking to the future, it is essential to foster personnel with technical expertise suitable for dealing with disaster prevention and disaster mitigation, managing surveys, and overseeing design, construction, and maintenance.

(e) Legal system development

Japan's experience with natural disasters in the past has driven rapid development of disaster-related laws. Together with reviewing laws relating to buildings, restrictions on land use, laws guaranteeing a steady and continuous upgrade process for safer social environment should be established on the experience of this disaster.

(f) Fragility of industrial structure and national land structure, and the opportunity for change

The fragility of the current industrial structure, in which globalization and the worldwide division of labor have become extreme, is now evident. There is a possibility that the scale of damage caused by this disaster and delays in recovery may become an impetus to the migration of manufacturing industry overseas and the hollowing out of industry.

While sharing concern over these issues, the JGS has been compiling its recommendations (preliminary recommendations) since the end of March as part of the social contribution of the geotechnical engineering field. Previously, the JGS published recommendations for mitigating geo-hazards due to earthquakes and flooding in 2009. With this enormous disaster occurring just two years after their publication, the summarized preliminary recommendations include a verification of the 2009 recommendations as well as coverage of new forms of damage.

A draft of the preliminary recommendations was published on 1st July 2011 along with a call for public comment, and many valuable responses were received. For these we are very thankful. The essence of most of these public comments has been integrated into this version of the recommendations. However, certain responses will take more time for us to fully discuss and integrate. Since it is imperative to publish the basic lessons learned and recommendations as soon as possible (so they can be referenced in ongoing restoration and recovery plans, design method reviews, and disaster prevention and disaster mitigation work), we have decided to delay incorporation of these until the final version of the recommendations, which is targeted for publication at the end of fiscal year of 2011. Thus it should be noted that discussion of the following points is not included in this document:

- Detailed investigation and theoretical explanation of the geotechnical mechanisms of various examples of geo-hazards, such as the collapse of soil structures including embankments, collapse of breakwaters and tidal embankments, etc., due to liquefaction or the tsunami;
- Specific detailed explanation and proposals for methods of restoration and countermeasures against individual cases of damage;
- Methodologies of disaster prevention and disaster mitigation on which opinion is divided.

The publication of this document and the various efforts of the JGS to survey and investigate the earthquake and tsunami damages would not have been possible without the financial support of many members and the organizations listed below. On behalf of the JGS, I wish to express our immense gratitude for their supports.

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- Korean Geotechnical Society
- Hat-Ring Construction Method Study Group
- Japanese Association for Steel Pipe Piles

Osamu Kusakabe
President, the JGS
July 2011

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Committee Members for Geo-hazards during Earthquakes and Mitigation Measures (the 2011 Great East Japan Earthquake)

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Cooperator	Toshihiro Yokota	Wastewater System Division, Water Quality Control Department, National Institute for Land and Infrastructure Management, Ministry of Land, Infrastructure, Transport and Tourism

1. Introduction

The 2011 Great East Japan Earthquake of 11th March 2011 was the most disastrous earthquake since the Second World War, and of the largest magnitude in Japan's history as a developed country. It was a large-scale subduction zone earthquake whose main motions were prolonged and that caused widespread damage at many locations. The damage was a combination of those from seismic motions and the accompanying tsunami, and was of much greater scale than that caused by the previous inland fault earthquakes in Japan. Though modern a-seismic technology and disaster prevention systems functioned well in many cases and reduced the seismic damage, breakwaters and tidal barriers were only partially capable of protecting against the massive tsunami. As a result, cities and urban areas all along the coast were engulfed by the tsunami, resulting in many deaths. Over a wide area, industrial facilities (including many fishing-related installations, fossil-fuel power stations and, in particular, Fukushima No. 1 nuclear power station), transport and distribution facilities, residential units and private houses, lifeline utilities such as water supply and sewage, and agricultural land suffered enormous damage. At the same time various ongoing problems arose, such as salinity of farmland, tsunami deposits, radiation-contaminated soil, disaster-related waste, etc., as well as problems such as widespread ground settlement and subsidence.

Some more details about the 2011 Great East Japan Earthquake, as well as partial report of damage, are summarized in Appendix, shown at the end of this report.

In this disaster, various types of geo-hazards made the overall damage more serious (Fig. 1-1a, b, c). Many soil structures such as embankments, retaining walls, etc. were damaged, causing serious societal harm. These soil structures are often constructed because construction is usually relatively quick and relatively low in cost, while soil embankments may balance well with soil from the construction of tunnels, cuttings, etc. As a result, soil structures can be economical and can have low impact on the natural environment. Further, their deterioration is generally slow and easily restored when damaged compared with other artificial structures. For these reasons, they have been constructed in large numbers throughout history and will no doubt continue to be used in the future. However, construction technology is constantly developing and required levels of safety, and functionality are constantly rising. As a result, there are currently vast numbers of "*old soil structures that may not satisfy current technical standards and societal reqirements*[1] *and natural ground and slopes of which the seismic stability has not been examined*.[2]" The society has received serious damages from failure of many of these soil structures and natural ground and slopes by the earthquake.

Note 1) Old soil structures that may not satisfy current technical standards and societal requirements. These are existing soil structures such as roads, railways, housing areas, reservoir dams, embankments, retaining walls, etc., river and coastal dikes, reclaimed land, and underground structures such as sewage manholes, piping, agricultural pipelines, etc., that have essentially been constructed in accordance with old technology and old standards, and that do not meet the functionality required by current technical standards and societal requirements. In the actual process, soil structures that are suspected of not satisfying the performance requirements of the current technical standards are subject to investigation of seismic stability, and the results determine whether the requirements are met or not.

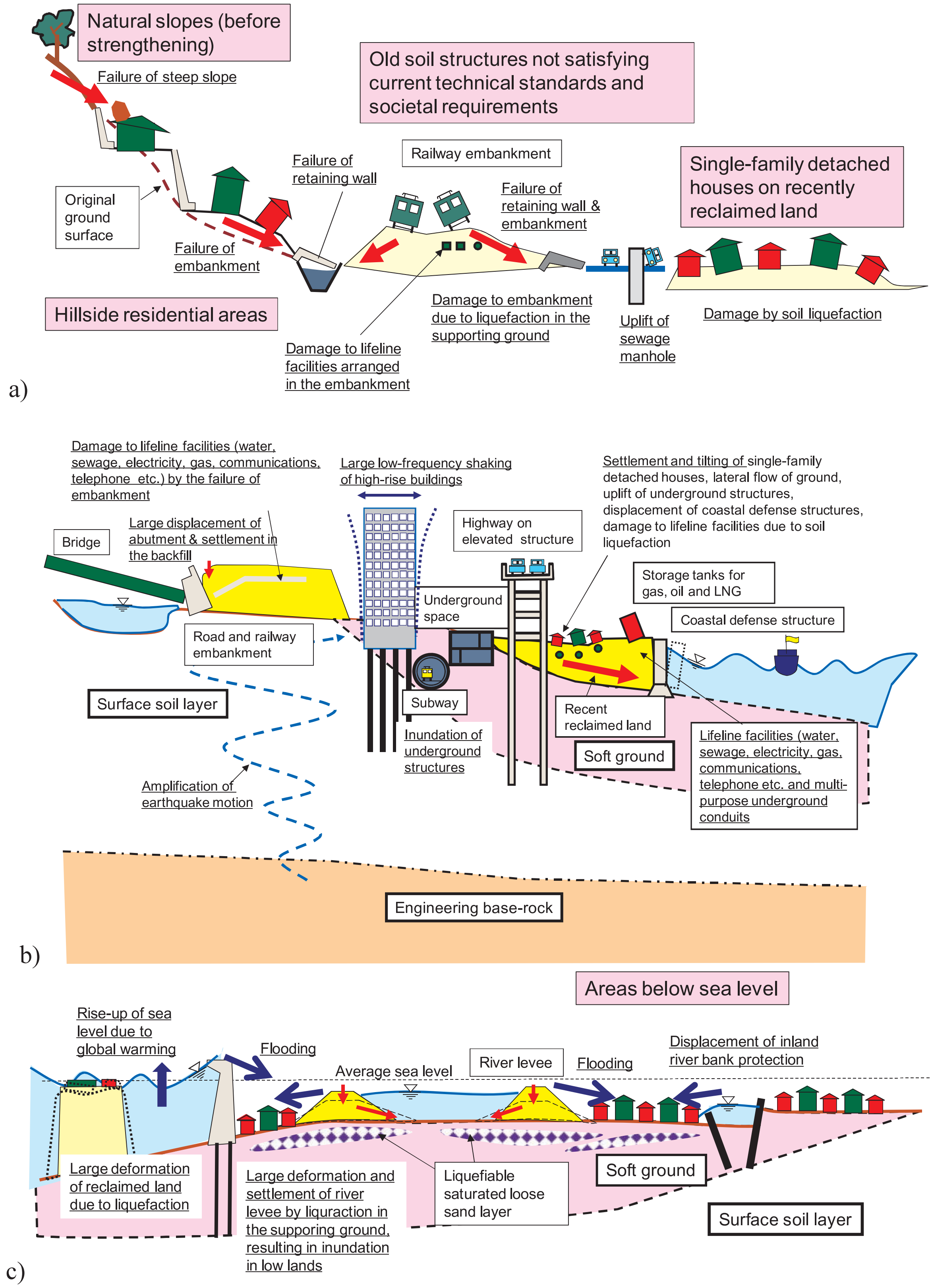


Fig. 1-1. Schematic figures illustrating seismic damage in general: a) inland area; b) coastal urban area; and c) lowland area.

Note 2) Natural ground and slopes of which the seismic stability has not been examined: There are natural ground and slopes that would have a large effect on society if they collapsed, but for which surveying and countermeasures have not yet been taken. In the actual process, natural ground and slopes that would have a large effect on society if they collapsed and that are suspected of not satisfying the performance requirements of the current technical standards are subject to investigation of seismic stability, and the results determine whether necessary countermeasures are to be taken.

Large-scale buildings and facilities relating to the public infrastructure are designed and constructed in accordance with design systems and design standards that, over time, are revised to reflect progress in technology and advancing societal requirements. Moreover, there are systems in place for ongoing maintenance of such structures. On the other hand, private assets such as private houses tend to lag behind in the application of the latest technological standards, and normally there is no ongoing maintenance system. In this earthquake, many private houses were damaged and many people suffered from serious harm as a result of the collapse of embankments on hillsides and the liquefaction of recently reclaimed land. At the same time, damage to water supply and sewage systems added to the difficulties of survivors. Where bearing ground liquefied, damage was caused to private houses and to soil structures such as embankments, retaining walls, pipelines, and other underground structures that did not take soil liquefaction into account in design, resulting in superstructure damage.

The two main causes of geo-hazards are:

a) poorly compacted embankments and the use of soft soil as the backfill; and

b) poor drainage for surface rainwater and groundwater.

A particular feature of this earthquake, in addition to the diversity of geo-hazards that it caused, is that it struck an extremely large area and caused damage at great many locations. As a result, recovery and restoration work has been significantly delayed and efforts are still continuing at many locations even a half year later.

On the other hand, there was little damage to elevated road and railway structures, bridges, multi-purpose underground conduits, airports, and other public structures where countermeasures against soil liquefaction had been made. The same is true for most medium- and high-rise buildings. This is in contrast to the fact that numerous sewage facilities, agricultural pipelines, river dikes, other similar public structures, low-rise housing, gasoline tanks, and other industrial facilities where no countermeasures had been taken against liquefaction suffered damage. High rockfill dams, which had been designed originally to withstand earthquakes, had little or no damage. Similarly, cuttings, embankments, retailing walls, etc., that had been constructed using the new geotechnical technology of soil-reinforcing suffered little or no damage..

The Japanese Geotechnical Society (the JGS) is a group with a membership of engineers and researchers. Many of them specialize in geo-hazards. They research and investigate geo-hazards and develop countermeasures, contributing to society by reducing the damage caused by geo-hazards. Hence the JGS has a long history of engagement in this area.

In this document, we summarize the initial lessons learned so far from this earthquake and offer concise recommendations. Through timely publication, we aim to contribute to recovery and restoration efforts and to prevent or reduce the damage caused by future disasters in Japan. In doing this, five basic questions have been addressed:

1) Have the mechanisms and causes of the observed geo-hazards been determined?

2) Has geotechnical engineering contributed to mitigating the disaster caused by this earthquake by reducing geo-hazards?

3) What kind of geo-hazards has this earthquake caused because damage prediction and countermeasures against damage were not carried out?

4) At this point in time, which geotechnical engineering methods or technologies can be proposed for use in recovery, restoration, disaster prevention, and disaster reduction?

5) In order to reduce geo-hazards in the future, what issues need to be resolved in geotechnical engineering investigations, design, implementation, and maintenance?

The first question is the basis for the following questions, 2) through 5). However, long-term research is necessary to correctly determine the causes of damage through on-site damage investigations, geological and ground investigations, field and laboratory testing, analysis, and investigations using the lessons learned from past earthquakes. This means that work to answer points 2) through 5) might be significantly delayed if waiting for an answer to question 1). Therefore, it was decided to take into account the circumstances listed below while pursuing efforts to answer questions 2) through 5).

a) The importance of rapidly restoring the strength and function of superstructures compromised by damaged soil structures and geo-hazards.

b) The need for geotechnical engineering and technology in developing concepts for a multi-pronged approach to tsunami defense, including moving residential areas to higher ground out of the reach of large tsunamis.

c) The need for appropriate treatments for restoring the ground of damaged private houses on embankments on hillsides or on recently reclaimed land, for evaluation of the possibility of the occurrence of seismic disaster in the future and retrofitting of existing private houses, and for the seismic design of new private houses.

d) The need for evaluation of the possibility of the occurrence of seismic disaster in the future to identify the likely very large number of existing soil structures that do not satisfy current standards and also the natural ground and slopes that would have a major impact on society if they collapsed, and the urgency of seismic strengthening based on the results.

e) The importance of ensuring stability of ancillary facilities against geo-hazards so as to maintain the functions of systems as a whole.

f) The need to apply a geotechnical engineering approach to various problems such as widespread ground settlement and subsidence, salinity of farmland, tsunami deposits, radiation contaminated soil, and the disposal or effective utilization of disaster-related waste, etc.

The intention is that these preliminary recommendations will provide effective defense against disasters that are considered possible in the near future anywhere in the country. While on the one hand more time will be required to prepare full and final recommendations, there is also an urgent need to provide recommendations that contribute to the restoration and recovery process and to defend against and mitigate future disasters. It is for this reason that the decision was made to summarize the draft recommendations now at this point in time.

2. Impact of the 2011 Great East Japan Earthquake

2.1 Background to the 2011 Great East Japan Earthquake

Prior to the 1995 Great Hanshin-Awaji Earthquake, there was no systematic seismic design, seismic risk evaluation, or strengthening of many soil structures of normal size such as embankments and retaining walls for railways, roads, and residential developments, river dikes, small-scale irrigation dams, quay walls, buried structures such as manholes, pipes, cuttings, and natural slopes that might have a major impact on society if they collapsed. On the other hand, such work was carried out for the foundations of elevated structures and bridges, medium- and high-rise buildings, high rockfill dams, and large-scale embankments. Then, in the 1995 Great Hanshin-Awaji Earthquake, a great deal of public infrastructure as well as many medium-rise buildings collapsed when seismic motion exceeded the highest levels of seismic loads that had been envisaged in the Japanese seismic design codes. Many natural slopes also collapsed and port facilities suffered damage due to liquefaction of reclaimed ground. In addition, many artificial soil structures such as embankments and retaining walls also collapsed. In response to this event, the concept of Level II design seismic motion[3)], in addition to Level I design seismic motion[3)], was introduced for seismic design.

Note 3) Level I design seismic motion: seismic motion with a high likelihood of occurring during the design life time of a structure. It is required that, in principle, all new structures have sufficient seismic resistance to ensure "no damage" when subjected to this seismic motion.
Level II design seismic motion: the strongest seismic motion thought likely to occur at the location of the structure in the future. It is required that a structure should not collapse, although damage that renders it unusable is acceptable if its functionality can be rapidly restored.
(Japan Society of Civil Engineers tertiary recommendations)

In earthquakes since the 1995 Great Hanshin-Awaji Earthquake (such as the 2004 Niigata Prefecture Chuetsu Earthquake, the 2007 Noto Peninsula Earthquake, the 2007 Niigata Prefecture Chuetsu Oki Earthquake, the 2008 Iwate-Miyagi Nairiku Earthquake, and the 2009 earthquake with its epicenter in Suruga Bay, and others), widespread collapse of soil structures greatly affected the overall transport function provided by rail lines and roads as well as the everyday lives of the people, resulting in considerable social problems.

Hence, since the experience of geo-hazards in the 1995 Great Hanshin-Awaji Earthquake and later seismic events, there has been a gradual introduction of seismic design in consideration of Level II seismic motion for soil structures, foundation ground, and the foundations of superstructures as outlined below, although the timing of the change and the level of seismic resistance required differed with the type of soil structure and the organization responsible for it:

a) Level II design seismic motion was introduced for important soil structures and foundation ground, such as retaining walls, large-scale embankments and superstructures, for which seismic design had been carried out in the past,

b) Seismic design was introduced for soil structures such as embankments which had not normally been subject to seismic design in the past, and

c) Seismic risk evaluation and a-seismic strengthening work were initiated for important soil structures based on these policies a) and b).

The JGS has long been engaged in various activities aiming at reducing geo-hazards. In 2005, the Kanto Branch of the JGS published "Protecting the Capital Area from Nearby Earthquakes – Recommendations based on Geotechnical Engineering.” This work was later expanded to cover the whole of Japan and also to include geo-disasters due to severe rainfall and flooding as well as earthquakes. The aim was to increase awareness of the mechanisms and risks of geo-hazards and the need to implement countermeasures, as well as to disseminate recommendations in specific fields and the knowledge needed to implement them. The contents of the resulting publication, "Protecting against Geo-hazards due to Earthquakes, Severe Rainfall, and Flooding – Recommendations based on Geotechnical Engineering (2009),” are summarized below.

1) Geo-hazards actually cause serious problems as well as being a major latent hazard to society. However, this is not widely recognized or understood in society.

2) The Japanese Geotechnical Society must not only point out the risk of geo-hazards, but also provide measures based on geotechnical engineering to prevent or reduce it.

3) Many of the large numbers of existing soil structures such as cuttings, embankments, and retaining walls constructed in older times using old methods, as well as natural slopes that would have a major impact on society if they collapsed, are insufficiently safe when viewed against today's societal demands and technical standards. It is important to evaluate the risk of seismic damage of important structures and to strengthen them against earthquakes, severe rainfall, and flooding when necessary.

4) When restoring soil structures such as cuttings, embankments, and retaining walls after earthquake, rain, or flooding induced collapse, a rapid method of regaining their function is desired. However, an old structure should not be restored to its original form; rather, it is necessary to carry out a "strengthening restoration" of the soil structure in such that an economical and highly disaster resistant structure is obtained based on the latest geotechnical technology.

5) It is frequently more effective to carry out integrated countermeasures against earthquake, severe rain, and flooding than to implement them individually. Also, it is necessary that the various organizations involved cooperate and work coordination.

6) The policy of not actively designing natural slopes, grounds, and soil structures such as cuttings, embankments, and retaining walls against earthquake, severe rain, and flooding should not be the norm. Instead, it should be standard practice to carry out design, construction, and maintenance such that disaster resistance is as high as possible.

7) Geotechnical engineering has come a long way must continue to develop further in the future. Various technologies must be brought to bear in efforts to mitigate geo-hazards.

8) Disaster reduction measures together with disaster prevention measures are necessary.

9) It is necessary that efforts related to geo-hazards and our response to it continue; this is a story without end that does not reach a conclusion in the near future. The JGS must continue to provide recommendations on this matter, and continue its public information and education work.

With respect to 9) above, the JGS has produced, under commission from the Japan Science and Technology Agency, "Course on Liquefaction of Grounds and Technology for its Reduction" (2008), and "Protecting the Public from Geo-hazards" (2009) for its web-based learning plaza. Anyone can take these courses on the Internet (http://weblearningplaza.jst.go.jp/). Further, technical courses are systematically given in the JGS's periodicals and at various technical meetings and courses for the lay person (including courses at clients' sites) on the topic of geo-hazards.

2.2 Summary of lessons learned from the 2011 Great East Japan Earthquake

The 2011 Great East Japan Earthquake of 11th March 2011 has been investigated against the background given above, resulting in the following understanding.

1) There were many examples of damage being effectively prevented through the application of geotechnical engineering. On the other hand, land use is spreading, so areas with weak grounds, reclaimed ground where liquefaction can easily occur, sloping areas, and other similar previously undeveloped sites are now in use. There are also many embankments on reclaimed ground or vacant ground. As a result, geo-hazards occurred in many residential areas and other locations.

2) There were many cases of damage where the cause and type of damage were not anticipated in the publications of the JGS mentioned above and in the technical standards. In particular, this category includes the massive tsunami, the huge area that suffered damage in so many locations, the ongoing large-scale aftershocks, the loss of system functionality due to geo-hazards in ancillary facilities, ground subsidence and ground settlement over a wide area, salinity of farmland, heavy tsunami deposits, radiation contaminated soil, and the management and disposal of waste resulting from the disaster. In particular, failure to anticipate the forms of damage listed below was noteworthy.

2.1) Damage due to the massive tsunami

Most of the damage inflicted by the tsunami was related to geo-hazards. Examples include the washing out of embankment-type tidal barriers and river dikes as they overflowed, collapse of gravity breakwaters due to scouring of the bearing ground, washing away of bridge beams, and washing out of embankment material behind road and railway bridge abutments, etc.

Geo-hazards of various forms also exacerbates problems relating to the management and rectification of salinity of farmland, disaster-related waste, toxic and nuclear soil contamination, tsunami deposits, etc.

2.2) Geo-hazards in ancillary facilities leading to loss of system functionality

Certain important industrial installations, including fossil-fired power stations along the coast, were adequately prepared for earthquakes having implemented measures against soil liquefaction, for example, so the main installations themselves suffered little or no damage. However, ancillary facilities such as quays, pipelines, and transport infrastructure related to these important installations were not sufficiently prepared and lacked measures to cope with soil liquefaction and tsunamis. As a result, there was unexpected loss of function when the earthquake and tsunami caused geo-hazards. This meant that in many cases industrial installations were unable to ensure business continuity, highlighting the importance of a business continuity plan (BCP). There was even one example of power transmission pylons being damaged by the collapse of an adjacent embankment. In other cases, there were examples where differential settlements of foundations caused buildings to tilt and suffer from structural damage, but did not lead directly to impairment of function. In several cases, electricity sub-stations were temporarily rendered unusable due to foundation damage.

2.3) Damage over a wide area and in many locations

One major feature of this earthquake was the large geographical area it affected, with many locations suffering damage. In a case where a small number of areas suffer damage over a wide area or where there is concentrated damage in multiple small areas, recovery is possible in a relatively short period of time. However, in this case, diverse damage occurred over an enormous geographical area and in a great many locations. As a consequence, disaster recovery and restoration work is taking a very long time while victims and society continue to suffer. This widespread damage is closely associated with the diverse forms of geo-hazards that occurred.

3) The severeness of geo-hazards differed greatly among three categories of structure, as described below.

3.1) Soil structures that were designed, constructed, and maintained in accordance with the latest seismic design standards by public organizations and large private organizations suffered little or no damage. This indicates that seismic design was effective as a result of construction technology that included geotechnical engineering. These structures were of the following types:

- Public infrastructure, medium- and high-rise buildings, industrial facilities, and their foundation structures
- Soil structures that were subjected to seismic design (such as reinforced earth retaining walls constructed for bullet train (Shinkansen) lines and roads, etc.)

- Modern rockfill dams
- Existing soil structures that had been subjected to seismic risk assessment and seismic strengthening (such as some river dikes)

Damage to recently constructed private houses due to seismic motion was also limited. This evidence indicates that the strength of the seismic motion was within the levels envisaged.

Also, where it had been assessed and the necessary countermeasures taken, soil liquefaction caused little damage to low-, medium-, and high-rise buildings, elevated road and railway structures, bridges, industrial installations including gasoline tanks, airports, multi-purpose underground conduits, pumping stations, sewage treatment works, and other public infrastructure, sewage pipelines backfilled with soil mixed with crushed rock and cement, , manholes protected against uplift, agricultural pipelines, etc. Therefore, it is considered that there is no urgent need to make major changes to the design seismic motion specified in the technical standards relating to seismic design published by various organizations, or to the rules relating to the prediction of soil liquefaction and its countermeasures.

3.2) Existing soil structures as public infrastructure that do not satisfy current standards and unexamined/untreated natural ground and slopes

Seismic risk assessment, seismic strengthening, and seismic design for soil structures in the public infrastructure has become quite common, such as for embankments and retaining walls for railways, roads, and residential areas as well as for reclaimed land, dams, river dikes, and underground structures such as sewage manholes, pipelines, etc. However, there is a large number of existing soil structures that were constructed in the past using old technology and to old standards, and that do not satisfy current standards. There are also unexamined/untreated natural ground and slopes that, if they collapsed, would cause damage to society. The soil structures that were damaged in this earthquake, causing harm to society, were basically these soil structures.

3.3) Private houses and other private assets to which public technical standards and maintenance systems are not applied (damage to individuals)

The application of seismic design and seismic risk assessment/strengthening to residential land for privately-owned houses lags behind progress in the public sector. In this disaster, private houses were washed away by the tsunami, while excessive deformation and collapse occurred to embankments and associated retaining walls in hillside residential areas away from the coast. In Sendai alone, there was serious damage of this type to more than 800 residential lots, resulting in them being classed as dangerous, while more than 1,200 residential lots were damaged and deemed to require caution. Further, more than 10,000 private houses constructed on recently reclaimed ground along the coast, in drained lakes, and on old riverbeds were significantly damaged due to liquefaction, causing severe hardship to very many residents. Water supply and sewage facilities were also seriously damaged by soil liquefaction, also having a severe impact on the lives of people and on society.

2.3 Restoration and recovery from the 2011 Great East Japan Earthquake and disaster prevention and mitigation

Based on the lessons learned from this disaster, the JGS has considered the contribution that geotechnical engineering should play in the restoration and recovery effort, as well as issues relating to seismic design and seismic risk assessment/strengthening in preparation for future possible disasters (meaning natural disasters in the general sense) nationwide.

1) Strengthening restoration of damaged soil structures

The function and safety of damaged soil structures should be restored as soon as possible. These damaged structures include embankments and retaining walls used for roads, railways, residential developments, and dams, river dikes, coastal dikes, tidal barriers in the form of embankments, underground structures such as manholes and pipelines for sewage, pipelines for agricultural use, and collapsed natural slopes. The strengthening and restoration work must bring these soil structures and slopes up to a higher level of structural seismic resistance while at the same time being economical. This can be done by adopting the latest geotechnical technologies, such as basic technologies for control of embankment compaction and installation of drainage facilities if rebuilding is carried out, and various ground improvement technologies and soil-reinforcing methods, etc., as shown schematically in Figs. 2-1, 2-2 and 2-3.

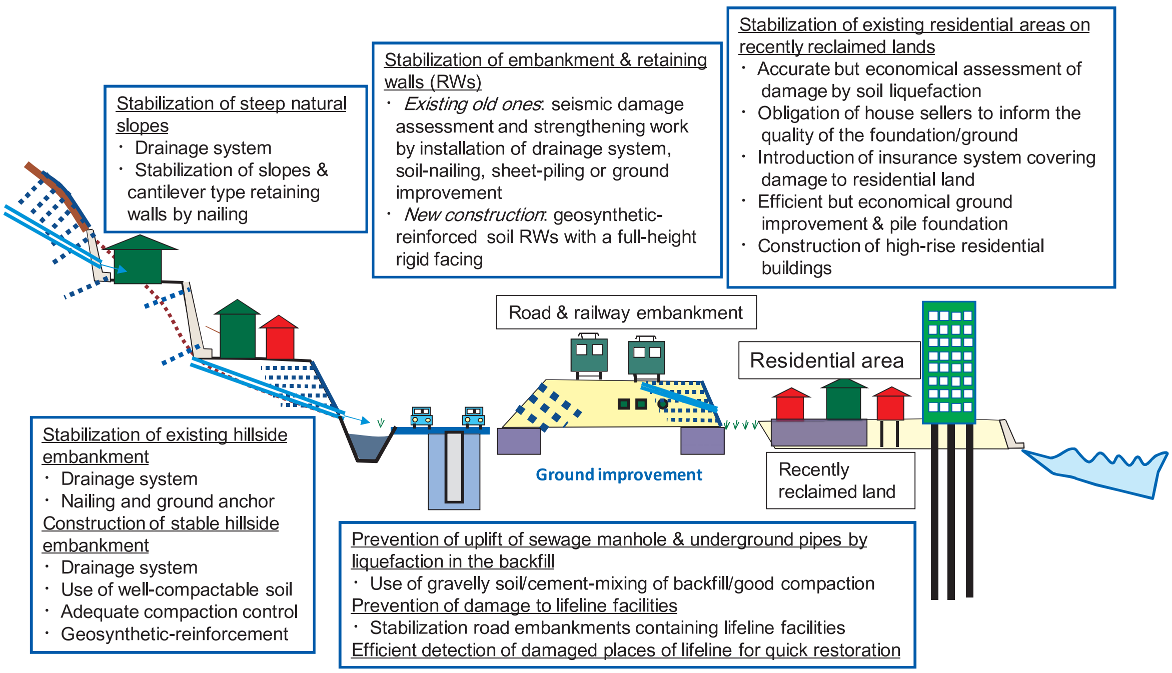


Fig. 2-1 Various geotechnical technologies to prevent and reduce geo-disasters in inland/coastal areas

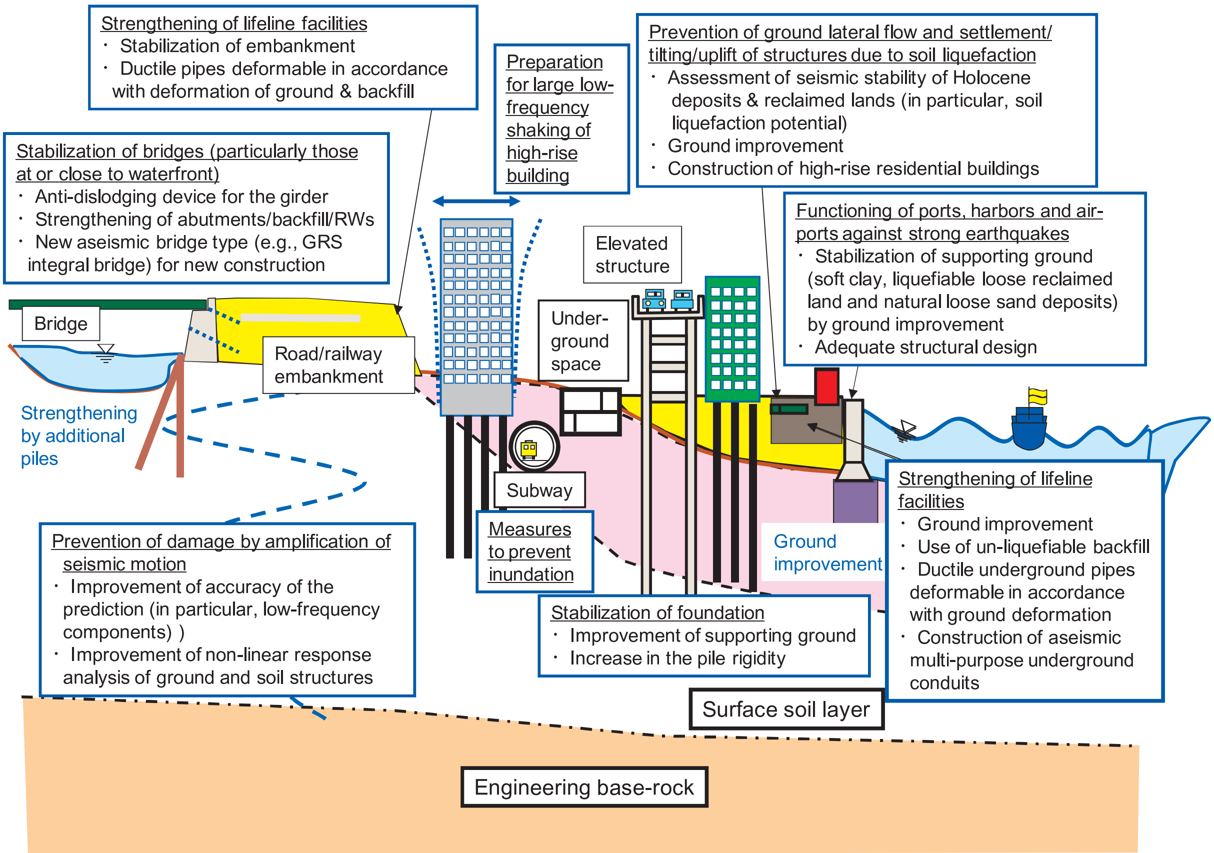


Fig. 2-2 Various geotechnical technologies to prevent and reduce geo-disasters in coastal urban areas

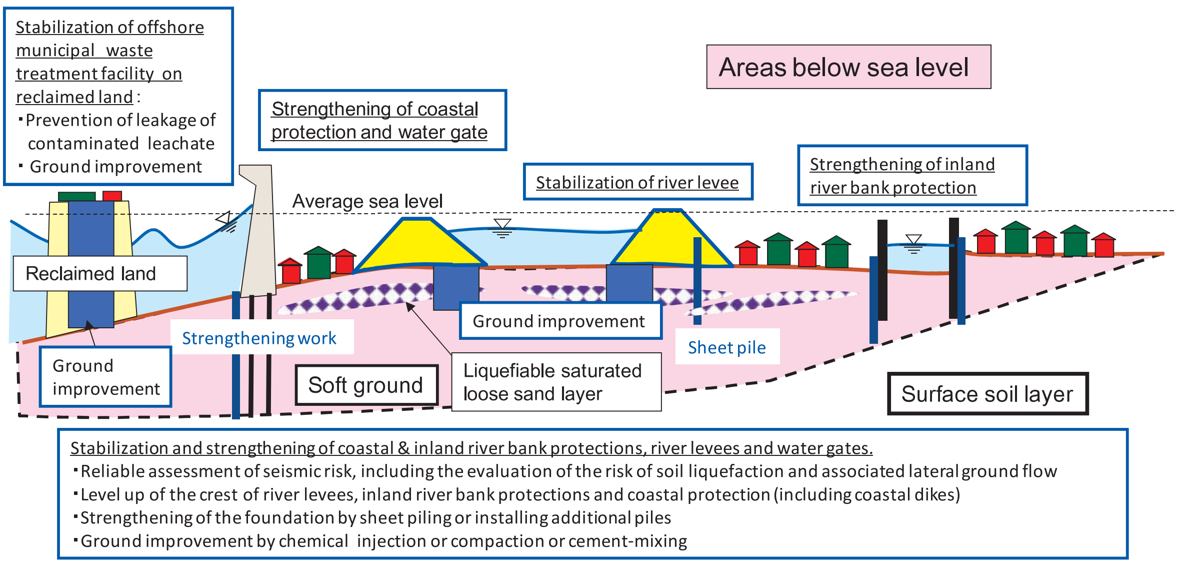


Fig. 2-3 Various geotechnical technologies to prevent and reduce geo-disasters in lowland areas

The aftershocks, as well as the main shock, have rendered many natural slopes unstable over a wide geographical area that includes their many epicenters. There is a need for continuous measurement and prediction of ground deformation and stability, and to take measures in accordance with the anticipated hazard, over a comparatively long time frame (years), not only this year. It is not just landslide damage during this year's rainy and typhoon seasons that is a danger.

The latest geotechnical technology also needs to be brought to bear on the problem of salinity of farmland, the need to effectively use as fill material the waste resulting from the disaster, the issue of radiation-contaminated soil, and the treatment of tsunami deposits as well as other soil-related problems.

2) Contribution of geotechnical engineering to the restoration of damaged areas

Various proposals can be and should be made based on geotechnical engineering for disaster restoration. For example, to counter the danger of tsunami, multiple tsunami defense systems could be considered as well as relocating residential areas to higher ground. Embankment-type tidal barriers may be constructed as the crest can be used as a public open space. Such barriers as above must be resistant enough to withstand the power and scouring effect of the tsunami so even in the case of overflow it will not suffer from total washout. In fact, in this earthquake disaster, many embankment barriers were washed away because of erosion and scouring associated with overflow. On the other hand, to prevent such overflow, the embankment might be constructed with a gentle slope using conventional technology, but then the width of the barrier and the quantity of earthworks would be extremely great (Fig. 2-4). Where road and railway embankments are expected to function as secondary tsunami barrier and evacuation location, a specific height will be required. Again, if normal embankments with gentle slopes are constructed, they will be wide and involve large quantities of earthworks.

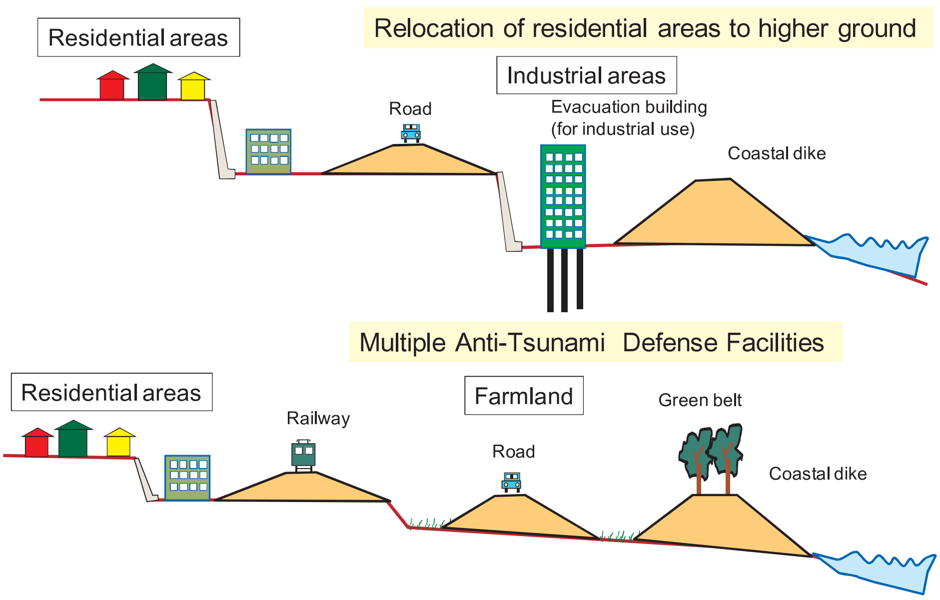


Fig. 2.4 Schematic diagrams showing applications of conventional geotechnical technologies to the restoration program (the first version) of Miyagi Prefecture (Asahi Newspaper, morning paper, 4th June, 2011)

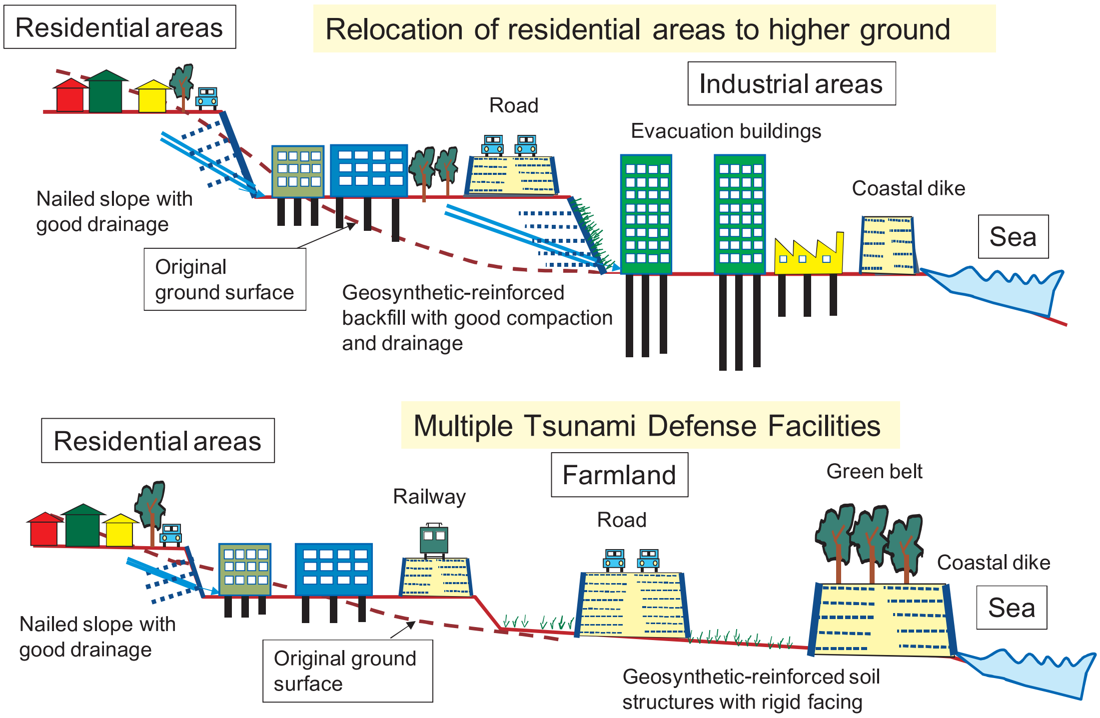


Fig. 2-5 Schematic diagrams showing applications of recent geotechnical technologies to the restoration program (the first version) of Miyagi Prefecture

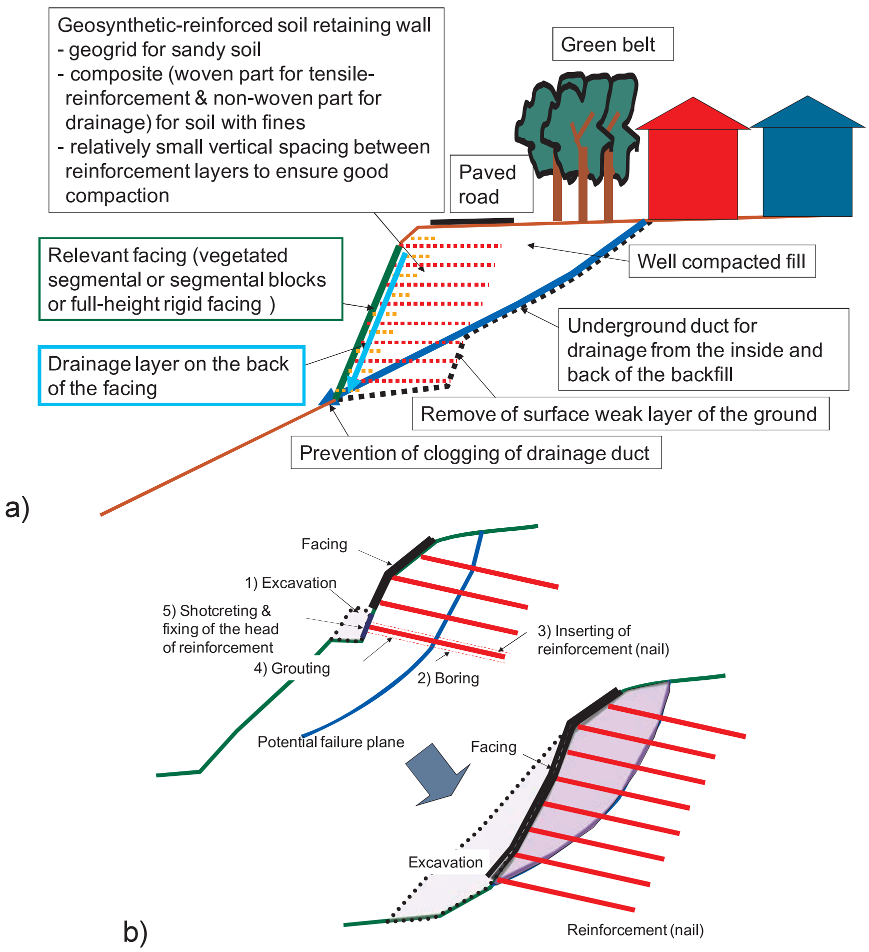


Fig. 2.6 Schematic diagrams showing: a) geosynthetic-reinforced soil retaining walls; and b) nailed natural slopes

It is being proposed to relocate residential areas to higher ground. However, if this is done, there is a danger of the new areas having insufficient seismic resistance if they include steep slopes excavated from natural ground that has not been adequately stabilized or if there is lax control of compaction or drainage installations. In this earthquake disaster, many embankments and retaining walls in residential areas that were constructed using old technologies collapsed in and around Sendai City. Natural slopes also collapsed in many areas.

These ideas – multiple tsunami defense facilities and relocating residential areas to higher ground – must bring to bear the latest geotechnical technologies if they are to be successful. These include the conventional technologies of appropriate compaction control and provision of suitable drainage, as shown schematically in Fig. 2-3a, as well as ground improvement by cement-mixing or similar, soil reinforcing technologies for embankments (Fig. 2-6a) and natural slopes (Fig. 2-6b), and so on. Corresponding to Fig. 2-4, Fig. 2-5 gives schematic examples showing how modern geotechnical technologies could be used. Figures 2-7, 2-8, and 2-9 are specific examples of the use of these technologies. For embankment-type tidal barriers, after ensuring the seismic stability of the embankment by the soil-reinforcing technology, certain technical measures must be implemented to ensure that the embankment face is capable of resisting scouring due to tsunami and overflow. This might include applying stiff reinforced concrete to the face and integrating it with the embankment itself using reinforcing members to prevent separation, or applying an appropriate anti-scouring prevention method (base protection), etc.

There is a possibility of using waste resulting from the tsunami damage to form new embankments such as for tidal barriers. This idea should be investigated, though it would be necessary to process the waste for salt and other contaminants.

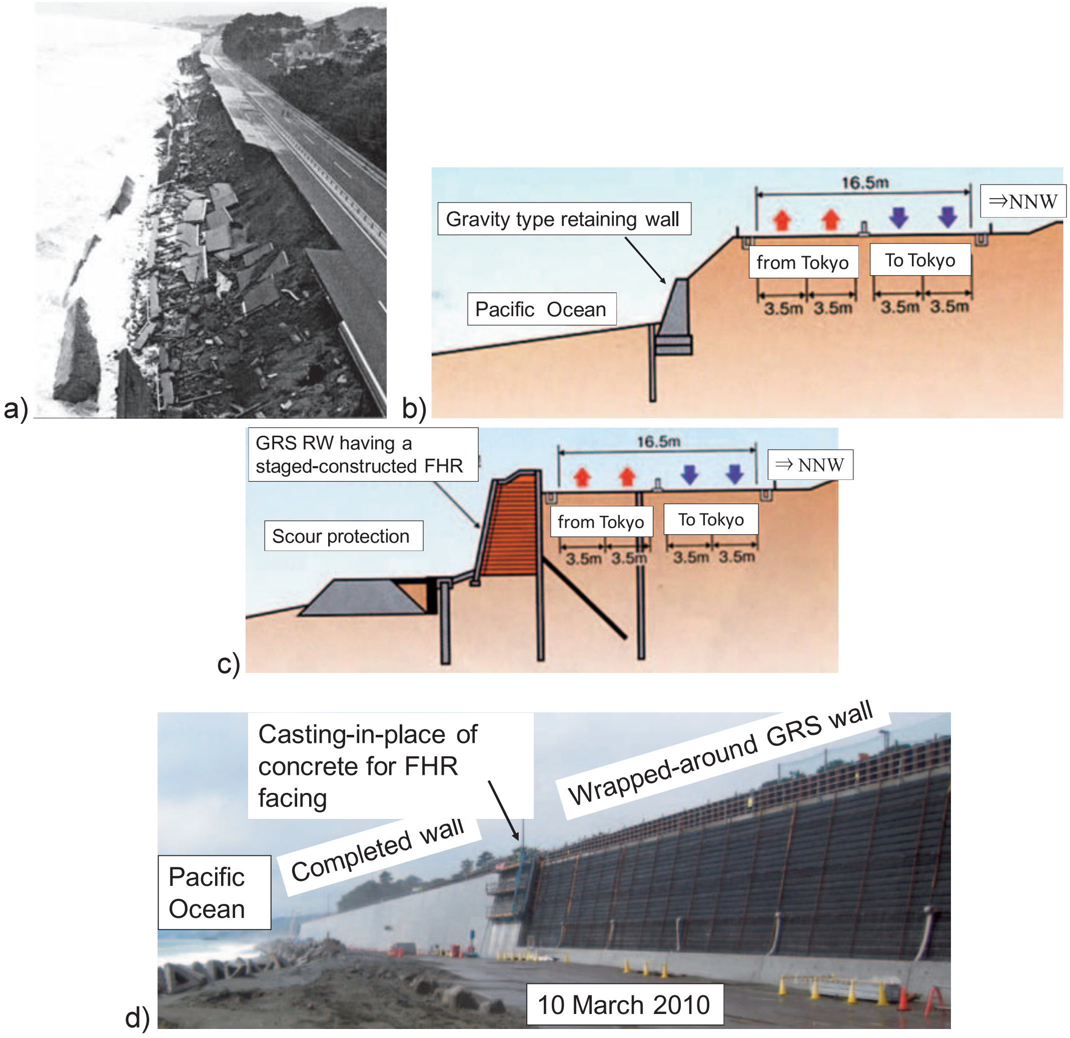


Fig. 2-7 Seawall of Seisho by-pass for National Road No. 1 in Kanagawa Prefecture, southwest of Tokyo: a) collapse for a length of about 1 km by Typhoon No. 9, 29th Aug. 2007; b) original structure; c) reconstructed seawall; and d) the wall during construction (a), b) & c): by the courtesy of the Ministry of Land, Infrastructure, Transport and Tourism; and d) by Tatsuoka, F.)

Fig. 2-8 Geosynthetic-reinforced soil retaining wall have a staged constructed full-height rigid facing for Tohoku line (railway), next to Natori River bridge, Sendai City; any damage by this earthquake (photo. by Okamoto, M.)

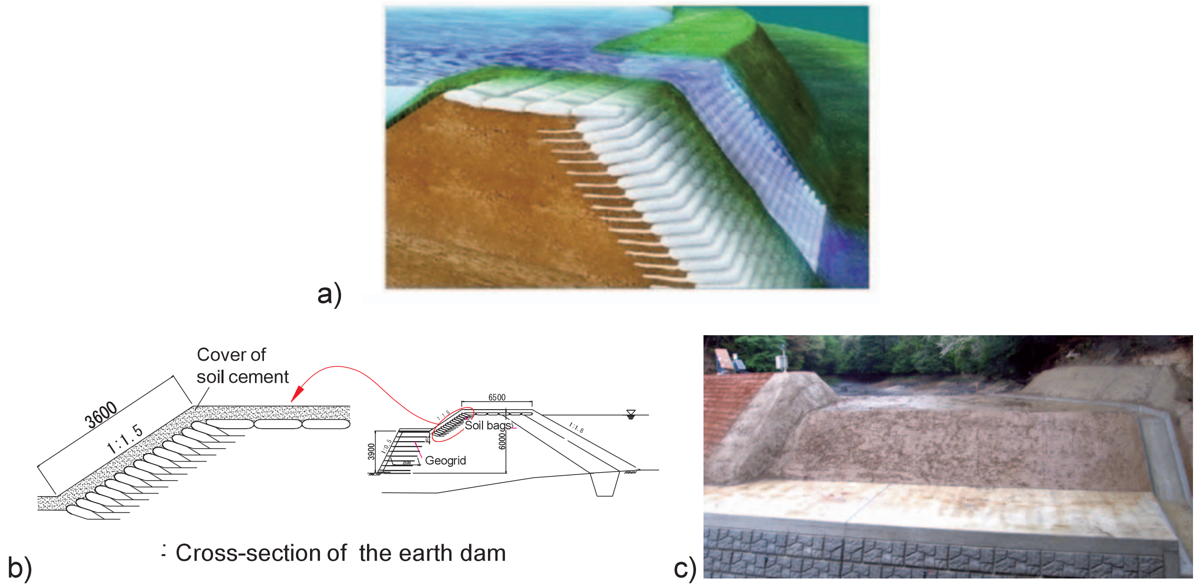


Fig. 2-9 a) artist's view of geosynthetic-reinforced earth dam; and b) &c) restoration of the spillway section of the earth-fill dam of Hirata Ike, Ishikawa Prefecture, that collapsed by the 2007 Noto-Hanto Earthquake (Mohri et al., 2009)

3) Dealing with existing old soil structures that do not satisfy current technical standards and unexamined/untreated natural ground and slopes

Throughout Japan there are existing old soil structures that do not satisfy current standards and societal requirements. There are also natural ground and slopes that may have low seismic resistance and are latent dangers that, if they collapse, would inflict great damage on society. Some have already been strengthened, but they are so large in number that, in contrast with bridges and elevated structures, the amount of seismic strengthening work carried out so far is utterly insufficient. If, in the event of a future earthquake causing widespread damage over a large area, the basic recovery policy were to restore collapsed soil structures and natural slopes to their original state as soon as possible, the task would be difficult and recovery could be greatly delayed. Therefore, to prepare for future earthquakes, it is an urgent task to implement seismic risk evaluation and strengthening on these structures without hesitation. In particular, in the case of strategic soil structures that are important for ensuring emergency transport routes and lifeline utilities after an earthquake, it is necessary to implement the following policies:

a) for new construction, ensure sufficiently high seismic resistance through seismic design by compacting well embankments, providing suitable drainage, and applying ground improvement technologies, soil-reinforcing technologies, etc., and
b) for existing soil structures that might not satisfy current standards and natural ground and slopes that would have a major effect on society if they collapsed while have not been examined, carry out seismic risk evaluation as soon as possible and, based on the results, carry out economical and effective seismic strengthening if necessary.

4) Countermeasures against damage to residential areas

Conventionally there has been a strong tendency to consider issues regarding private houses as a matter for their owners, and to leave the matter to the private sector. As a result, the situation in this area is as follows (and as described in detail in Section 3.2.4.)

a) There is no system of quality assurance by which a local government or a corporation that has developed reclaimed land or an embankment for residential is obliged to describe the quality of the grounds to the housing developers and a house developer selling completed houses sited on such land is obliged to describe the quality of the grounds to house purchasers.

b) The latest technologies for predicting the stability of hillside embankments and retaining walls during an earthquake and then taking countermeasures are not being substantially and effectively used. The same goes for technologies for predicting liquefaction of reclaimed land for residential areas and taking appropriate countermeasures. Further, no technical management system has been developed.

c) Seismic risk evaluation methods for residential areas on hillside embankments and recently reclaimed land and restoration methods and countermeasures that are of low cost enough for individual persons have not been developed.

d) There is as yet no insurance system that covers damage to residential land.

An additional problem is the lack of countermeasures against damage to underground lifeline utilities (such as sewerage systems) resulting from soil liquefaction. Methods are needed for improving the supporting soil and backfill soil for these utilities, which are basic life needs. Solving these various issues is an urgent matter.

Soil liquefaction damage to the ground of private houses can be avoided either by preventing residential areas liquefying or by making the building foundations withstand effects of soil liquefaction in some way. However, at present, the Act on Regulation of Residential Land Development and the Building Standard Law do not address such issues, so there is almost no residential building constructed in consideration of effects of soil liquefaction. The JGS needs to contribute towards creating a system within which soil liquefaction damage in residential areas can be prevented.

Another role for the JGS is to contribute to various issues relating to the restoration of damaged private houses on hillside embankments and on recently reclaimed land. Technical standards need to be set for seismic risk evaluation and strengthening of existing housing and for the seismic design of land for new private houses. The development and promotion of low-cost remediation methods and proposals for a suitable insurance system also need to be addressed. The same applies to the various issues relating to strengthening and restoration of buried lifeline utilities, as well as their seismic risk evaluation, strengthening, and design.

2.4 Actions of the Japanese Geotechnical Society

In the case of an earthquake, the JGS sets in motion various activities related to geo-hazards. The target of these efforts is national and local public organizations that are responsible for the development and management of the public infrastructure as well as engineers belonging to these organizations, engineers working on the design and construction of such public infrastructure and large buildings, and the general public. These activities are as follows.

- Development and publication of technical materials forming the basis for technical standards
- Promotion of research and effective communication of its results
- Collection and compilation of information and dissemination to specialists
- Education of engineers
- Provision of information to the general public
- Collection, compilation, and dissemination of geo-hazards-related information, and the publishing of recommendations for basic consideration of disaster prevention and land-use plans based on it.

In the case of this earthquake, it is necessary to generalize the lessons learned and provide suitable recommendations. Within these recommendations, it is necessary to touch upon the effective application of geotechnical technology and the need for new laws for the sustainable and fail-safe development of the national land and steady development for constructing safer living environment.

3. Characteristics of Geo-hazards, Issues Arising, and Recommendations

3.1 Examples of earlier countermeasures having expected effect

Though there are very many examples of geo-hazards caused by this disaster, there are also many cases where improved ground investigation methods, design methods, countermeasures, and maintenance methods had the desired effect and geo-hazards and the damage was limited. In order to contribute to restoration and recovery from the present disaster and to prevent or mitigate future disasters, it is necessary to generalize these cases and utilize the experience in the future.

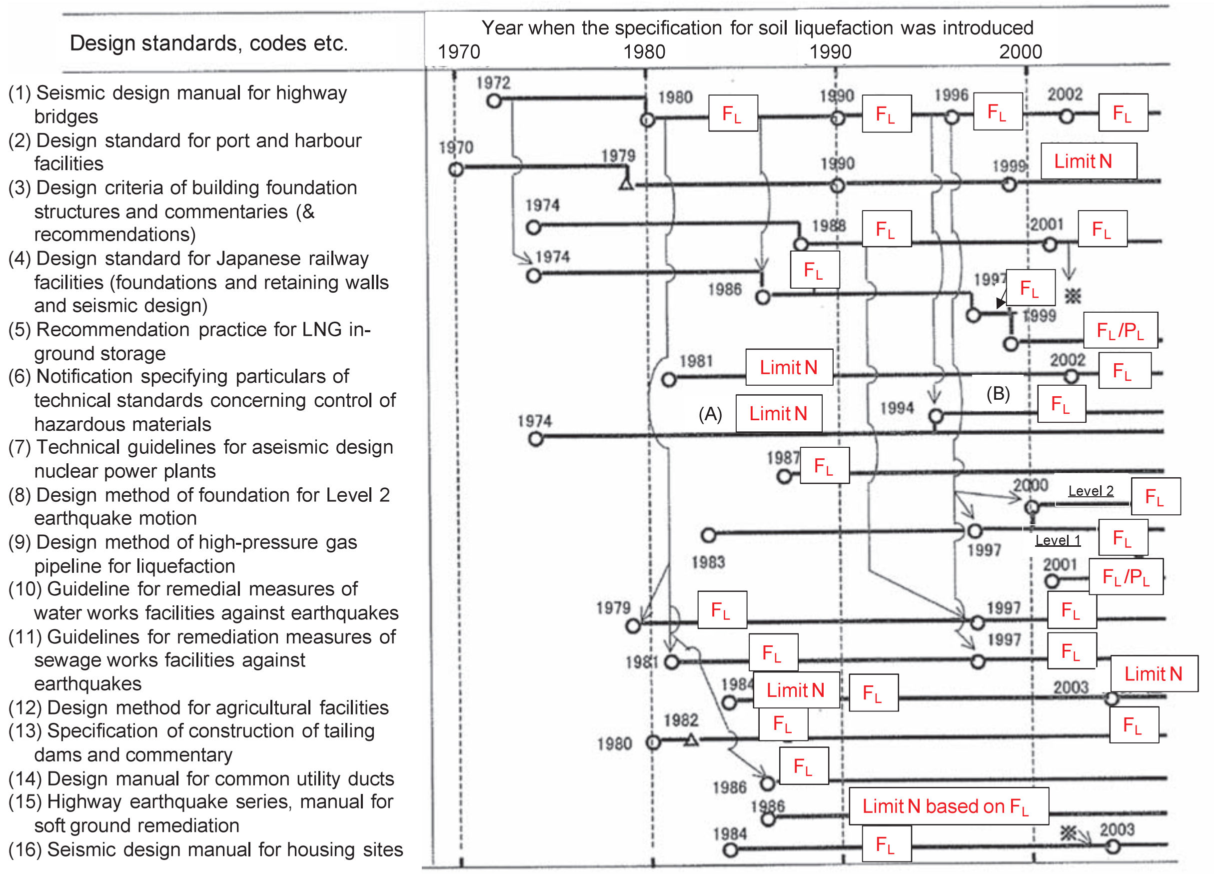


Fig. 3.1 History of inclusion of the terms for prediction and mitigation of soil liquefaction in Japanese design standards and codes for infrastructures

(Note)

F_L: the method to predict the safety factor against soil liquefaction of a soil element based on "the Liquefaction Resistance Factor (F_L)" of the soil element, which is obtained by dividing the "strength with respect to soil liquefaction" by the "liquefaction-inducing seismic load acting on the soil element.")

P_L: the method to predict the soil liquefaction potential of a given strata based on "the Liquefaction Potential Index (P_L)", which represents the degree of liquefaction predicted for the whole of a given strata obtained from the vertical distribution of F_L value.

Limit N: the method of soil liquefaction prediction based on "the limit value of N (the number of blow count by the standard penetration test".

(A): Oil tanks designed following the design code established 1974

(B): Oil tanks constructed before the year of 1974.

Level 1 and Level 2: Design seismic load levels for which soil liquefaction is predicted.

3.1.1 Soil liquefaction

A number of technical standards and design codes introduced specifications of the prediction and mitigation of soil liquefaction after the 1964 Niigata Earthquake, in which a great number of major structural damage was caused by liquefaction of ground. Public organizations responsible for developing and managing the public infrastructure (such as roads, railways, quay walls, coastal defenses, and multi-purpose conduits) were obligated to predict soil liquefaction and implement countermeasures in accordance with these technical standards and design codes.

Figure 3-1 shows when regulations related to soil liquefaction were incorporated into the design standards and codes for various types of structure. The Liquefaction Resistance Factor (F_L) of a soil element is obtained by dividing the "strength with respect to soil liquefaction of the soil element" by the "liquefaction-inducing seismic load acting to the soil element." Using this value, the degree of liquefaction of the soil is predicted. On the other hand, the Liquefaction Potential Index (P_L) represents the degree of liquefaction predicted for a given strata as a whole.

The prediction of soil liquefaction and implementation of countermeasures have come into common use also among engineers at contractors, consultants, and construction companies when medium- and high-rise buildings are constructed for large private organizations (including Urban Renaissance Agency (UR) housing estates, etc.). In the examples given below, prediction of soil liquefaction was carried out at the survey and design stage and countermeasures were taken where necessary. In this earthquake, there was little or no damage due to soil liquefaction to such structures as listed below.

a) Elevated structures (i.e., RC framework structures), bridges, for railways (Keiyo Line, etc.), roads (Bay Shore Route of the Metropolitan Expressway and national road) and multi-purpose conduits crossing recently reclaimed land in the Tokyo Bay area was not damaged by soil liquefaction. Only at Higashi-Ohgishima, the Maihama ramp, and Ichikawa parking area, there was some deformation of the road surface due to soil liquefaction. This was rapidly restored within a few days. No measures were taken against soil liquefaction in these areas at the design stage.

b) Pile-supported medium-and high-rise buildings (including residential buildings) as well as a UR residential development (RC wall 2-story housing estate with ground improvement by the sand compaction pile method in Urayasu City) in the Tokyo Bay area was not damaged by soil liquefaction.

c) Buildings at Tokyo Disneyland and elsewhere in the Tokyo Bay area - Urayasu city where ground improvement had been applied was not damaged by soil liquefaction.

d) At Sendai Airport's runway B, assessment of soil liquefaction had been carried out and, based on the results, countermeasures against soil liquefaction below the runway were carried out by cement-mixing. The runway suffered from no damage. In an untreated area, ground settlement was caused by soil liquefaction (Fig. 3-2).

e) In the seismically strengthened quays at Takamatsu Wharf in Sendai's Shiogama Port and the Hitachinaka section of Ibaraki Port, countermeasures had been carried out based on results of soil liquefaction analysis of the backfill soil and the wall supporting strata.

These quays suffered little damage, so a few days after the earthquake they were already in use as landing points for emergency supplies.

f) The bearing stratum for major structures of industrial facilities including chemical plants and tanks in the coastal area that were prepared for soil liquefaction were not damaged by soil liquefaction.

g) Kasumigaura water pumping station, which is supported on piles (Japan Water Agency), was not damaged by soil liquefaction that took place in the supporting ground.

h) Large-diameter pipelines for agricultural use (diameter 1.5 to 2.6 m) suffered from little damage by soil liquefaction where they had been backfilled with crushed gravelly soil.

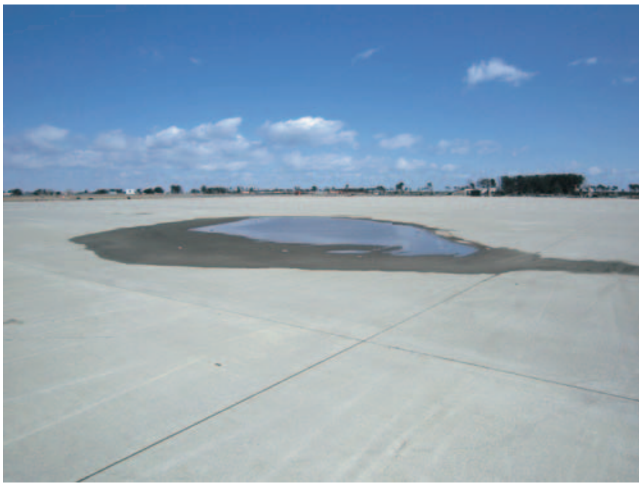


Fig. 3-2 Settlement of the apron at the Sendai airport due to soil liquefaction in the area where countermeasure against soil liquefaction had not been taken (by the courtesy of PARI, Port and Airport Research Institute)

In a number of cases, as listed below, suitable countermeasures had been taken as part of the recovery process from a previous disaster, so in this earthquake, little or no damage due to soil liquefaction occurred.

a) Sewage manholes and pipes that had been protected against buoyancy by backfilling with crushed gravelly soil or cement-mixed soil: in Kurihara City, Miyagi Prefecture, at locations where pipelines had been damaged in the 2008 Iwate-Miyagi Nairiku Earthquake, PVC pipes with ribs + crushed gravelly soil backfill had been used in the recovery work and there was little or no damage in this earthquake. Similar results were seen in the 2007 Niigata Chuetsu Oki Earthquake, where there was very little damage in areas strengthened after the 2004 Niigata Chuetsu Earthquake using compacted backfill.

b) At locations where strengthening works against soil liquefaction had been carried out in the supporting strata of river dikes (for example, the levee along the lower reaches of the Kitakami River, which was damaged in the 1978 Miyagi Prefecture Oki Earthquake and the 2005 Miyagi Prefecture North Earthquake, etc.), there was generally no damage. There were also locations where internal levee drainage (using gabions or similar) as a measure to reduce water level proved to be an effective countermeasure also against soil liquefaction (however the detailed mechanism of this is not fully understood).

c) In Sendai City, Miyagi Prefecture, at locations where tubular steel piles or groundwater drainage works had been carried out after damage to residential land in the 1978 Miyagi Prefecture Oki Earthquake, the damage to ground was light.

In summary, the effect of regulatory changes gradually introduced over a period of more than 40 years is clear in this earthquake. Regulations concerning prediction of soil liquefaction and suitable countermeasures for ground have gradually entered the technical standards (standard specifications, design criteria, design standards, etc.) and these had to be strictly complied with by public organizations responsible for developing and managing the public infrastructures (i.e., structures used for roads, railways, ports, etc.). Further, in the design of large-scale private buildings (medium- and high-rise buildings, UR and other housing, industrial facilities, etc.), engineers working for both those commissioning the work and those contracting to carry it out have taken soil liquefaction into consideration. The effects can be seen at this time.

This contrasts with the 1964 Niigata Earthquake, when many road and railway bridges collapsed, many medium-rise buildings suffered from settlement and tilting, oil tanks settled and caught fire, buried pipes floated upwards because of buoyancy at many locations, river dikes settled, laterally spread and moved, etc., as a result of soil liquefaction. At that time, there were no technical standards/design codes taking in account soil liquefaction. Further, the 1995 Great Hanshin-Awaji Earthquake gave impetus to more thorough countermeasures against soil liquefaction for such structures, as Level II design seismic motions then had to be taken into consideration in assessing the potential for soil liquefaction.

There are two issues to be taken up.

(1) Improvement of soil liquefaction prediction capabilities

In most of the current technical standards/design codes, the assessment of soil liquefaction is based on a common design seismic motion for the whole country. This means that design details must fully embrace ground conditions and seismic motions. It is intended to make a safe-side prediction for use in the design of a given individual structure at a given individual location. On the other hand, with the technical standards/design codes that are set for a national wide use, the accuracy of soil liquefaction predictions for each unique situation is not necessarily high. It is important to note that the current technical standards/design codes did not under-estimate the danger of soil liquefaction occurring in recently reclaimed land along the Tokyo Bay area, despite that the effects of detailed characteristic feature of the actual seismic motions (e.g., unusually long duration of earthquake motion) and ground conditions (e.g., ageing effects, a large fines content) are not duly taken into account in the prediction of soil liquefaction. This is an important engineering point of view.

Before the introduction of Level II design seismic motion into the technical standards/design codes for soil liquefaction prediction for public infrastructures and medium- and high-rise buildings, the prediction of soil liquefaction was made based on Level I design seismic motion. Even so, soil liquefaction was anticipated to take place in recently reclaimed land such as around Tokyo Bay, including that described in examples a), b), and c) on Page 20, that was actually liquefied in this earthquake and necessary countermeasures for soil liquefaction was made.

So recently reclaimed land around Tokyo Bay did liquefy very badly in this earthquake regardless of the fact that ground accelerations were about Level I and the seismic damage to most of the structures was little or none. It is thought that this greater than expected soil liquefaction arose because the seismic motion continued for a very long period of time. In other words, for a given ground acceleration, if all other conditions are the same, soil liquefaction will occur more readily if the duration of motion is long than if it is short. Further, the scale of liquefaction is thought to be partially explained as an effect of a large aftershock that occurred 30 minutes after the main earthquake.

Since the 1995 Great Hanshin-Awaji Earthquake, almost all technical standards have specified that soil liquefaction predictions should be carried out using Level II design seismic motion, but the effect of seismic motion duration is not given sufficient weight. However, if following these current technical standards, the seismic acceleration taken into consideration is considerably higher than the Level I design seismic motions. Therefore, despite that the effects of unusual long duration of shaking is not duly taken into account, soil liquefaction in recently reclaimed land around Tokyo Bay is to be anticipated and therefore necessary countermeasures are to be taken.

The above discussion demonstrates that liquefaction of the recently reclaimed land along Tokyo Bay is not an unexpected phenomenon from the engineering standpoint.

On the other hand, soil liquefaction tended not to occur in land reclaimed prior to the World War II although it was adjacent to recently reclaimed land where severe soil liquefaction occurred. It is important to note that the effect of the age of the ground is also not given sufficient weight in the current technical standards/design codes, along with the duration of seismic motion already noted above. These two are issues for future investigation, in particular to alleviate the following problems:

1) When the liquefaction risk of soil structures and supporting ground originally designed in accordance with the earlier standards (which did not take Level II motion into consideration) is re-evaluated according to the current technical standards/design codes, the input acceleration that would cause soil liquefaction at each location is likely to be over-estimated (which is an unsafe side evaluation) if the earthquake motion continue for such a very long duration as observed in recently reclaimed land around Tokyo Bay in this earthquake.
2) Further, when an epicenter and earthquake motion is specified for the prediction of soil liquefaction at a given site, long duration seismic motion should be taken into account even if the amplitude is equivalent to that of the Level I design seismic motion. In particular, for the anticipated Tokai, Tonankai, and Nankai earthquakes that have a high risk of occurring in the near future, there would be a possibility of soil liquefaction in recently reclaimed land along the Pacific coast and also around the Seto Inland Sea and in the San-in region by being subjected to long-duration seismic motion like that experienced around Tokyo Bay in this earthquake.
3) There is a possibility that the danger of soil liquefaction might be overestimated for old soil deposits that are less susceptible to soil liquefaction due to the age effect.

In summary, in order to improve the accuracy of prediction methods of soil liquefaction in the current technical standards/design codes, it is necessary to investigate the following specific points.

a) It is necessary to verify whether or not it is possible to correctly predict soil liquefaction of soil deposits that were subjected to Level II seismic motion in this earthquake. In other words:

- Are there soil deposits that were subjected to seismic motions of about Level II where soil liquefaction actually occurred even though it was predicted not to occur? If so, was the earthquake duration responsible for this inconsistency?

- Are there old soil deposits, such as Pleistocene Era formations, etc., that were subjected to seismic motions of Level II where soil liquefaction actually did not occur even though it was predicted to occur? If so, was the age effect responsible for this incosistency?

b) It is necessary to verify whether or not it is possible to correctly predict the soil liquefaction of soil deposits subjected to Level I seismic motions in this earthquake. In other words:

- In recently reclaimed land that was far from the epicenter and that liquefied when subjected to lower seismic motions of about Level I, it is necessary to determine the mechanisms by which soil liquefaction and damage occurred as a result of the long duration of the motion and the occurrence of aftershocks.

- In Urayasu City and elsewhere, there were large numbers of sand boils and ground subsidence was large. It is necessary to understand this phenomenon, as well as the effect of particle diameter and fines content on the resistance to soil liquefaction.

Further, it is necessary to investigate specific method to: a) set in detail the earthquake loading for predicting soil liquefaction, ii) take into account the age effect (for example, the influence of age on the N value and liquefaction strength relationship); and iii) take into consideration the effect of particle diameter and fine-particle content. A database is required for this, into which the degree of soil liquefaction of relevant areas of reclaimed ground, the year formed, and the old topography is input.

(2) Development of low-cost soil liquefaction countermeasures

Table 3-1 lists the ground improvement methods that can be applied as countermeasure against soil liquefaction. It is necessary to investigate whether or not these methods actually had any positive effect against soil liquefaction in this earthquake.

Table 3-1 Classification of ground improvement methods for soil liquefaction countermeasure (Kishida, Sandanbata, Sueoka et al., "Report of technical committee: ground improvement method for beneath and around existing structures aiming for contribution to business continuity", Kanto branch of the Japanese Geotechnical Society, March 2009)

Basic principle	Technique	Outline	General cost (JPY/m^3)	Noise, Vibration	Disturbance of soil	Machine size	Displacement control
Densification	Sand compaction method	Compacted sand piles are installed by driving down and extracting up a vibrating steel shaft.	1,000 ~ 2,000	Higher	More	Big	More
	Vibro compaction	A vibrator implemented at tip of extension tube carries out compaction at designated depths.	1,000 ~ 2,000	Higher	More	Big	More
	Quiet compaction	Casing pipe is penetrated and withdrawn a little at a time with rotational force to achieve soil compaction.	2,000 ~ 3,000	Lower	More	Big	More
	Compaction grouting	A very stiff grout mix, with an almost zero slump, is injected under relatively high-pressure to compact surrounding soil.	10,000 ~ 15,000	Lower	More	Small	More
Drain	Gravel drain	Gravel piles are vertically installed into the ground to accelerate the dissipation of excess pore water pressure induced by seismic events.	2,000 ~ 4,000	Lower	Less	Big	Less
	Artificial drain	Artificial drains such as PVD are installed into the ground to accelerate the dissipation of excess pore water pressure induced by seismic events.	2,000 ~ 4,000	Lower	Less	Middle	Less
Replacement	Pre-mixed soil	Stabilized grounds are constructed using soils mixed with chemical agent such as cement prior to placing in dry or slurry form.	3,000 ~ 4,000	Lower	More	Big	More
	Light weight soil	Stabilized grounds are constructed using soil mixed with cement along with foam or light weight material.	8,000 ~ 12,000	Lower	More	Big	More
Solidifying	Deep soil mixing	In-situ soils are mixed with a binder, such as cement or lime supplied in dry or slurry form, using rotating blade.	4,000 ~ 6,000	Lower	Less	Big	More
	Jet grout	A high pressure fluid is jetted out from the tip of extension rod, to allow in-situ soils eroded and mixed with cement grout.	20,000 ~ 60,000	Lower	Less	Small	More
	Chemical grouting	Chemical grouts, composed of additives such as sodium silicate or polymer, are injected into ground to improve its strength or lower its permeability.	20,000 ~ 30,000	Lower	Less	Small	Less
	Permeation grouting	Durable chemical grouts, specially manufactured to remove anti-durable factor, is injected into ground to increase liquefaction resistance.	20,000 ~ 30,000	Lower	Less	Small	Less
Reinforcing	Additional piles	Additional pile installation or reinforcing around pile heads increase structural resistance.	(20,000 ~ 50,000)	Lower	Less	Small	More
	Sheet pile reinforcing	Sheet piling surrounding structures works to protect its foundation; also effectively works as a stopper of the excess pore water pressure during seismic events.	(20,000 ~ 50,000)	Lower	Less	Small	More
	Solidifying reinforcing	Solidifying soils around foundations works, in some degrees, as structural reinforcing.	(20,000 ~ 50,000)	Lower	Less	Small	More

3.1.2 Railways and roads

Road and railway bridges that had been subjected to seismic risk assessment and seismic strengthening based on the design standards amended after the 1995 Great Hanshin-Awaji Earthquake and bridges constructed since that earthquake did not suffer major damage either to the superstructure or to their foundations. On the other hand, there were many examples of damage to RC columns and bridge bearings, etc., of elevated structures that had been constructed to the old standards and not strengthened.

3.1.3 Reinforced soil structures

In recent years, reinforced soil structures (Fig. 2-6a) and the nailed natural slopes (Fig. 2-6b) have been constructed in many locations.

a) In this earthquake, there were virtually no examples of damage to nailed cut natural slopes. For example, in Onagawa town, Miyagi Prefecture, there was no damage to a nailed cut natural slope that was inundated by the tsunami after being subjected to an earthquake motion reaching seismic intensity 6 or higher (Fig. 3-3a). In another example, an existing embankment in Sukagawa City, Fukushima Prefecture suffered from a slip failure in the backfill of a gravity-type retaining wall and a modular block retaining wall, but there was no damage to the adjacent retaining wall with nailed backfill and natural slope (Fig. 3-3b).

a)

b)

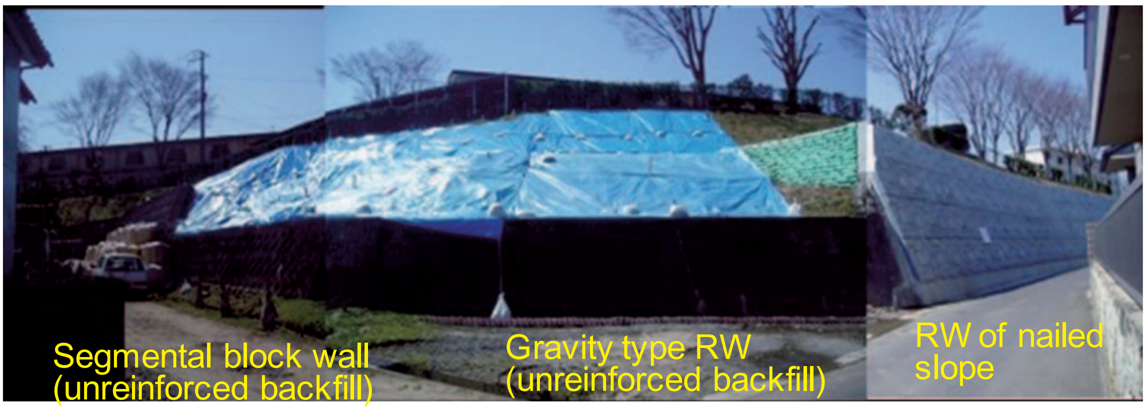


Fig. 3-3 a) Nailed wall of cut slope that survived the earthquake; and b) damaged conventional retaining walls (segmental block wall and gravity type wall) and an adjacent undamaged nailed wall of cut slope (Kodaka, T.)

b) Geosynthetic-reinforced soil retaining walls having a staged-constructed full-height rigid facing constructed for railways including bullet train lines (Shinkansen) of East Japan Railway (with examples near Sendai, Fig. 2-8, near Ichinoseki, and near Morioka), roads, and bridge abutments, were virtually undamaged and exhibited a good seismic resistance compared with conventional unreinforced embankments. Also, there were examples of geosynthetic-reinforced soil retaining wall constructed for residential areas (Yamamoto Town) that also exhibited good resistance. Moreover, at Tsukue Beach, Tanohata Village, Iwate Prefecture, an unreinforced road embankment was seriously eroded by the tsunami and the top layer of a cut slope above it collapsed. However, a reinforced earth retaining wall on the opposite side was not eroded by the tsunami and was not deformed.

3.1.4 Dams of 15 m and higher

The seismic motion of this earthquake had strong components with periods from 0.1 seconds to about 0.7 seconds, which is within a range of natural frequencies of all types of dams. Consequently, the earthquake had a powerful detrimental effect on dams. However, according to inspections carried out at concrete dams (about 260 in total) and fill dams (about 140 in total), they were generally able to withstand this strong seismic motion. That is, there was virtually no damage to the main structures of concrete dams. On the other hand, in the case of earthfill dams, there was a breach in one dam (Fujinuma Dam) providing reservoir water for irrigation. This dam was completed in 1949, so is regarded as one of the existing old soil structures that did not satisfy the current technical standards (Fig. 3-4). With the other earthfill dams, although cracks were seen in the crests of about 10 dams and some slopes had deformed, there were no safety problems. Many of the earth fill dams in which cracks occurred were those constructed prior to 1960. Rockfill dams constructed during and after 1970s exhibited good performance. There was one asphalt-concrete facing type rockfill dam in which cracks did occur in the facing. This was largely because, at the time of the earthquake, the temperature was low and the levels of very cold water were high in the upper ponds of pumped storage power stations, which resulted in a very low flexibility of the asphalt concrete facing. However, there were no abnormalities with regard to the main structures, and safety did not suffer. It is estimated that the damage to fill-type dams was greater than to concrete dams because of a very long duration of the earthquake and the many aftershocks.

A major future issue to be dealt with at the national level is to identify those fill-type dams among the older ones that were not designed and constructed according to recent standards that could cause damage downstream, and then to carry out appropriate strengthening.

Fig. 3-4 Failure of Fujinuma dam in Sukagawa City, Fukushima Prefecture (Yasuda, S.)

3.2 Damage that was not envisaged or poorly envisaged, or where recommendations were lacking or non-existent

As noted previously, there were many cases of damage whose cause or type had not been envisaged in the conventional standards. In outline, unanticipated damage was:

- Damage caused by the massive tsunami
- Continuous large aftershock
- Damage over a wide area and at many locations
- Damage to a very large number of privately-owned houses
- Structure collapse due to complete loss of function
- Loss of system functionality due to geo-hazards to ancillary facilities
- Ground subsidence and ground settlement over a wide area, salinity of farmland, tsunami deposits, radiation contaminated soil, problems of disaster wastes and its effective utilization, etc, requiring geotechnical engineering response.

3.2.1 Massive tsunami

There are two fundamental technical issues to be considered as regards the tsunami.

1) The design, construction, and maintenance of tsunami defenses

Most tsunami defenses ((breakwaters, tidal barriers, coastal dikes, river dikes in the vicinity of river mouths, etc.) functioned as expected until the tsunami exceeded the anticipated height. Thereafter, most collapsed due to foundation failure caused by scouring and erosion associated with the overflowing water. Coastal dikes of the embankment type are faced with concrete on three sides: the two sloping surfaces and the crest. However, in many cases, the overflowing tsunami caused strong upward suction as water rushed down the landward face, leading to peeling of the crest slab and the upper part of the concrete slab on the landward side, both not tied to the embankment. As soon as this happened, scouring of the embankment began, leading eventually to complete loss of the cross-section. Figure 3-5 shows an example of the early stage of this pattern of collapse.


a)

b)

Fig. 3-5 Embankment-type coastal dikes; the concrete slab at the crest and the top concrete panel on the downstream slope were lifted up and washed away followed by the start of erosion of the backfill caused by over-flow of tsunami; a) Koshikiri, Sanriku-cho, Ohunato City: and b) Tsugaruishi, Miyako-minami (note: the full-section of dike was lost at sections close to these sites) (Tatsuoka, F.)

Still, there were breakwaters and tidal barriers that contributed to reducing the force of the tsunami, such as the breakwater at Kamaishi (Fig. 3-6). In general, however, the mechanisms by which collapse proceeds and then leads to complete loss of function (but in some cases, functions have been partially maintained) remain unclear, so future countermeasures will have to be developed on the basis of investigations of damage and follow-up research (discussed later). Not only will these problems with tsunami defenses need to be solved, but also issues with multiple tsunami defense facilities and evacuation systems (discussed later).


Fig. 3-6 Damage to a breakwater by tsunami at Kamaishi Port (by the courtesy of PARI)

2) Ensuring that public infrastructures other than tsunami defenses is resistant

This disaster has raised various issues related to the damage and collapse of various elements of public infrastructures in the tsunami, including the following types of structure.

- Port and harbor facilities such as quays. Figure 3-7 shows the damage to the sheet pile quay at Soma Port. It is thought that this damage was caused by not only the leading tsunami surge; instead, a certain amount of deformation was caused by the seismic motion, then the tsunami (including the return surge) compounded the damage.
- River dikes and ancillary equipment (sluices, sluice gates, pumping stations) (Fig. 3-8)
- Electricity distribution facilities (distribution cables, sub-stations, pylons, etc.)
- Sewage treatment facilities (along the coast)
- Railway and road embankments (collapse due to erosion and washout of embankment slopes, collapse of bridges and washing out of embankments behind bridge abutments, bridge abutments, and footings) (Fig. 3-9)

- Expressways (closure of roads and interchanges due to tsunami deposits)
- Overturning of low- and medium-rise buildings associated with pull-out of pile foundations (Fig. 3-10)

Fig. 3-7 Damage to a sheet pile type quay wall at Soma Port (by the courtesy of PARI)

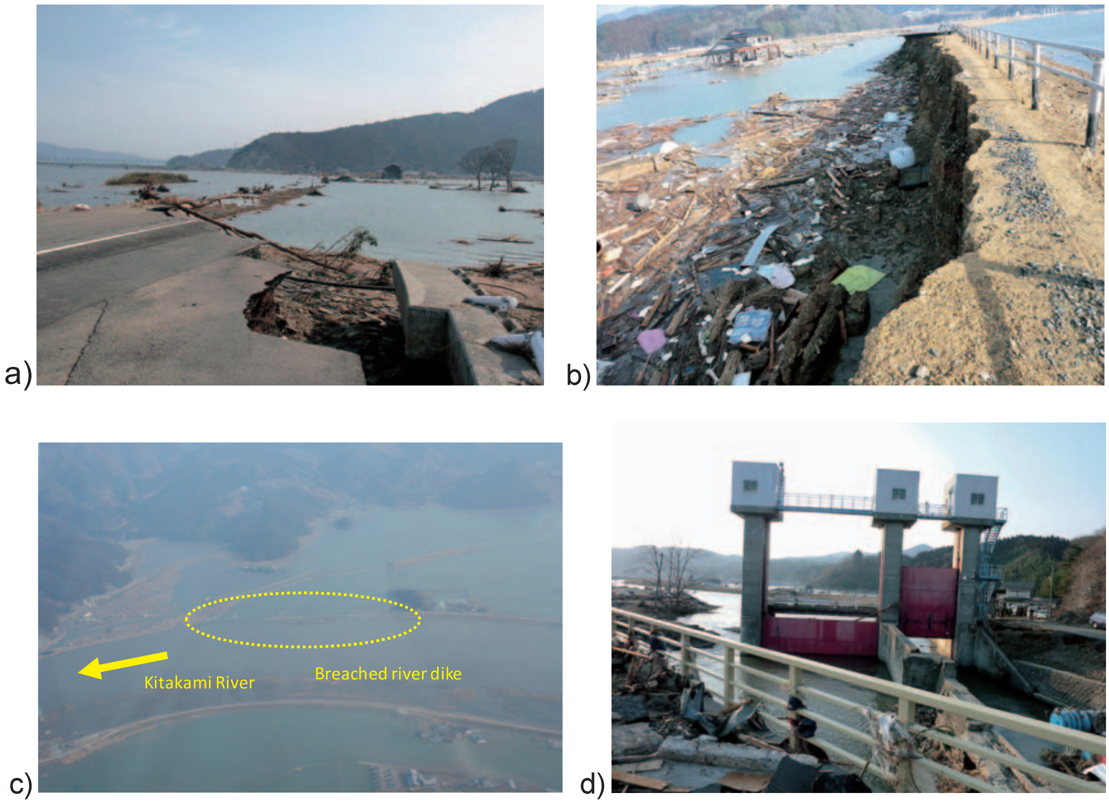


Fig. 3-8 Damage by tsunami around the river mouth of Kitakami River: a) breach of the river dike on the right bank 4 km from the river mouth; b) breach of the river dike on the left bank 3.0 km from the river mouth; c) an air view of the breached right bank; and d) Damage to Second Tsukihama water gate on the left bank at the river mouth (by the courtesy of the Ministry of Land, Infrastructure, Transport and Tourism)

a)

b)

Fig. 3-9 a)Collapse of river dike in the upper reach of a bridge abutment on the left bank of Tsuya Rive, Motoyoshi, Kesen-numa City, Miyagi Prefecture (Uzuoka, R.) : b) a view from the upstream of Tsuyagawa Bridge, between Motoyoshi and Rikuzenkoizumi stations, Kesen-numa line, East Japan Raiway: several girders were washed away and piers in the river tilted by tsunami (Tatsuoka, F.)

Fig. 3-10 A RC building over-turned by tsunami, Onagawa (Kodaka, T.)

In order to counter these types of damage by tsunami in future, efforts are needed in the following areas.

1) Determination of mechanisms of damage to coastal dikes and river dikes under the influence of incoming tsunamis, in particular:
   i) The failure of conventional type concrete facing by tsunamis (see Fig. 3-5)
   ii) The collapse of the embankment of coastal dykes by scouring and erosion caused by tsunami surge and overflow (see Fig. 3-5)
   iii) The scouring in the supporting ground

2) Design issues to resist against tsunami forces
   i) Coastal dykes and breakwater structures that are resistant to tsunami surges and during overflow
   ii) Design of port facilities taking tsunami loading into account
   iii) Design of river dike ancillary equipment (such as sluices, sluice gates, and pumping stations) that is resistant to collapse by tsunami force

iv) Design of roads and railways to resist against tsunami forces and tsunami-borne debris
- Bridges: cost-effective structures with a high washout-resistance of the backfill behind abutments, and bridge girders and abutments that can resist against being washed away by tsunami and scour-resistant foundations
- Embankments: for those that are expected to function as a secondary defense against tsunami, as shown in Fig. 2-4, cost-effective structures with a high resistance against overflow erosion, washing away, and scouring (see Fig. 2.5)
- Route selection and structural measures: disaster prevention plans should include the planning of road and railway routes as a part of urban planning against tsunamis, with corresponding structural measures and plans for the control and evacuation of trains and vehicles also needed. In the case of the Tokyo area, the inundation of underground spaces and the subway system is a serious issue as it could result in great loss of life.

Coping with a massive tsunami such as this one by means of a single approach is difficult. This has led to the concept of multiple-level tsunami defenses and also the idea of moving residential areas to higher ground (Fig. 2-4). Both of these proposed responses require the setting of a design tsunami height, but this is not touched upon here. However, the following recommendations can be made with respect to these proposals from the viewpoint of geotechnical engineering (Fig. 2-5):

1) The waste resulting from tsunami damage should be used to construct embankments such as coastal dykes, etc. after being processed for salt.
2) Regarding coastal tsunami defenses and breakwaters, etc.:
   - The supporting ground under foundations of RC structures (as a coastal tsunami defense facility) should be protected from scouring by using anti-scour protection work, sheet piles, etc. Further, foundations of a RC structure, such as piles, etc., must be provided with extremely good shear and pull-out resistance so as to prevent sliding and overturning of the RC structure. And, depending on the circumstances, it may be necessary to take the effects of soil liquefaction into consideration.
   - The following points should be considered in the design and the development of construction technology to maintain a high stability of the landward faces of coastal dykes so that they can function correctly.
     a) There are weak points adjacent to gates.
     b) Failure of embankment-type coastal dykes was triggered by destabilization of the crest concrete slab and concrete facing on the landward face by overflow of tsunami, leading to erosion of the embankment and scouring of the ground on the landward side.
     c) Joint research with hydraulics engineers is necessary to clarify the mechanism of destabilization of embankments and of the crest concrete slab and concrete facing on the seaward side caused by the tsunami surge and the return surge from the landward side.

   - Where embankment type coastal dykes with trees planted on the crest as a disaster prevention measure are to be constructed, due to a restraint of land use and the need to reduce the quantity of earthwork, the base width is required to be reduced. Then the slope becomes steep and conventional type embankment type may not be stable enough when subjected to strong earthquake motion. In addition, in this disaster, so many conventional type embankment-type coastal dykes located close to the coast were completely destroyed by erosion and scouring as this tsunami surged over them. Such embankment-type coastal dikes must be constructed resistant to tsunami wave forces and scouring so that they survive even if a tsunami surge flows over them.

Geosynthetic-reinforced soil structures with the crest concrete slab and concrete facing connected to reinforcement layers can have a high seismic stability and a high resistance against tsunami surge and overflow and therefore is suitable as tsunami barriers. A fill-type irrigation dam shown in Fig. 2.9 is a good example of a fill structure that is highly resistant to erosion and washout during overflowing.

3) Regarding tsunami evacuation points near the coast:

- Where a medium rise building is an evacuation point, it must be sufficiently resistant to tsunamis. In particular, the foundation piles must have sufficient pull-out resistance (and, depending on circumstances, soil liquefaction should also be taken into consideration).

- The feasibility of underground shelters should be investigated.

4) If road and railway embankments are expected to function as secondary barriers to a tsunami surge and overflow, and even as an evacuation point, as in the case of Sendai East Road, then, as well as seismic resistance, a certain height is necessary. Using the conventional type embankment structure, the base width and hence the quantity of earthworks may be too large. It can be propose to construct steep-sided embankments stabilized by geosynthetic-reinforcing the backfill or geosynthetic-reinforced soil retaining walls with a near-vertical facing.

5) If residential areas are to be developed on higher ground or moved to higher ground, consideration must be given to the fact that many old embankments in residential developments around Sendai City collapsed in this earthquake. The lesson from this is that seismic resistance cannot be assured for embankments constructed using old technology with insufficient compaction or insufficient drainage or where associated retaining walls are constructed are not sufficiently stable or the natural ground is steeply cut away without taking adequate measures to ensure stability. Further, depending on a particular situation, cutting and embankment slopes may need resistance to tsunamis. This means that, as far as possible, housing and other important facilities should be located on original stable ground with stable cuttings, while to solve the problem of providing both stabilization and suitable area for building, stabilization methods should be used that allow for stable steep slopes, such as by using the soil nailing method in which reinforcing members (usually steel bars) are set into the natural ground behind a slope (Fig. 2-6b). Further, embankments for residential streets and community parks should also be well compacted and provided with suitable drainage. In these cases, also, the problem of embankment stabilization and providing as much land as possible, can be solved by constructing steep slopes or retaining walls of geosynthetic-reinforced soil (Fig. 2-6a).

6) Farmland should also be protected from massive tsunamis through the concept of multiple-level defenses. Protection is provided in stages by introducing not only linear structures, as typified by coastal dykes, but also planar structures including agricultural or forestry ground behind the dykes.

3.2.2 Seismic motion

The level of ground motion caused by this earthquake (peak ground acceleration, or PGA) was not unanticipated as compared with the Level II design seismic motion conventionally adopted in the seismic design. However, as it was coupled with a plate boundary event, the seismic magnitude reached 9.0. This coupling gives rise to issues related to the choice of design earthquake that are not anticipated or are insufficiently considered in the conventional approach.

1) The duration of motion was extremely long, so the number of load repetitions was large. As a result, degradation of soil structures and ground (including that caused by soil liquefaction) increased. Further, the dominant frequency of the seismic motion tended to fall with distance from the epicenter. For a given ground acceleration, the lower the predominant frequency, the greater the strains produced in the ground and the more severe the degradation of the ground. These points should be taken into account when specifying seismic motion (acceleration time history) of the Level II design seismic motion together with peak acceleration level, so as to achieve a more rational seismic design of soil structures and ground.
2) An extremely wide area was subjected to strong seismic motions, so damage was widespread and occurred at many locations.
3) There were many large aftershocks and these continued for a long period of time. Significant effects of these aftershocks on the seismic resistance and reconstruction of soil structures were not anticipated. Both the main shock and the aftershocks had a wide influence, so restoration of railroads between the Tohoku region (the north-eastern part of Japan) and the Kanto region (the region around Tokyo) was delayed when aftershocks occurred. Also, these aftershocks contributed to the deformation of residential land on embankments and soil liquefaction of recently reclaimed land. In an earthquake that occurred the day after the main event at the Nagano-Niigata border, which was an induced earthquake, an embankment on the East Japan Railway Company's Iiyama Line, which was one of the existing soil structures that did not satisfy current standards, collapsed.

The task of accurately predicting that a certain level of seismic motion will occur at a certain location within a specific time period (such as the service life of a structure) is an extremely difficult one and, for the present, can be considered impossible. However, postulating an earthquake in the future is necessary in the design of important structures. For the purpose of setting a suitable earthquake for design, cooperation should continue among the fields of seismicity, geology, and applied geology in studying the traces of historical earthquakes (evidence of liquefaction and tsunami deposits, etc.) and promoting research into seismic activity (seismic forces, fault displacements, crustal movements) based on the results. Joint working among these fields is necessary because of the deep links of surveying technology and seismic activity (seismic forces, fault displacements, crustal movements) with geotechnical engineering. Results must be recorded in a geotechnical database and reflected in disaster potential predictions and land use plans.

3.2.3 Damage over a wide area and at many locations

If an earthquake causes damage over a wide area, but with damage restricted to certain locations, quite rapid recovery is normally possible. However, in this earthquake, though the damage at each individual location was not very severe, damage was spread widely at so many locations. As a result, restoration and recovery took an extremely long time. In fact, recovery work is still ongoing at many locations at this time (at the end of September 2011), making the damage to victims and society yet more serious. The reasons for this slow recovery are as follows.

- It took a very long time to determine the overall extent of damage.

- There were many damaged locations that could not be accessed immediately.
- The number of damaged locations that required a response was very high.
- Supplies of essential goods, such as gasoline, etc., ran short.

This relates to the ongoing effort to implement the necessary seismic damage inspection and assessment and seismic strengthening for existing soil structures (embankments, retaining walls, etc.) that may not satisfy current standards and for un-dealt natural ground and slopes that could have a major effect on society if they collapsed. The number of locations requiring seismic damage inspection and assessment is enormous, so the task is still far from complete. There has been, therefore, an implicit assumption that the number of locations likely to be damaged in an earthquake would be few or, if greater in number, that they would occur over a restricted area. Inevitably, this led to a policy of: 1) not taking seismic countermeasures in advance against low-probability huge earthquakes and 2) immediately restoring any damage if such an earthquake strikes.

If this basic policy pertains in the future also, then any event that causes damage over a wide area and at many locations will give rise to a situation where an adequate response is not possible. In particular, for railways, roads, river dikes, water supply and sewage works, electricity distribution equipment, and similar that have a large linear or area extent, a failure at one location can damage functionality over a wide area, requiring urgent restoration. This means that seismic damage inspection and assessment and seismic strengthening of existing structures should proceed as rapidly as possible so as to prepare for damage that is widely spread at many locations.

The following proposals are made with respect to widely spread damage at many locations

1) An overall system for damage estimation should be developed for use in initial response.

   - In this earthquake, there were examples where electricity remained available (Tohoku Electric).

   - Rail transport is a very large and complex system consisting of civil engineering structures, track and related structures, signaling equipment, electrical equipment, rolling stock, station infrastructure, and operational systems. If any one part or section of this system is lost in an earthquake, normal, safe operation cannot continue. It is necessary to establish a seismic damage inspection and assessment technology for the rail system as a whole, with continuous improvement based on the results of assessment. As of now, there is no system for locating undamaged and damaged parts of the rail system, so there is a need for research into post-earthquake damage estimation systems for the railway network as a whole.

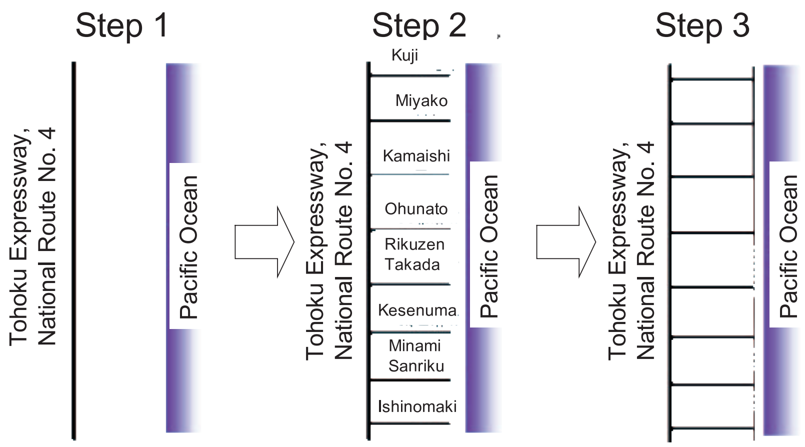


Fig. 3-11 Restoration of inland north-south routes by a strategy called the "teeth" of the comb (by the courtesy of the Ministry of Land, Infrastructure, Transport and Tourism).

2) Lifeline service networks should be provided with reserve capacity.

Total loss of the lifeline services (expressways, high-speed railways, electricity, gas, water, sewage, communications, and telephone services, etc.) over a wide area absolutely must be avoided. To this end, the following measures are necessary.

- Comprehensive measures must be implemented to give systems an overall margin (redundancy) and flexibility. For example, this disaster, the normal road network was destroyed because of washed-out embankments, washed-out bridges, bridge collapse, and other failures. Emergency road transport routes were secured about a week after the earthquake by the "teeth of a comb" strategy. This was possible because of the existence of a road network with redundancy. As shown in Fig. 3-11, inland north-south routes (Tohoku Expressway, National Route No. 4) were secured first, then the "teeth" of the comb were secured by opening east-west routes. Finally, this enabled coastal north-south routes (National Route No. 45, etc.) to be opened about a week later.

- In systems containing many existing soil structures that do not satisfy existing standards, which are therefore their weak points, it is necessary to continue work to implement seismic risk assessment and seismic strengthening.

- The construction of new trunk networks should also be investigated, with the aim of completing a dual network (as in the example of the Kobe City water supply and sewage system.)

Fig. 3-12 a) Embankment collapsed in the Nagano-Niigata Border Earthquake induced the next day after the 2011 Great earthquake; and b) reconstruction to embankment retained by a GRS-RW having a FHR facing, between Yokokura and Morinomiya, JR East Iiyama Line (by the courtesy of the East Japan Railway Co.)

3) Move from a basic policy of "repair after damage" to "preparation"

- Firstly, in restoring damaged soil structures, ground, and natural slopes, it is necessary to use the latest geotechnical technologies so as to achieve cost-effective strengthening of structures and provide them with good seismic resistance. For example, an embankment on the JR East Iiyama Line – which collapsed in the Nagano-Niigata Border Earthquake induced on the day after this disaster – has been restored by strengthening (Fig. 3-12) using the geotextile-reinforced soil retaining wall technology (Fig. 2-6a).

- Secondly, there should be a revised basic policy of implementing, as quickly as possible, seismic damage inspection and assessment and seismic strengthening of the existing soil structures that may not satisfy current standards and all unexamined/untreated natural ground and slopes at locations vital for the maintenance of system functionality. The methods used must be economical and effective. Appropriate seismic resistance must also be ensured for all new soil structures. This is an issue with great urgency from a nationwide perspective as a way to prevent and mitigate future disasters.

3.2.4 Damage to private housings on developed hillside embankments and on recently reclaimed land

1) Background

Besides being washed away by the tsunami, damage to private houses was mainly caused by the collapse of hillside embankments and soil liquefaction of recently reclaimed land. In these cases, damage to lifelines such as sewage systems, etc., made the disaster more serious for the life in the damaged areas. These have been summarized as follows:

a) There is no system of quality assurance requiring local governments or corporations that develop reclaimed land and embankments for residential use to explain the quality of the developed land to housing providers. Similarly, there is no requirement for residential developers to provide information regarding the quality of the developed land to house purchasers. Therefore, there is the situation where detached houses are purchased without the buyer receiving information regarding the developed land or having any awareness of its quality. In April 2004, the Law to Promote Assurance of Quality in Housing came into force, obliging construction companies and housing agents to, among other things, underwrite repairs for 10 years. However, the quality guarantee for housing does not deal with prediction of and countermeasures against soil liquefaction.

b) No technical management system has been developed so, for example, in many cases the latest technologies against soil liquefaction are not being substantially or effectively applied. A "Residential Land Disaster Prevention Manual" was formulated for housing design and construction in 1988 and later amended in 1998 and 2007. An article on soil liquefaction was incorporated into the 2007 version. Each local government has formulated its own "Residential Land Development Technical Manual," which indicates that surveys for soil liquefaction should be carried out at locations where ground weakness is expected. However, there have been no legal regulations regarding soil liquefaction based on the "Law on Regulation of Residential Land Development," and investigations leading to such regulations have been limited.

c) The development of seismic damage inspection and assessment methods for housing lots on hillside embankments and recently reclaimed land and low cost restoration methods or countermeasures that a private individual can afford are overdue.

d) An insurance system for foundation ground damage related to geo-hazards has not been developed.

In addition, in lifelines buried in the ground, such as sewage facilities that are directly related to lifestyle, measures against soil liquefaction by improvement of supporting ground and backfill soil were insufficient.

2) Housing on hillside embankments

Public awareness of the problem of seismic damage to soil structures such as embankments and retaining walls forming part of the public infrastructure (such as roads, railways, river dikes, coastal defenses, and electricity supplies, etc.) and the importance of its consequent social effects has increased following the occurrence of geo-hazards that many earthquakes in recent years have caused. These earthquakes also caused geo-hazards to private houses on hillside embankments to suffer from damage from geo-hazards.

Where the development of residential land is regulated, a permit for the sale of private houses is issued only if the standards set in the Law on Regulation of Residential Land Development at the time of construction are met. However, this regulation of residential land development applies to no more than 2.7 % of the area of Japan; consequently, in all other areas there are no regulations governing the safety of residential land. Further, even if standards are satisfied at the time of construction, the responsibility for maintenance of a private house rests with the individual owner once a sale has been made; currently almost no maintenance is carried out. As a result, little attention is paid to any rise in groundwater level in the years after completion or to the displacement of embankments and retaining walls. In fact, much residential land suffers from high groundwater levels. If an earthquake occurs under these conditions, soil liquefaction damage can easily occur to residential embankments on sloping ground or hillsides and where embankments have been widened.

In 2007, new standards were put in place that consider seismic resistance to earthquakes. This change was driven by investigation of the 1995 Great Kobe Earthquake and the 2004 Niigata Chuetsu Earthquake, in which there was widespread damage to housing. However, these standards lack power and only apply to new housing; there is no coverage of existing housing. On the other hand, to prepare existing housing for future earthquakes, projects to promote the seismic strengthening of existing residential land are underway. The effect of these efforts has yet to be seen, however, partly because the law was amended only recently. Locations still remaining in a dangerous state, like that shown schematically in Fig. 3-13, are far more numerous than those that satisfy the latest standards. That is, most of Japan's housing is not prepared for earthquakes and, in the 2011 Great East Japan Earthquake, Sendai City alone saw more than 800 housing lots suffer from serious damage leading to them being condemned, mainly as a result of retaining walls associated with hillside embankments collapsing (Fig. 3-14). A further 1,200 or more housing lots suffered damage and are deemed to require attention.

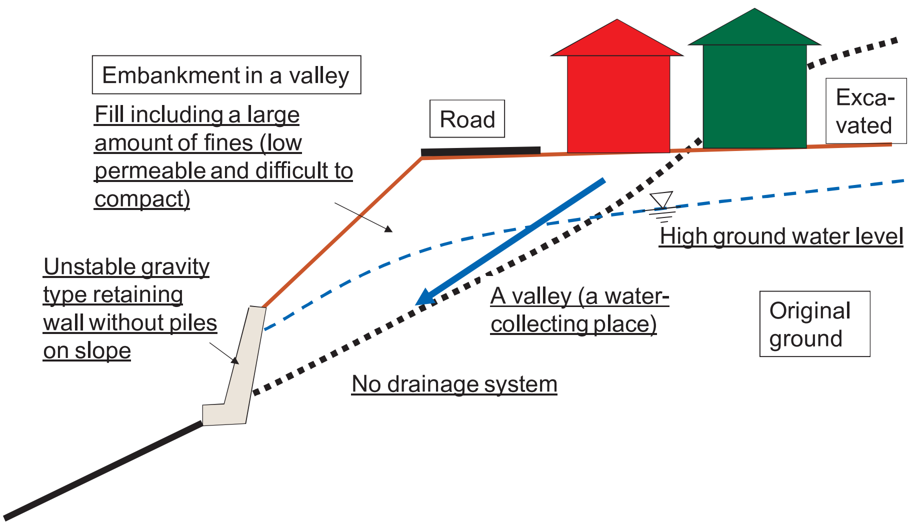


Fig. 3-13 Schematic figure showing several majors causes for the failure of embankment in a valley in a hillside residential area

Fig. 3-14 A view of typical damaged houses in hillside residential areas, Oritate, Aoba District, Sendai City (Kazama, M.)

The characteristic patterns of damage in this earthquake were as follows.

(1) At many locations, there was damage to residential land developed by cut and fill in hilly areas. In Miyagi Prefecture, damaged locations included some that were previously damaged in the 1978 Miyagiken-oki Earthquake, as well as some new locations. One reason for damage occurring in new locations is considered to be a greater amplitude and longer duration of the motion than in the 1978 Miyagiken-oki Earthquake.

(2) Normally, the earthquake damage mechanisms affecting residential land developments can be classified into the patterns shown in Fig. 3-15. Of these, there was almost no large scale damage to residential land due to pattern a), where a slip surface in natural ground leads to a landslide. On the other hand, there were many cases of large-scale damage caused by pattern b), where damage takes place near a filled valley. Figure 3-16b shows an example of this damage pattern, where deformation has taken place in proximity to an embankment slope. A photograph was taken near the top of the embankment slope, as seen in the map in Fig. 3-16c. There were also many cases of pattern e), where settlement of an embankment takes place. This is thought to have resulted from the long duration of the seismic motion. The damage due to differential settlement under houses at the boundary between cut and fill was significant.

Figure 3-16a shows an example from Shiroishi City in Miyagi Prefecture, where the earthquake damage was of pattern b). Here, land developed residential land that suffered from damage in the 1978 Miyagi Prefecture Oki Earthquake was damaged again. However, as a result of countermeasures that included the construction of water collection wells, damage was limited this time. At Midorigaoka, Taihaku-ku, Sendai City, countermeasures had been carried out through a combination of restraining piles and methods to lower the groundwater level; as a result, slip failure of the whole embankment was avoided in this earthquake. There are examples from the 2004 Niigata Chuetsu Earthquake and the 2007 Niigata Chuetsu Oki Earthquake of residential land that was damaged once, and then again suffered damage.

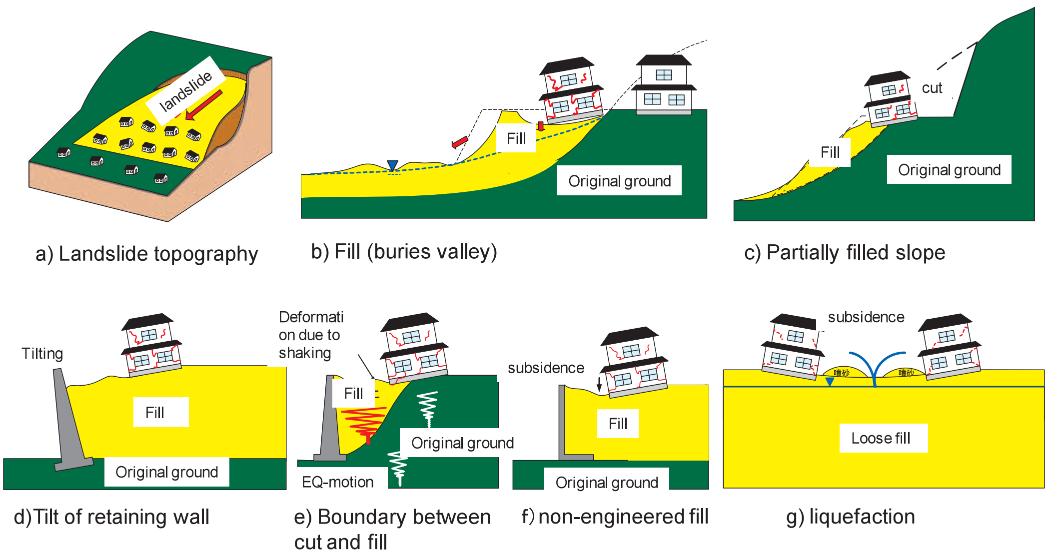


Fig. 3-15 Classification of damage mechanism of residential fill ground (Kazama, M.)

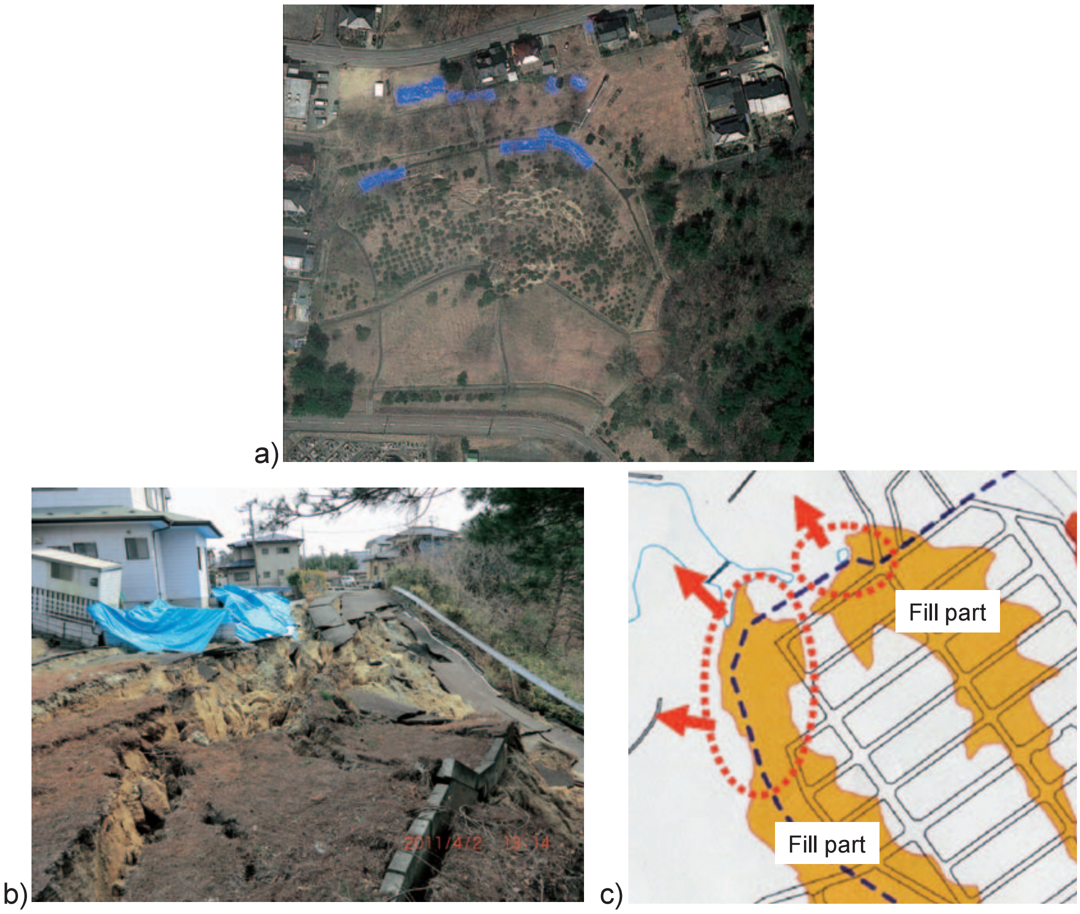


Fig. 3-16 a) Typical re-damage case of residential fill ground that had been damaged by the 1978 Miyagiken-oki Earthquake, Shiroishi City, Miyagi Prefecture; b) another typical damage case of embankment in narrow valleys; and c) the location of damage case shown in Fig. b in the plan view at the site (Sato, S.)

In addition to technical materials for use in restoring residential land after an earthquake disaster, such as "Residential Land Retaining Wall Restoration Technical Manual (1995)" and "Damaged Residential Land Restoration Technical Manual (Provisional Edition) (1994)," there are publications aimed at the education of homeowners themselves, such as "Retaining Wall Checklist for My Home" and "Residential Land Safety Manual for My Home." However, implementation remains the responsibility of individuals, so in practice the use of these materials was low. Further, at present countermeasures against future earthquakes are not clearly stipulated in the methods of restoration, so it is possible that measures against periodic large earthquakes are inadequate. Against this background, the Law on Regulation of Residential Land Development was amended in 2006, allowing prefectural governors to designate residential land developments with large-scale embankments and posing a high risk of harm to residents during an earthquake as "Developed Residential Land Disaster Prevention Areas." In accordance with this law, many local governments all over Japan have begun carrying out surveys to predict deformation during an earthquake. However, this process is still at the survey stage and the actual taking of countermeasures has yet to begin.

One difficulty that faces these efforts is that, frequently, the cost of any work must be covered by individuals. In other words, if a housing lot has suffered from damage due to geo-hazards, the cost borne by the individual is not limited to rebuilding or repairing the building alone. Further, restoration work usually requires working in confined spaces within residential developments and secondary damage from rainwater also has to be considered. Finally, it has long been known that lifelines such as sewerage systems are easily damaged by deformation of residential embankments, but countermeasures against this type of damage are in fact almost never taken. As a consequence of these shortcomings, considerable damage occurred in many locations in this earthquake.

3) Private housings on recently reclaimed land

Here, the situation was virtually the same as above, with widespread soil liquefaction affecting structures from the Tohoku region (north-east) to the Kanto region (around Tokyo). One of the most distant locations from the epicenter suffering soil liquefaction was Kanazawa-ku in Yokohama City, a distance 422 km. This is not a particularly great distance as compared with the range of soil liquefaction that has occurred in past earthquakes, both in Japan and elsewhere. However, in this case, the liquefaction-induced damage had special characteristics because of the magnitude of the earthquake. For example, a wide area of recently reclaimed land in Tokyo Bay at a distance 380 km from the epicenter suffered from soil liquefaction, as shown in Fig. 3-17, causing great damage in residential areas. More than 10,000 detached houses suffered from settlement and tilting, such as that shown in Fig. 3-18. Also, lifeline utilities such as sewage systems as well as roads suffered great damage. Similar damage occurred on recently reclaimed land throughout the Kanto Plain where marshes and rivers had been reclaimed. In the Tohoku region, soil liquefaction occurred in some land developments in hilly areas. Major damage was caused by soil liquefaction to river dikes, etc., throughout the Tohoku and Kanto regions.

Fig. 3-17 Estimated liquefied zones (delineated by red lines) along Tokyo Bay (Yasuda, S. and Harada, K.)

Fig. 3-18 Damaged houses and road due to soil liquefaction (Yasuda, S.)

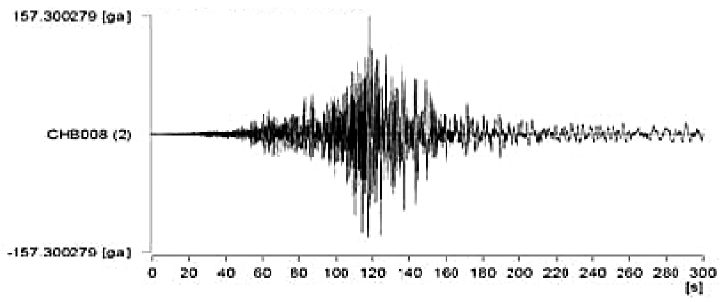
There are no clear technical obligations on private construction companies erecting detached houses to ensure that they predict soil liquefaction and implement countermeasures against soil liquefaction, so many private houses suffered from damage. The problems can be outlined as follows.

(1) There is no codified or standardized method of assessing soil liquefaction for the case of private houses, like that incorporated in the design criteria for public infrastructures (Fig. 3-1).

a) Hazard maps are sometimes used to predict soil liquefaction. However, there is no standardized method of preparing such hazard maps, so the method depends on each organization. Further, these maps are not normally accurate enough to predict soil liquefaction for individual houses. Also, the occurrence and degree of liquefaction depends on the magnitude of the assumed seismic motion, and these factors are usually not taken into consideration.

b) The seismic input that should be assumed when comparing the "assumed seismic load" and the "estimated strength against soil liquefaction" for determining soil liquefaction is not uniform.

- In the Architectural Institute of Japan's "Recommendations for Designing Small Buildings Foundations", which applies to detached houses, the "Method of assessing soil liquefaction" does not make clear whether Level II design seismic motion is taken into consideration. However, the seismic motion at reclaimed locations around Tokyo where widespread liquefaction occurred did not reach Level II (Fig. 3-19). Therefore, the unanticipated soil liquefaction in these locations cannot have been a result of not taking Level II seismic motion into consideration. However, it is certain that engineering opinion on this subject is divided.



Fig, 3-19 Time history of horizontal ground acceleration at a K-NET station in Urayasu City (the PGA= 157,3 cm/s^2)

In assessing soil liquefaction for public infrastructures and medium- and high-rise buildings where countermeasures have been taken, it has been normal until now to assume Level II seismic motion. Therefore, even though there was insufficient consideration of the effect of the main seismic motion duration, the potential for liquefaction in recently reclaimed land around the Tokyo Bay in the present earthquake was not substantially underestimated.

This demonstrates that there is a problem of consistency between the methods of setting the design seismic motion for liquefaction assessment for private detached houses and for public infrastructures and medium- and high-rise buildings. For the former, the assessment will differ depending on the engineer carrying out the work.

c) When carrying out site investigations for detached houses, simple methods such as Swedish sounding tests are normally used. With such tests, it is difficult to determine soil type (clay, silt, sand, etc.) and groundwater level, while there is also a limit to the depth of measurements. For these and other reasons, accuracy is not sufficient for predicting soil liquefaction. On the other hand, prediction of soil liquefaction for public infrastructures and medium- and high-rise buildings involves the standard penetration tests in boreholes and laboratory soil tests of soil samples taken from boreholes. This type of comprehensive method has generally been considered too expensive for use when designing detached houses.

(2) No clear system has been established for organizations and companies that develop residential land to explain ground quality and, when necessary, offer guarantees of ground quality. As a result, actual housing providers that purchase reclaimed land for residential development do not pass on such information to house purchasers. Such explanations would include the potential for embankment collapse and soil liquefaction, the damage that could result from such an occurrence, the need for and cost of site investigations to confirm ground quality, and the methods and costs of any necessary countermeasures, etc.

Notification 1113-2 (2001) of the Ministry of Land, Infrastructure, Transport and Tourism states that, where ground is at risk of liquefaction in an earthquake, it shall be ensured that no building or part of a building shall suffer harmful damage, deformation, or settlement, taking into consideration settlement due to the building's own weight and other ground deformations. Similarly, the commentary to Building Standard Law Enforcement Regulation No. 93 (Allowable stresses in the ground and foundation piles) states that, when assessing the allowable stress on foundations, if there is a risk of liquefaction within the foundation area, the short term allowable stress may not be set as long as it has not been confirmed that the effect of settlement, etc., due to soil liquefaction will be slight. If these provisions are interpreted as being applicable to detached houses, then it would be necessary to investigate soil liquefaction even for individual houses.

It is well known among construction engineers that recently reclaimed land readily liquefies in an earthquake. This means that designers ought to investigate soil liquefaction even in the case of detached houses. However, the reality is that checking for soil liquefaction is not carried out as part of compliance with the regulations based on the Building Standards Law; that is, the normal interpretation is that soil liquefaction verification is not obligatory. Further, the necessary technical means and criteria have not been developed for investigating soil liquefaction and for implementing countermeasures against it when necessary, and engineers have not been trained to deal with this issue.

4) Recommendations for preventing damage to detached houses due to geo-hazards

The following are recommendations for common problems of housing lots of hilly land and reclaimed land.

(1) For existing housing, there is a need for urgent implementation of "seismic damage inspection and assessment of large-scale embankments" to be carried out by prefectural, city, town, and village governments throughout Japan as demanded by the amendment to the 2007 Law on Regulation of Residential Land Development. This will advance projects designed to prevent slip failure of large embankments.

(2) Most damage to hillside embankments in residential developments is caused by slip failures that typically involve several tens of privately owned housing lots with different owners. Also, in addition to damage to individual housing lots and retaining walls, there is usually accompanying damage to the public infrastructure, including roads, etc. Restoration of this public infrastructure is normally part of the process of restoring road and transport functions by repaving, etc. The permanent stabilization of roads and residential developments requires overall slip failure prevention, so the cost that should be borne by private owners should be reduced. This means that the government should be involved in the process in accordance with the extent of the damage (see Table 3-2). That is, there is a need to introduce a policy of public support for restoration measures aimed at damaged residential land.

Table 3-2 Relationship between damage level and restoration method for developed housing lands (see Figure 3-15)

Classification of damage level	Classification of damage mechanism	a)	b)	c)	d)	e)	f)	g)
1) Large-scale damage involving a dozen of house (exceeding the scale affordable by individual homeowners)		◎	◎	—	—	—	—	◎
2) Medium-scale damage involving several houses with influence to public infrastructures and neighboring areas		—	○	○	○	—	—	○
3) Small-scale damage for individual house, affordable by individual homeowners		—	—	△	△	△	△	△
Damage to a large number of individual houses by a common cause.		—	—	—	○	○	○	◎

Remarks for restoration works from damage: ◎ : cases that need full administrative support; ○ : cases that need administrative support; , △ : cases that do not need administrative support

Examples of such funding mechanisms include projects carried out as special measures to prevent the recurrence of damage to private retaining walls, etc., after the 1995 Great Hanshin-Awaji Earthquake. These were projects such as road restoration projects and emergency measures to prevent the collapse of steep slopes. In the 2011 Great East Japan Earthquake, also, the use of this type of funding mechanism should be investigated.

(3) There is a need for surveys of large hillside embankments (valley filling embankments and widening embankments). These surveys should cover those that suffered from earthquake damage as well as those that did not, so as to clarify the causes of damage and to compare these with common explanations such as insufficient compaction, insufficient drainage, lack of retaining wall strength, etc. The results should be used to improve the seismic resistance of residential land developments in the future.

(4) It is necessary to determine suitable ground-quality criteria for private houses on new and existing residential lots on hillside embankments and reclaimed land.

a) Establishment of land use plans and disaster prevention plans that reflect the realities of land and ground. For example, this should take account of alluvial fans (locations where landslides frequently occur), flood plains (where flooding frequently occurs or where there is a high possibility of weak ground that could liquefy in an earthquake), natural levees and hinterland wetlands (saturated sandy ground that can easily liquefy in an earthquake and areas with weak soil ground where long term consolidation settlement can easily occur), weak ground in deltas, valley filling embankments, reclaimed and other artificial ground, etc.

b) Establishment of survey methods for determining the prevalence of reclaimed land and embankments:

- Develop and make public a database containing land history surveys, information about the old topography, land use prior to reclamation or embankment building, year of reclamation or embankment construction, past disaster history, history of changes to land, etc. (including legal adjustments)

- Construction history and present status (embankment materials, degree of compaction, N-values by the standard penetration tests, deformation state, groundwater, surface water, etc.)

It is normally difficult for individuals to implement such measures, so the active support of local governments is necessary.

(5) Development and establishment of a system for seismic damage inspection and assessment of residential land embankments for existing detached housing lots, and develop low-cost methods of seismic strengthening and countermeasures against liquefaction in reclaimed land

(6) Establishment of a system by which countermeasures are proposed for residential embankments and reclaimed land based on newly developed criteria for the use of

various construction methods (drainage, compaction, etc.) and development of a system for their implementation

(7) Amendment of the applicable laws concerning damage insurance. For example, introduction of a system in which the insurance premium is reduced if mitigation measures for geo-hazards are taken.

(8) New detached housing developments: Sellers should be obliged to provide information on the quality of the foundations/ground that is certified by a specialist engineer. This will allow buyers to confirm the quality of the ground. For this purpose, it is proposed that a system of ground quality assessors be introduced. These assessors will provide information regarding ground quality. There is already in place a system of assessors of disaster-damaged residential land operated by prefectural governments. The proposed ground quality assessors will possess a qualification that enables them to assess damaged residential land and also assess and describe the quality of existing residential land.

(9) Providing public access to geo-hazard-related information that will be useful for preliminary confirmation of the quality of ground. The JGS has, in addition to distributing copies of the 2010 edition of "Geo-hazards areas in Kanto," collected geo-hazard-related information from all over Japan and made it available on the society's website in an "electronic geo-hazards map" that can be viewed by anyone. Prerequisites to further promotion of this map are the following:

a) Ongoing disclosure and updating of geo-hazards information by national and local government bodies

b) Disclosure of geo-hazards information obtained by local governments during checking for compliance with the regulations based on the Building Standards Law

c) Cooperation of private companies responsible for development and management of the public infrastructure, including roads, railways, electricity, gas, etc., in the disclosure of geo-hazards information.

For this purpose a certain number of legal arrangements will be necessary.

Particular recommendations for countermeasures against soil liquefaction in recently reclaimed land are as follows.

(1) Development of a standard method of assessment of soil liquefaction that can be applied to residential land:

a) The preparation of hazard maps, which are a significant provisional assessment method for determining whether a soil liquefaction survey should be carried out, should be standardized and the accuracy should be increased. In particular, all local governments should re-draw their hazard maps, making them more reliable by taking into consideration previous formations such as old river channels, marshes, etc.

b) The setting of appropriate and uniform seismic loads for assessment of soil liquefaction, to be adopted as reference values or as standard values by organizations or engineers responsible for assessing soil liquefaction. The JGS should take the leadership in developing these standards. In particular, it is necessary to consider whether residential land for private houses should be assessed for soil liquefaction against Level II seismic motion, the same as for ordinary public infrastructures and medium- and high-rise buildings. It is also necessary to investigate the specification of the peak ground acceleration (PGA) and waveform (duration, predominant periods).

c) The estimation of resistance to soil liquefaction must be increased in accuracy. To date, the Swedish sounding test has generally been used for investigations of residential land. However, accurate prediction of soil liquefaction is difficult with this method for various reasons, such as the difficulty in determining soil particle sizes and its coefficient of uniformity, the inability of survey to great depth, and the difficulty in estimating the groundwater level. This method is suitable for preliminary surveys aimed at identifying locations where a more detailed survey is necessary. To make this possible, it is necessary to collect and compile data on the Swedish penetration test from locations where soil liquefaction occurred and where it did not occur in the Tokyo Bay area in this earthquake, so as to increase the accuracy of these preliminary surveys.

   On the other hand, site investigations for public infrastructures and medium- and high-rise buildings are carried out by the standard penetration tests using boreholes and laboratory tests on soil samples, etc. Such methods can easily assess the soils in deep layers. Conventionally, it has been considered that the cost of applying such investigation methods to detached house lots is too high for individuals to pay. However, the cost of a standard penetration test using a borehole ranges upwards from several hundred thousand yen (or several percent of the overall cost of constructing the house), so in the future this method could be recommended for residential land also if necessary. At the same time, it is also necessary to develop survey methods that can be carried out at a lower cost while maintaining accuracy.

d) It is necessary for the JGS to indicate a suitable preliminary method for predicting soil liquefaction that can be used by individuals.

e) For residential land that has been damaged by soil liquefaction, it is necessary to take into consideration possible re-liquefaction in future earthquakes.

(2) Development of countermeasures against soil liquefaction that can be applied to residential land:

a) Where residential land suffers damage, there is a need for simple methods of recovering from settlement and correcting house tilt, as well as for the development of a ground improvement technology applicable to ground directly below a house, at a cost of less than ¥2 million. At the same time, there is a desire for a method of preventing soil liquefaction or ensuring that there is no settlement even if soil liquefaction occurs. Recently there has been rapid progress in technologies that can improve the ground directly below a building, such as compaction grouting (CPG, Fig. 3-20), chemical injection, high-pressure injection, etc.

Fig. 3-20 Ground improvement by compaction grouting for restoration of a private house damaged by soil liquefaction, Urayasu City (Yasuda, S.)

b) For existing detached housing lots, it is necessary to develop low-cost countermeasures costing up to 2 million Japanese yen (such as simple piles to prevent settlement and tilting) for cases where houses were constructed on ground with the potential for soil liquefaction.

c) For new detached housing lots, it is necessary to develop low-cost countermeasures against soil liquefaction (such as by improving the surface strata, carrying out column-shaped cement-mixed ground improvement, driving small-diameter piles, etc.) for use when it is assessed that the ground has the potential for liquefaction. In this regard, it should be noted that raft foundations, which are conventionally regarded as reducing soil liquefaction damage to detached houses, tended to result in greater settlement in Urayasu City (near Tokyo) in this earthquake than strip footings. This may be because raft foundations are heavier than strip foundations. The use of small-diameter piles to prevent a house settling even if liquefaction of the supporting ground occurs also raises questions because, if the unimproved ground around the house settles, a level difference will be formed and there will be damage to lifeline utilities.

(3) Publicity to prevent damage to detached houses due to soil liquefaction
Information regarding soil liquefaction and countermeasures against it should be widely disseminated to the general public. In the past, the JGS has made some progress in this regard, but greater efforts are needed.

5) Sewage systems

The uplifting of sewage pipes following soil liquefaction caused significant damage for the residents of private houses on recently reclaimed land. Manholes and pipes also uplifted due to the liquefaction of backfill in all areas, but particularly in Miyagi Prefecture and Fukushima Prefecture. Sewage systems constructed with old technology and to old standards are common throughout Japan. These systems have low seismic resistance and the potential for damage due to soil liquefaction in future earthquakes is high where they pass through reclaimed land or where soil is backfilled. It is necessary to urgently respond to this situation. Several methods for improving the seismic resistance of existing sewage system manholes have been developed and applied. For example, the mass of the manhole may be adjusted or a system for dissipating the excess pore water pressure implemented. However, at present, no methods have been widely adopted for existing pipelines. There is a need to develop these methods to make the introduction of countermeasures more practical.

Fig. 3-21 Differential settlements of private house and road, Urayasu City (Ishihara, M.)

Sewage systems work on the basis of natural flow under gravity, so they are particularly susceptible to differential settlement of the ground compared with other lifeline utilities. In places such as Urayasu City, where soil liquefaction occurred over a wide area, housing lots settled much more than the roads, as shown in Fig. 3-21. Sewage systems have been damaged by longitudinal slope defects associated with this type of differential settlement. In such cases, also, reducing the level of the road may result in inadequate soil cover over sewage pipes. With water, gas, and other lifeline utilities also buried under sidewalks and roads in many cases, areas with widespread soil liquefaction (reclaimed land or developed land) have suffered considerable damage. In restoring damage caused by this earthquake, it is important for seismic countermeasures be implemented with the cooperation of all those involved.

6) Deformation of roads due to soil liquefaction
Roads at all levels of responsibility – national, prefectural, city, town, and village – suffered surface deformation as a result of soil liquefaction, causing considerable traffic disturbance. Because this type of damage occurred over a wide area and at many locations, recovery has been delayed in many locations.

3.2.5 Postulation of failure processes for complete loss of function and issues regarding setting functional requirements

The 2011 Great East Japan Earthquake was on a giant scale and the associated tsunami exceeded all conventional scenarios in height and power. As a result, the damage caused was enormous. Such devastating disasters occur extremely rarely, but the question of rationally designing structures in the knowledge that they occur has to be faced. Generally, standards of safety are set in consideration of the balance between the demand for safety by society and the cost to society of realizing them.

Based on the experience with the 1995 Great Hanshin-Awaji Earthquake, seismic design for public infrastructure normally considers two levels of seismic motion (Level I, Level II). The structure is designed so that the serviceability limit state is not exceeded in the case of Level I motion and the repair limit state (ultimate limit state) is not exceeded by Level II motion, respectively. Evaluations following this earthquake are that, generally, this concept of performance-based design has functioned effectively in respect of structures whose main materials were concrete and steel, apart from some exceptions such as damage caused by the tsunami. Also, although considerable damage to such concrete and steel structures was caused by the tsunami, which exceeded the Level I tsunami which has a frequency of occurrence from once in several tens of years to once in a hundred and several tens of years, there was in many cases no complete loss of function and a certain level of disaster reduction effect was exhibited.

However, the damage to soil structures was different. There were cases where a part or the whole of a structure was washed away or suffered severe deformation, leading to its destruction and complete loss of function. As a result, extremely serious damage was caused. The following are examples.

- Tsunami defense barriers and tidal barriers that suffered severe damage in the initial tsunami then suffered scouring and erosion due to overflow or backwash. They were dysfunctional in subsequent tsunami surges.

- Storage dams that were constructed using old technology (for example, the Fujinuma Dam, Fig. 3-4) were damaged and large quantities of reservoir water flowed downstream as flash floods, damaging houses.

Soil structures reached this limit state of destructive failure (collapse with total loss of function) because, when flows of water over part of the surface or through the interior initiated surface erosion or scouring including debris flow, or 'piping' erosion of the interior, the foundation material was soon washed out and the erosion spread to adjacent parts of the structure. This type of sudden collapse of soil structures is also seen in the flow-type collapse of slopes (when a slope collapses rapidly and with displacement over a great distance) during an earthquake; liquefaction is thought to play a role in this type of collapse.

There were also examples of severe collapse in this earthquake that had never been envisaged in the past, such as overturning of structures with pile foundations where pullout of all piles occurred. In the coastal area of Onagawa Town, which was struck by the massive tsunami, a medium-rise RC building was flipped on its side with the piles, measuring several tens of meters long, left sticking out from its bottom surface (Fig. 3-10). Various groups are investigating the exact cause of this, but it is thought to have resulted from a combination of liquefaction around the piles due to the seismic motion and the power of the tsunami surge, which exceeded 10 meters. That is, this is an example of destructive collapse (collapse causing total loss of function) of a foundation structure due to the combined action of soil liquefaction and tsunami; such failures must be avoided for tsunami evacuation facilities.

From this perspective, there are structures that can be considered extremely important from the viewpoint of public safety and for which, although a certain amount of damage is inevitable if loading (seismic or tsunami, etc.) exceeds the design level or occurs in combinations not envisaged in design, it is important that damage should not snowball into destructive collapse (collapse causing total loss of function). In other words, such structures should be designed to be tough and resilient so that even if an initial or partial failure occurs, its effects will be limited and the structure will not be rendered useless (meaning its disaster reduction effect is completely lost) as a result of the applied load or a subsequent load. Conventional design methods, however, do not incorporate the concept that, even if the repair limit state (or ultimate limit state) is exceeded, a certain level of disaster reduction effect should be maintained and the damage should not develop unlimitedly.

On the other hand, there are an extremely large number of soil structures of various types that have been constructed with the aim of maintaining public safety. Many of these existing soil structures were constructed using old technology and may not yet have been subjected to seismic risk assessment and seismic strengthening, so they may not satisfy the performance required by the current standards. (That is, they cannot be said to be safe with respect to currently envisaged loads or combinations of loads.) Further, human knowledge is not perfect, so even in the case of those structures designed and constructed in accordance with current technical criteria, the possibility of loading by a massive tsunami that exceeds the envisaged height cannot be ruled out, as in this disaster. An example of this is in the seismic design of nuclear power stations, where the concept of "residual risk"[4)] has been introduced based on the recognition that, from the seismological point of view, it is not possible to rule out the possibility that seismic motion stronger than the level, Ss, will occur.

> Note 4) In "Guide to Assessment of Seismic Design of Nuclear Reactor Facilities for Electrical Power" adopted by the Nuclear Safety Commission of Japan on September 19, 2006, there is reference to "the risk of major damage to the facility, and of release of large quantities of radioactive material from the facility, and of irradiation damage to the surrounding public as a result of this release." Efforts should be made to reduce this risk as much as is reasonably practicable, while adequately recognizing the existence of this "residual risk."

Under these circumstances, it is neither rational from a socio-economic point of view nor practical to design all soil structures to withstand the seismic motions and tsunami heights envisaged in the current technical standards, or the higher loads that might arise from combinations of these loads. Further, the definition of Level II seismic motion is "the maximum seismic motion conceivable at a particular location from now through the future." However, as noted above, human knowledge cannot be said to be perfect, so it is difficult to completely rule out the occurrence of seismic motion that exceeds the currently envisaged maximum strength.

Therefore, design to ensure that function is not completely lost in the event that a structure is subjected to loads that exceed those envisaged (seismic motion and tsunami, etc.) or that arise in combinations not envisaged is conceivable only for structures that meet certain conditions. These will be structures that are extremely important to public safety and that, if there were destructive collapse (collapse with complete loss of function), it would result in enormous damage. The following are examples of such structures.

a) Tsunami barriers, tidal barriers, and river dikes near river mouths that protect densely populated urban areas

b) Breakwaters, tidal barriers, river dikes, and coastal defense structures that protect areas at or below sea level in Japan's three great metropolitan areas

c) Dam structures for large-scale disposal sites containing highly toxic materials

d) Fill dams for water storage, water reservoir dams, and mine tailings dams that are upstream of cities, towns, villages, or residential areas

e) Soil structures at major disaster evacuation centers

If any soil structures of these types suffer destructive damage during the seismic motion of a main earthquake or an initial tsunami, followed by the seismic motion of large aftershocks or subsequent tsunami surges, or by heavy rain or severe flooding immediately after the disaster, it is likely that severe damage will take place and the time and effort required for recovery will be enormous.

In addition to “soft” measures to minimize danger, such as through land use planning and evacuation systems, approaches to the design of such structures can be considered as follows.

a) Ensure that excessive scouring, erosion, or internal “piping” erosion does not affect tidal barriers or breakwaters when they are overtopped by waves or overflow (to prevent large-scale tsunami damage).

b) Ensure that excessive scouring, erosion, or internal ”piping” erosion due to overtopping waves or overflow does not occur in the case of levees that protect areas at or below sea level (to prevent large-scale, long-term inundation damage).

c) Ensure that large-scale collapse does not occur to fill dams, reservoirs, or waste pool dams, and that erosion and scouring does not occur due to overtopping (to limit loss of water storage function and prevent large-scale damage downstream).

d) Combine multiple defense mechanisms, both structural (hard) and evacuation-related (soft). For example, where collapse of a dam is postulated, capacity for temporary storage of some of the flood flow might be provided downstream as an additional defense mechanism.

This approach relies on being able to evaluate the behavior of a soil structure when loads (seismic motion or tsunami) or combinations of loads that exceed the level envisaged in the current design standards arise. It is necessary to evaluate this behavior for structures built to the current design standards as well as for those built to the old design standards (and which therefore have a high risk of collapse). To make this possible, the concept of loads (seismic motion or tsunami) or combinations of loads that exceed the currently envisaged level is introduced. The performance required when such loads occur must then be clarified.

As to the magnitude of such loads, they should be of theoretically conceivable scale, so the maximum loading thought to have occurred in history could be adopted. Alternatively, this historical maximum might be incremented by a certain percentage to take uncertainties into account.

Considering the required performance under such loading, it is assumed that the ultimate limit state (repair limit state) will be reached, where the structure fails or is damaged such that repair is not possible in the short term. However, the following performance criteria should also be met.

a) The effect of the damage is limited, meaning that there should be no threat to a large number of people. In other words, the structure should be designed so that after initial or partial collapse, the residual deformation of the structure is sufficiently small that a minimum level of function remains. Re-building will be necessary to restore full functionality, but the structure remains capable of providing at least a certain level of function to contribute to disaster reduction. (Maintenance of residual function [secondary function])

b) For compound loads, such as a series of tsunami surges or aftershocks (the second and subsequent seismic loads) or severe rain, the structure should be designed such that destructive collapse (collapse with complete loss of function) occurs. (Prevention of disaster by compound loads or repeated loads)

A number of issues could arise in connection with establishing this design concept, as follows.

a) Development of technology for predicting deformation or damage beyond structural failure (clarification of structural collapse mechanisms and processes in disasters).

b) Setting the required functional performance for loads or combinations of loads that exceed the conventionally envisaged level (maintenance of human safety, lifesaving, catastrophe mitigation, etc.).

c) Determining the performance of the structure (residual performance after failure) with respect to the required functional performance.

d) Determining the scope to which the design concept is applicable (structures that are classified as extremely important disaster prevention facilities).

e) Designing a single system that combines hard and soft measures or several disaster prevention installations (the concept of multiple defenses).

3.2.6 Damage to system function due to occurrence of geo-hazards to ancillary facilities

Damage to important industrial facilities along the coast in this earthquake was minor or negligible, where adequate measures had been taken against seismic effects, such as countermeasures against soil liquefaction, etc. However, as in the examples below, where adequate measures had not been implemented for ancillary facilities that support these important installations, unexpected geo-hazards occurred. The tsunami surge and associated scouring led to instability and eventual loss of functionality. As a consequence, business continuity of the system as a whole could not be maintained.

a) At an oil company's storage facility for inflammables, the seismic resistance of storage tanks for oil, etc., was adequate. However, the piping between these tanks and a nearby jetty and other installations was damaged, with the result that the required performance of the facility (the supply of oil) was not fulfilled immediately after the disaster.

b) Similar failures occurred at fossil-fuel power stations. Although the seismic resistance of important facilities was high, piping and other peripheral equipment was damaged by the seismic motion or the tsunami, and immediately after the earthquake it was not possible to fulfill the important mission of supplying electricity.

c) In the 2007 Niigata Chuetsu Earthquake, the Kashiwazaki nuclear power station suffered damage at the interfaces between facilities installations that had been designed to different seismic design levels. It took time to restore power supply functionality. There is a need to confirm whether similar phenomena occurred in this earthquake.

These examples indicate that it is important to develop countermeasures against geo-hazards so as to ensure that ancillary facilities to important installations have seismic resistance, as well as to develop technology for improving the seismic resistance of interfaces between important installations and their ancillaries. In particular, with respect to soil liquefaction, the following measures are necessary.

a) In order to ensure stability against tsunami-induced scouring of structures such as quay walls, loading bays, etc., loss of bearing capacity of the bearing ground due to soil liquefaction must be avoided. For this purpose ground improvement or protection of the surface strata is necessary.

b) Rapid restoration of installations that have uplifted, settled, or tilted due to soil liquefaction is quite difficult. It is necessary to develop technology for handling this.

c) Various measures are already available in the field of geotechnical engineering, but suitable countermeasures from the points of view of cost and reliability need to be proposed.

3.2.7 Ground subsidence and ground settlement over a wide area

During an earthquake the ground subsides or rises in accordance with the crustal movements, while uncompacted loose ground may also settle due to the shaking and due to dissipation of excess pore water pressure after liquefaction. In this earthquake, both of these phenomena occurred over a wide area.

1) Ground subsidence over a wide area

Ground subsidence occurred over an extremely wide area along the Pacific coast from the Tohoku region south to the Kanto region. This was not a consequence of ground compaction, but was associated with crustal movements. Subsidence reached several tens of centimeters in many locations and 1.2 meters on the Oshika Peninsula. This type of ground subsidence has occurred repeatedly from ancient times along the Sanriku coast, forming a ria coastline. Ground subsidence is a natural phenomenon that is difficult to avoid from a historical perspective.

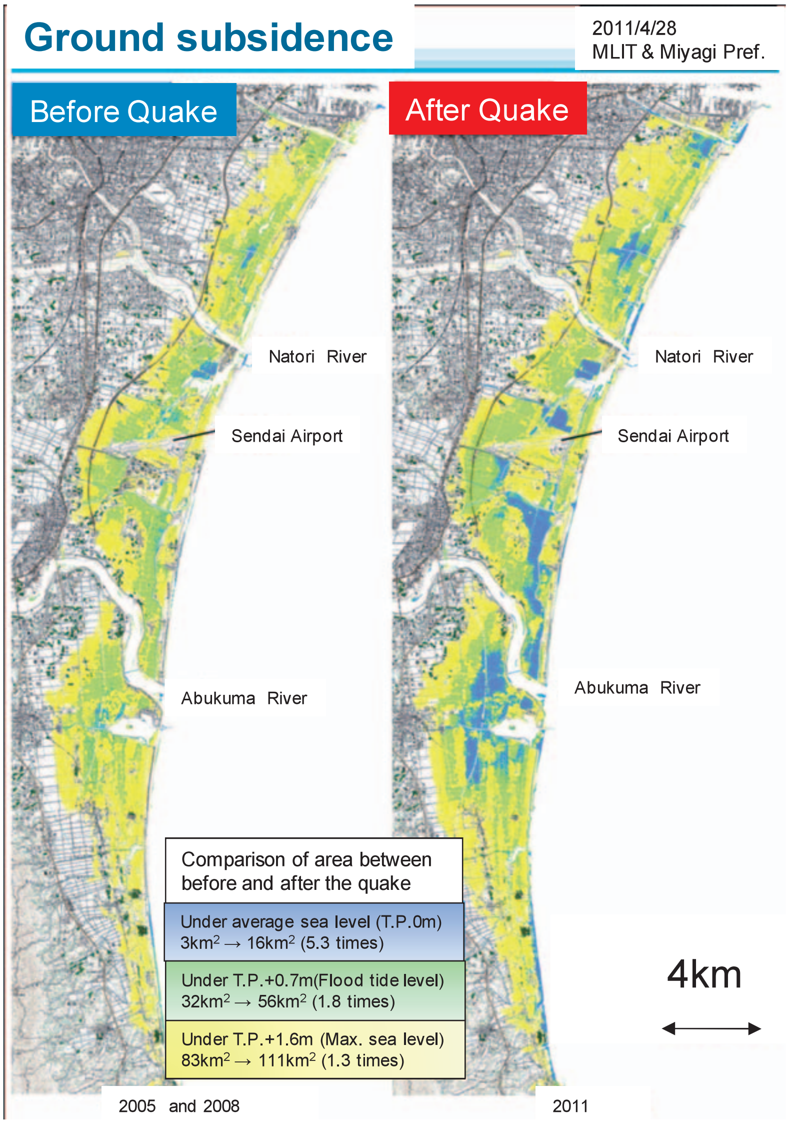


Fig. 3-22 Areas of ground subsidence, South region of Miyagi Prefecture (by the courtesy of Tohoku Regional Bureau of MLIT and Miyagi Prefecture Government)

On the Sendai Plains, the area lying below sea level increased by a factor of 5.3 from 3 km^2 prior to the earthquake to 16 km^2 afterwards (Figs. 3-22, 3-23, Table 3-3). As a result of ground subsidence, houses and agricultural land at many places remained flooded even until June 2011, as shown in Fig. 3-24. The subsidence hindered recovery efforts in areas damaged by the tsunami. Work to drain the water was hampered by collapsed coastal dykes or by dykes of insufficient height. Restoration of the coastal dykes will take a long time and until it is complete inundation damage will continue. Further, groundwater is becoming progressively saline as a result of the subsidence, which is causing additional serious problems for the restoration effort.

As a result of this ground subsidence over a wide area, many coastal areas, port facilities, and urban developments now lack sufficient drainage, so damage has been caused by inundation and flooding. These areas are exposed to the future danger of submergence. The effect is similar to the expected rise in sea level due to global warming, so problems of inundation damage due to high tides, tsunami, severe rain, and flooding as well as salination of groundwater will become more serious in the long term. In particular, where the ground has subsided near coastal levees, the relative difference between ground level within the levees and the tide level outside has increased. As a result, the hydraulic gradient of seawater permeating into the ground has risen. In order to deal with the issue of dyke stability and also prevent salination of the ground (in particular land used for agriculture), it will be necessary to widen the dykes or build water impermeable walls. Geotechnical engineering knowledge will be indispensable to this task.

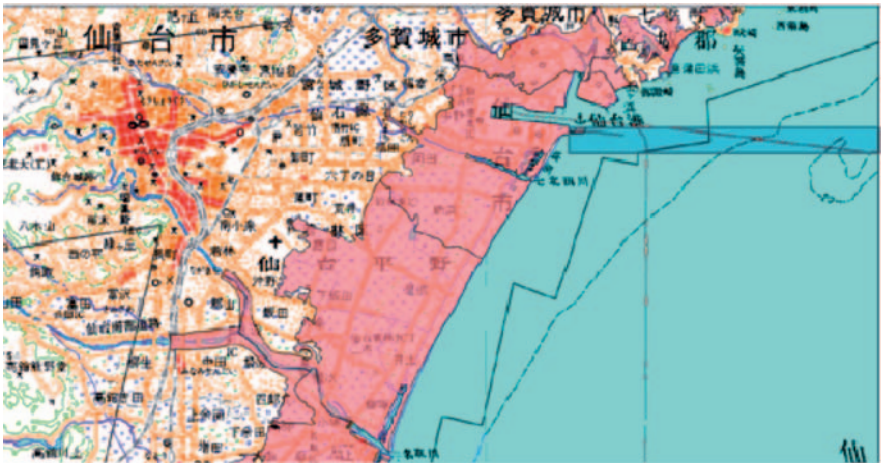


Fig. 3-23 Inundated areas, Sendai Plain (by the courtesy of GSI, Geospatial Information Agency of Japan)

Table 3-3 Ground subsidence investigated by GSI (2011)
http://www.gsi.go.jp/sokuchikijun/sokuchikijun40003.html

Iwate Prefecture		Miyagi Prefecture		Fukushima Prefecture	
City/town	Amount of subsidence	City/town	Amount of subsidence	City	Amount of subsidence
Miyako City	0.50 m	Kesen-numa City	0.74 m	Soma City	0.29 m
Yamada Town	0.53 m	Minami-Sanriku Town	0.69 m		
Ohtsuchi Town	0.35 m	Oshika peninsula	1.20 m		
Kamaishi City	0.66 m	Ishinomaki City	0.78 m		
Ohfunato City	0.73 m	Higashi-Matsushima City	0.43 m		
Rikuzen-Takada City	0.84 m	Iwanuma City	0.47 m		

Fig. 3-24 Inundation by ground subsidence, two days after the earthquake, Ishinomaki City, Miyagi Prefecture (by the courtesy of Tohoku Regional Bureau of MLIT)

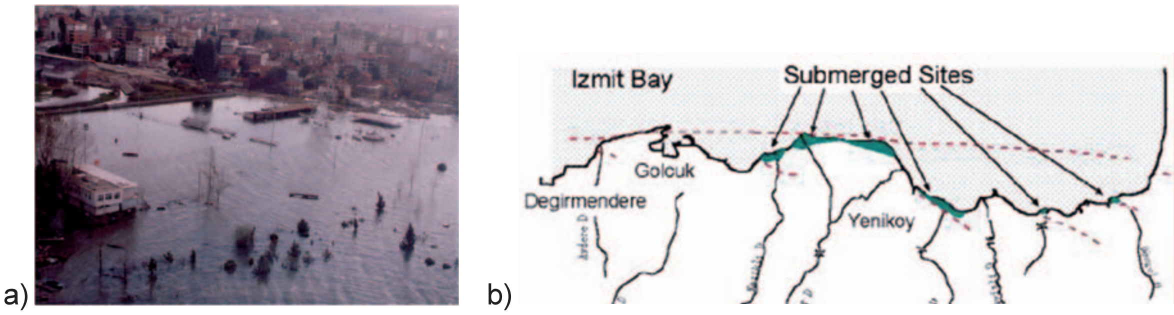
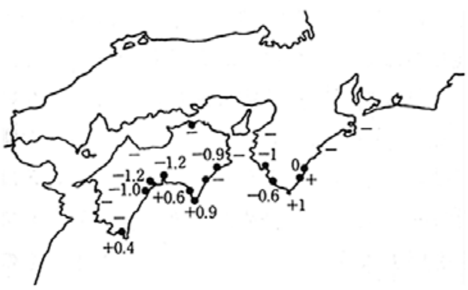


Fig. 3-25 Submerged area in Gölcük due to ground subsidence during the 1999 Kocaeli, Turkey earthquake (Yasuda, S.)

In the 1999 Kocaeli Earthquake in Turkey, ground subsidence occurred over a wide area along the Izmit coast, as shown in Fig. 3-25a, including subsidence of about 1.5 m at Gölcük (Fig. 3-25b) where an area of 1 km^2 was flooded. The JGS dispatched a survey team to carry out a detailed investigation of the damage, but the mechanism by which the subsidence occurred was not established. Within Japan, also, ground subsidence has previously occurred in many places during past earthquakes. At the time of the Nankai Earthquake there was about 1-1.5 m of subsidence around Kochi City, as shown in Fig. 3-26, and the city suffered flood damage. There is a high possibility of the same type of ground subsidence occurring in future due to the anticipated Nankai, Tonankai, and Tokai earthquakes.



Fig, 3-26 Ground subsidence and heaving (in meter) by the Nankai Earthquake (21th December 1946) (after Kawasumi, Hiroshi)

The future relative difference in elevation between ground within levees and the tide level outside will be the sum of ground subsidence to date, future subsidence, and the sea level rise associated with global warming. Going forward, it will be necessary to monitor and track each of these changes.

The following are recommendations for countermeasures against earthquake-induced subsidence.

a) Carry out long-term monitoring of relative level differences as the sum of long-term ground subsidence and the rise in sea level associated with global warming

b) Compile examples of the effect of ground subsidence on the public as a result of this earthquake

c) Develop explanations for the mechanisms of ground subsidence over a wide area

d) Carry out digital mapping of changes in topography due to the damage

e) Use of disaster wastess, tsunami deposits, and excavated soil to raise urban areas, and also in breakwaters and land reclamation.

Fig. 3-27 A typical case of ground settlement by soil liquefaction, Urayasu City (Yasuda, S.)

2) Ground settlement over a wide area

In the reclaimed land along the fringes of Tokyo Bay (see Fig. 3-27), where widespread soil liquefaction occurred, ground settlement of about 50 cm was recorded over a wide area. Fortunately, no inundation occurred, but in Urayasu City and elsewhere, there was overall settlement of the ground over large areas. This caused major problems, such as with sewage systems that rely on natural flow under gravity. Large-scale ground settlement like this (as well as subsidence) causes great difficulty in people's daily life and makes areas prone to flooding during high tides and similar damage. Many areas in Tokyo are below sea level, but fortunately there was no damage to river and coastal dykes or other coastal defenses, so inundation did not occur. However, many low-lying areas in Japan remain prone to this type of damage.

Seismic strengthening of coastal levees and river dikes in the below-sea-level areas of Tokyo is proceeding, so the danger of inundation damage in an earthquake is gradually decreasing. However, this danger has not been completely eliminated, so urgent efforts such as seismic damage inspection and assessment and seismic strengthening are necessary. Also, in other areas throughout Japan that are in danger of inundation, it is necessary to investigate the hazard and take countermeasures if necessary.

3.2.8 Dealing with disaster wastess, tsunami deposits, and soil contaminated with salt and radioactivity

This earthquake produced enormous quantities of disaster wastess and tsunami deposits, while huge quantities of soil are likely to be contaminated with radioactive materials, salt (Fig. 3-28a), and tsunami deposits (Fig. 3-28b) in agricultural areas. The processing and use of these are major issues.

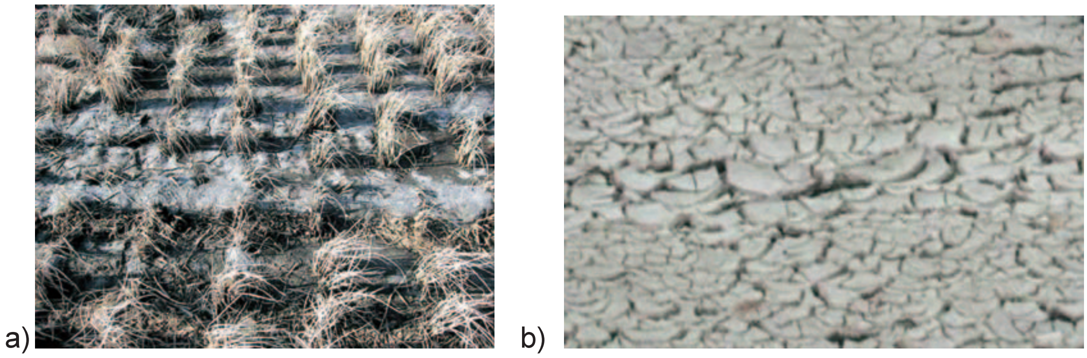


Fig. 3-28 Damage to agricultural areas by tsunami at Watari Yamamoto District, Miyagi Prefecture: a) rice field covered by salt from sea water that came via a drainage (the ground subsided); and b) rice field covered by tsunami deposits with a thickness of several centimeters (Mohri, H.)

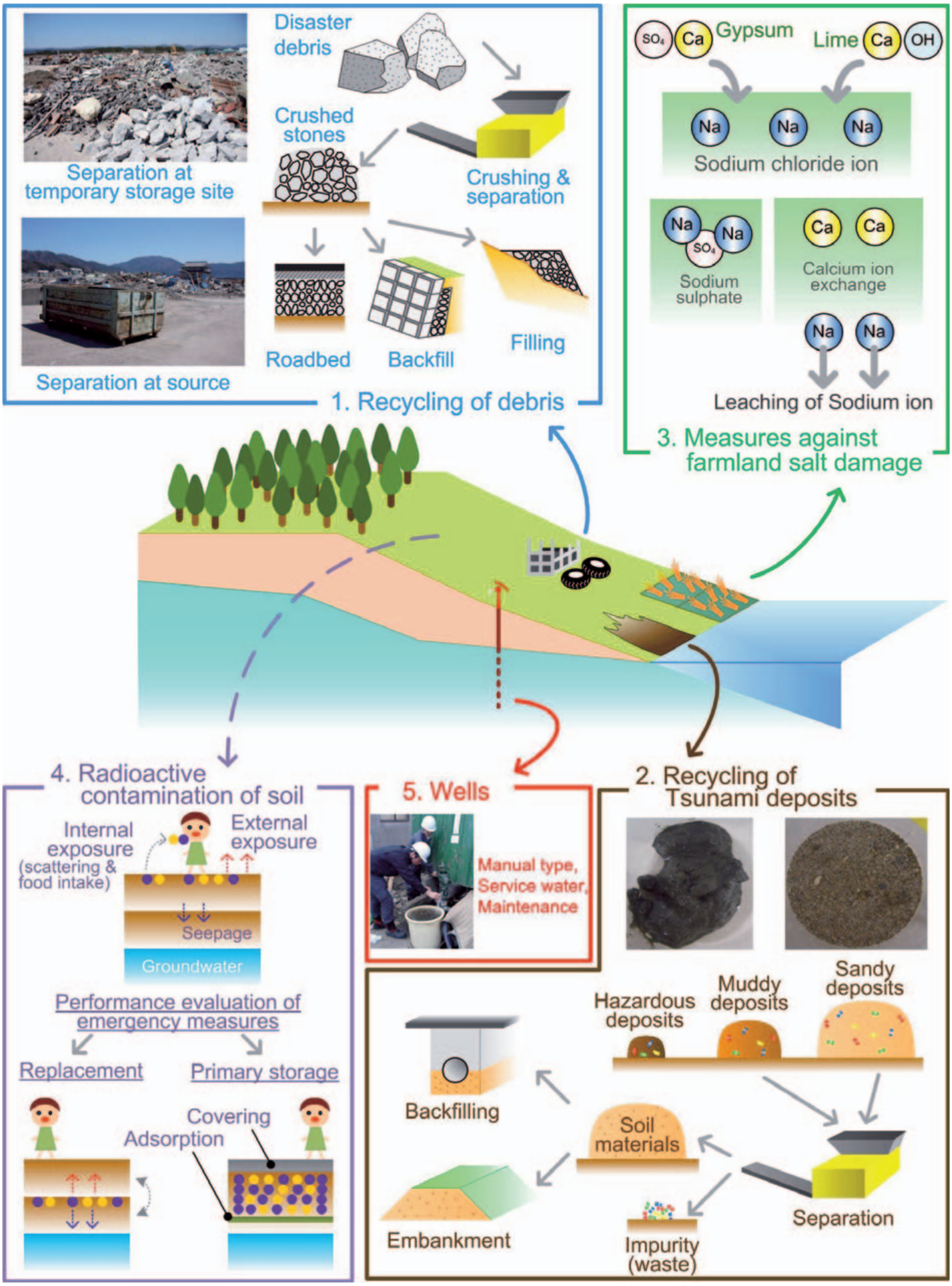


Fig. 3-29 Treatment of disaster wastess, tsunami deposits, and soil contaminated with salt and radioactivity (Endo, K.)

The following are recommendations for dealing with these problems; they are illustrated simply in Fig. 3-29.

1) Safe and effective processing of disaster wastess and tsunami deposits and their reuse as a resource

The earthquake and tsunami disaster generated enormous quantities of rubble and similar waste, including disaster wastess left by the tsunami and tsunami deposits brought onto the land. It has been estimated by the Ministry of the Environment that the quantity of disaster wastess generated in the three prefectures of Iwate, Miyagi, and Fukushima is 24.9 million tons, while the National Institute for Environmental Studies estimates that the quantity of tsunami deposits amounts to 10 million m^3. Disposal of all this in landfill would be difficult both from an economic viewpoint and in terms of securing landfill capacity. Therefore, it is desirable that as much as possible be effectively re-used in the recovery and restoration effort. In particular, earthquake-generated waste with no potential environmental effects and any tsunami deposits that are mainly sand can be easily and effectively used. Ideally, sorting would be carried out at collection and temporary storage facilities, and that efforts be made to re-use the waste as a geotechnical engineering resource. This will reduce the quantity of waste subject to a final disposal solution.

A number of issues arise in implementing such a re-use of disaster wastess.

a) It is necessary to establish evaluation and processing methods for the re-use of resources. Some of the tsunami deposits are sandy soil that can be considered predominantly sand, so it has potential for use as a sandy construction material. It is thought that waste and sandy soil can be separated based on "Manual for Processing Soil Mixed with Waste Arising in Construction" (by the Public Works Research Institute) or similar publications. Applicability of the sandy soil can then be evaluated according to its fines content, water content, ignition loss, etc based on the criteria for classification of soils. However, after the grading process, the sandy soil may still contain residual organic matter such as tree fragments and the like; it is not easy to efficiently remove this from large quantities of material. Normally there is a tendency to avoid using materials including organic matter as a material for embankment construction or the like, so investigation and research is necessary into methods of effectively using such materials correctly and in the right place. Where tsunami deposits are suspected of containing harmful substances, the sand component can in many cases be effectively used, because the harmful substances are contained in the fine particle content, such as clay or silt (although this does not apply to material of natural origin). The finer fractions can be removed by the soil washing method, enabling the separated sand to be used as a geo-material and reducing the quantity of material requiring disposal. Regarding other waste materials, they can be sorted into combustible and non-combustible components. Any waste that can decompose cannot be used as a resource, but by machine-crushing the material into small fragments the voids are reduced and volume reduction after landfill disposal is reduced.

b) The evaluation of possible environmental effects of tsunami deposits that possibly contain harmful substances is described in the next sub-section. However, depending on the type and concentration of harmful substances, and their leaching rate, it may be that the environmental risk is extremely small. For such materials, the concept of “managed effective use” might be applied, so that they can be used in public works for filling and embankments. In these cases, an absorption function or sealing function might be added, and subsequently continuous monitoring could take place. Depending on location, materials containing heavy metals of natural origin in concentrations above the environmental criteria could be considered, but it is necessary to establish a policy for dealing with such materials based on an appropriate risk assessment, taking into consideration the characteristic soils of the area.

c) It is thought that the salt concentration in waste generated by the tsunami is high, so in order to effectively use it as a construction material, there is a requirement to determine the effect of the salt. To this end, it is important to carry out specific investigations into methods of rapidly estimating salinity as well as criteria for assessment, technology for removing salt, allowable salt concentrations for users, and its long-term effects when used as a resource.

d) In applying the recycled material to filling, embankments, and tidal barriers, it is important to evaluate its suitability in geotechnical engineering terms. This earthquake caused widespread damage to embankments due to liquefaction, so an important issue is to form seismically resistance soil structures using the reinforced earth method and so on, in addition to carrying out sufficient compaction and providing drainage. On the other hand, it is important to compile information regarding many examples of embankments built from waste that remained sound in the earthquake and tsunami, leading to the establishment of methods of designing infill, embankments, and tidal barriers using recycled materials.

e) In the recovery from disaster, there has been little demand-side questioning of what kind of material can be used in which location. This is causing delays in the effective use and processing of recovered materials. It is important to match recycled materials with suitable usage applications, as well as to map both onto a demand-side database as a ”soft” support for geotechnical engineering restoration work.

f) If difficulties arise in determining the quantities and characteristics of the tsunami deposits, establishment of an overall processing plan will be delayed. Therefore, it is necessary to establish methods of estimating the amount and characteristics of tsunami and flood deposits.

Other academic societies also have initiatives concerned with disaster wastess and tsunami deposits. It is necessary to work in cooperation with these organizations and with researchers and engineers in other fields.

2) Evaluation of subsurface environmental impact and appropriate countermeasures

The earthquake and tsunami damaged offices, oil-storage facilities, and storage facilities for other harmful substances. As a result, there is concern about possible leakage and resulting soil contamination. There is also concern that, depending on location, the deposits left by the tsunami may contain fluorine or arsenic of natural origin, as well as other harmful substances that leaked from businesses as a result of the damage. The presence of contaminated soil and contaminated deposits is not only an obstacle to reverting to earlier land use, but also gives rise to fears that the subsurface and groundwater environments at greater depths will be affected by contaminant seepage. This could lead to greatly increased cleanup costs. The following recommendations have been drawn up concerning contaminated soil and tsunami deposits so as to minimize their subsurface environmental impact

a) Efficient surveys: A wide area was damaged by the tsunami, so it is necessary to apply efficient survey methods to evaluate its effect on the ground. The results of the surveys should lead to the implementation of rapid, efficient, and strategic countermeasures. An effective way of implementing the surveys efficiently is to use available information such as that regarding facilities that had harmful substances in storage. In a similar way, the concentration of heavy metals in tsunami deposits depends greatly on the source of the deposits and the natural level of heavy metals there. For this reason, it is suggested that survey points should be chosen according to this information.

b) Evaluating soil contamination, groundwater contamination, airborne dust, bad smells, etc.: Where it is not possible to remove tsunami deposits quickly, the possible spread of contamination as harmful substances seep from the deposits into the original ground is a concern. For this reason, in addition to surveying the contamination, it is necessary to analyze the behavior of the contaminants in the deposits and in the original ground so as to evaluate their long-term effect on the subsurface environment and the groundwater environment. The same applies to soil contamination; it is necessary to survey the contamination, analyze the behavior of the contaminants, and evaluate their long-term effect on the subsurface environment and the groundwater environment. The affected ground also generates a lot of airborne dust originating from the tsunami deposits, so it is necessary to evaluate the dust carried by the air, looking in particular at the amount of dust, and consider countermeasures against it. There have been complaints of malodors arising from waste and tsunami deposits, while there is a lot of stagnant water standing on inundated land that no longer drains, so countermeasures against these odors are one issue faced in the recovery and restoration process. As an example, efficient and strategic spreading of lime might be carried out with the objective of improving sanitary problems, though possible pH problems must also be taken into account.

c) Environmental effect of temporary disaster wastess storage locations: Evaluations and countermeasures are necessary to ensure that sites used for the storage of disaster wastess do not become contaminated, that subsequent land use is not prejudiced, and that large cleanup costs are not incurred. To reduce the environmental impact of rubble landfills, there are geotechnical technologies that can make a contribution, such as technologies to line the bottoms and sides of the fill site with an impermeable layer.

d) Large quantities of debris and waste were deposited in the sea in this disaster. There are concerns that any seriously harmful substances present in the debris and waste will contaminate the seabed or seawater. It is necessary to survey and evaluate this issue.

e) Any difficulties in determining the quantity and characteristics of the tsunami deposits will hold up the establishment of an overall processing plan for disaster wastes and tsunami deposits. To ensure rapid progress, it will be useful to make efforts such as constructing models to estimate the amount of deposits of tsunami or flooding origin, mapping facilities that had stocks of harmful materials, and constructing flooding and tsunami flow models to simulate the effect of harmful substances in tsunami deposits. Such efforts would also be effective disaster-prevention initiatives, allowing the spread of harmful substances to be determined in advance of a disaster striking.

3) Earthquake and tsunami damage to the waste treatment facilities

There have been no reported cases of major damage to waste landfill and containment facilities as a result of this disaster. There were no coastal landfill sites in the areas affected by the tsunami, but the observed damage caused by this earthquake to coastal structures (including publicly owned sea reclamation sites) indicates a need to take into consideration the seismic resistance and tsunami resistance of coastal landfill sites with respect to future earthquakes and tsunamis. Waste landfill sites play an important role in the handling of disaster wastes, so it is necessary to study methods of surveying sites, both new and existing, and developing criteria for diagnosing and strengthening their seismic and tsunami resistance.

Sewage treatment facilities also need attention, as there is a risk that salinity has made raw sewage processing ineffective, reducing overall processing capacity. There is a clear need for tidal barriers and levees to protect such facilities from salination as well as from structural damage.

4) Salinity of farmland

The prevention of tsunami damage to agricultural land requires multiple lines of defense as well as area-wide infrastructure, including tidal barriers, drainage systems, etc. The technology used to reclaim Hachirogata lake and the experience gained offer a useful guide. There is also the experience of agricultural land in Yatsushiro City, Kumamoto Prefecture, which suffered damage due to a tidal surge associated with typhoon 18 in 1998.

The production of rice in paddy fields requires soil with a salt concentration of 0.1% or less. Methods of reducing salt contamination to this level include removal through sodium absorption by applying lime or gypsum, or increasing vertical seepage to reduce surface salt concentration. With both methods, it is important to promote drainage, so the provision of underground drainage systems and drainage channels is essential. Any water channels and drainage channels constructed for this purpose should have good resistance to earthquake and tsunami so that, once inundated, agricultural land can be quickly cleaned.

5) Radioactive contamination of soil

Large quantities of soils contaminated with radioactive substances have resulted from Fukushima Daiichi nuclear disaster. Here, what is being discussed is soil that contains radioactive substances above the allowable level. This soil will require long-term management and processing. The following are recommendations for handling this from the viewpoint of minimizing effects on the subsurface environment.

a) Evaluating subsurface environmental effects to contribute to in-situ management of contaminated soil: At this time, the spatial radiation dose in locations such as school grounds is being reduced by removing radioactive contaminated topsoil. The soil is being buried on site by deep burial or the vertical replacement method. For long-term management of contaminated soil using these methods, it is necessary to evaluate not only the spatial radioactive dose, but also the effect on the subsurface environment and groundwater environment of radioactive soil in the deeper strata.

b) Examining methods of removing radioactive substances from the contaminated soil: It is necessary to develop technology and evaluation methods for reducing the volume of radioactive contaminated soil requiring long-term management. Improved methods for separating and cleaning soil are needed. In this regard, it should be noted that the adsorption of the contaminant cesium by clay minerals is high.

c) Evaluating technology for processing and isolating soil and waste contaminated with radioactivity: It is assumed that in the future large quantities of waste with various levels of radioactivity and radioactive contaminated soil will need to be handled. The disposal and isolation of these materials will rely on evaluating suitable technologies for their long-term management. The technologies used must minimize the radiation dose received by people associated with the processing and management work, prevent dispersal and leaching of radioactive contaminated soil, and prevent any long-term impact on the nearby subsurface environment and groundwater environment.

6) The role of wells in disaster recovery

There were widespread failures of the public infrastructure after this disaster and it is likely that in many areas water supplies will not be restored for a long time. Private households with their own wells were able to obtain non-potable water, and there were cases in which these private households made their wells available to neighboring households. Although not suitable for drinking from a water quality point of view, this water was extremely effective helping people continue their daily life and maintain public sanitation. This indicates a need for a positive approach to the use of groundwater in disasters, such as by promoting the sinking of wells for people to use in disaster areas.

To respond to this and future earthquakes, it is considered necessary to determine the amount of available groundwater and to choose well sites that will be free of chemical contamination at times of disaster. The use of groundwater in daily life should be promoted as a disaster prevention measure. Further, in order to be sure that the groundwater is safe in times of disaster, there should be routine monitoring of subsurface and groundwater pollution in each area in normal times. Areas where groundwater could be tainted with salt due to tsunami or ground settlement should be predicted in advance.

Other learned societies are preparing their own initiatives regarding groundwater and wells for use in times of disaster, so this issue must be tackled in cooperation with these other societies and researchers and engineers in other fields.

3.3 Issues related to strengthened rebuilding, seismic risk assessment, and seismic strengthening of existing unexamined/untreated soil structures and unexamined/untreated natural slopes

There is a pressing need to restore the function of damaged soil structures such as embankments and retaining walls as soon as possible, as well as to ensure the safety of natural slopes. On the other hand, restoration work should not bring them back to their original structural condition. Rather than using methods that were conventional prior to this disaster, efforts should be made to ensure that the restored structures are stronger, using latest cost-effective methods to obtain highly seismic resistant soil structures and slopes.

From a historical perspective, it is inevitable that, in Japan today, there is an enormous number of existing soil structures that were constructed to old standards and that may not satisfy current standards. Similarly, there are many unexamined/untreated natural ground and slopes that could cause major social impact if they collapsed. The importance of seismic risk assessment and seismic strengthening of these existing soil structures and unexamined/untreated natural ground and slopes including disaster prevention risk assessment and strengthening has been raised in the past, but actual implementation of countermeasures has been insufficient. Because the number of structures is very large, seismic risk assessment and the implementation of countermeasures is still in progress; it is a chase to catch up with safety standards. As a result, this has become a never-ending issue. Still, continuous progress with seismic risk assessment and, when necessary, strengthening is the clear and essential path to a safe country. Henceforth it will be necessary to reactivate efforts to implement countermeasures. Conventional geotechnical technologies, such as proper compaction of embankments and provision of adequate drainage, will play a major role, as will recent advances in geotechnical engineering such as the latest site investigation technologies, ground improvement technologies, and reinforced soil technologies, etc. The sections below summarize the lessons learned from this disaster and our recommendations.

3.3.1 Issues and recommendations regarding soil structures that do not satisfy current standards

a) Future earthquakes are highly likely to cause many instances of damage to recently reclaimed land in old river channels or along the coast, hillside embankments and associated retaining walls and private houses and associated lifelines on recently reclaimed land. Seismic risk assessment of these structures must be carried out as a matter of priority.

b) In this earthquake, significant damage was caused to road and rail embankments, retaining walls, and embankments behind bridge abutments due to soil liquefaction and slip failure of the support ground, as well as slip failure within the body of dykes. In restoring these damaged soil structures, there may be cases where strengthening is compromised because rapid recovery of road and rail functionality is required. Technologies are needed for the rapid restoration of function with a strengthened structure.

c) In this earthquake, many river dikes settled due to soil liquefaction and slip failure in the supporting ground, as well as soil liquefaction and slip failure within the body of the levees (Fig. 3-30).

Fig. 3-30 Damage to river dike on the right bank of Sunaoshi River caused by earthquake motion, Tagajyo City, Miyagi Prefecture, and resulting inundation of lowland by tsunami (by Uzuoka, R.)

After past earthquakes, sections of dykes that suffered from major damage by which the hinter land may be inundated, either due to normal water levels or a tsunami, have been subjected to seismic performance analysis against the Level II seismic motions. However, as of May 2011, only 47% of dyke sections along nationally managed rivers that should have been analyzed have actually been checked. Nationwide, it cannot be said that this work has progressed well. It is essential that the work continues.

In this earthquake, there was widespread damage to reclaimed land along old river channels, dyke settlement due to soil liquefaction in the supporting ground, and damage associated with soil liquefaction within dykes where the groundwater level had risen. In addition to measures already being taken in response to liquefaction in the foundation ground, there should be gradual implementation of seismic performance analysis taking into consideration liquefaction within the dykes, including surveys of water levels within the dykes, and the implementation of measures to strengthen the dykes against seepage and liquefaction.

It has been regulated that the flood water level used in the seismic performance analysis should be that with a 1/10 probability of occurrence in a 14-day period, taking into consideration that emergency restoration of dykes after an earthquake generally takes 14 days. Also, if there is a possibility of a tsunami surging upstream, the height of the tsunami should be taken into consideration. The criterion for determining whether or not emergency restoration work must be implemented after an earthquake should be the planned high water level (HWL), not the flood water level used in the seismic performance analysis, from the point of view of flood control. Therefore, even in areas not subject to seismic performance analysis, if the crest height has fallen below the HWL as a result of settlement, or if a crack resulting from an earthquake reaches below the HWL, emergency restoration work would be carried out. In this earthquake, of the 48 dykes where emergency restoration work was carried out along nationally managed rivers in the Kanto Region, no one had been subject to seismic performance analysis (in the Tohoku Region, it was three locations out of 22).

In an ordinary earthquake, when the number of damaged locations is relatively few and the extent of damage is relatively small, emergency dyke restoration work after the earthquake has generally been completed within 14 days. However, in this earthquake, the damage to river dikes in this earthquake occurred at so many locations, and there was damage over a wide area. Yet, it was a comparatively long period of time after the occurrence of the earthquake until significant raining. Moreover, materials and equipment were first used to open roads, etc. Consequently, the start of emergency restoration work on river dikes was delayed somewhat. In future, if damage occurs over a wide area and at many locations to river dikes, it may be difficult to complete emergency restoration work within this 14-day period. Therefore, when it is necessary to complete emergency restoration within a particular period when an earthquake occurs, one option is to increase the preparation level with respect to the earthquake higher than at present.

d) Port and airport facilities: After damage to the quay in Akita Port in the 1983 Nihonkai-Chubu Earthquake, many of these facilities were seismically strengthened so that it could be used for bringing in emergency relief supplies to damaged areas after an earthquake. However, most other quays have been constructed to old standards, so it is desirable that they be checked against the Level II seismic motion envisaged in the latest standards. At airports, also, seismic strengthening (including countermeasures against soil liquefaction, etc.) had been in progress for the basic facilities, but this has not been completed. It is important that this strengthening work be continued in the future.

e) Sewage systems have long been recognized as requiring countermeasures to prevent pipe uplift (countermeasures against liquefaction of the backfill soil). However, compulsory application of seismic standards to sewage pipes, etc., commenced comparatively recently, in 2006. This means that there remain many sewage facilities constructed to old standards with old technology and that consequently have low seismic resistance. It is important that an order of priority be established, based on a risk evaluation, and that seismic strengthening measures are implemented first in the places where the risk is greatest.

   Many sewage treatment facilities are in low-lying areas along the coast, so they are susceptible to tsunami and to damage due to soil liquefaction. However, recognition of issues relating to seismic risk assessment and strengthening (for existing structures) and design (newly constructed structures) of treatment works against tsunamis remains undeveloped. Seismic strengthening of existing treatment facilities has not progressed sufficiently. Future consideration of these issues should ensure that facilities are designed and strengthened against tsunami and seismically strengthened so that the sewage treatment can continue with a certain minimum level of function after an earthquake (or can be restored with minimal repairs).

   Buried facilities such as pipes in hillside embankments should be the responsibility of the developer of the residential land, working together as a unit with other public infrastructure providers.

f) Agricultural installations: Although there has been recognition since 1953 of the need for improvement of seismic stability, including countermeasures against soil liquefaction, of agricultural pipelines, water-storage dams, and fill dams for agricultural use, the number of these installations is very large and the implementation of measures has not caught up.

In this earthquake, the Fujinuma dam, an irrigation dam located outside the river area which was completed in 1949, collapsed (Fig. 3-4). It is likely that the compaction control at the time of construction was lower than specified in the current standards, so this can be considered a soil structure that did not satisfy current standards. The reasons for the collapse of the dam have not yet been established, such as whether it was due to a slip failure in the dam, liquefaction in the dam, a slip failure that included the foundations, seepage failure, water overflowing the crest due to a seiche or the inflow of a landslide, etc.

In this earthquake, main agricultural pipelines suffered from damage due to uplift caused by soil liquefaction of backfill soil, as shown in Fig. 3-31.

Fig. 3-31 Damage to a main agricultural pipeline for a length of about 1.4 km due to uplift caused by liquefaction of backfill soil. The largest depth of opening was about 1.6 m (Mohri, H.)

There were also cases of disconnection and water leakage in main agricultural pipelines. These are thought to have resulted from the effect of dynamic water pressure during the earthquake. This type of damage is not anticipated in the current technical standards. A future task is to clarify the mechanism of this damage and quantitatively evaluate the dynamic water pressure that occurs during an earthquake, based on which countermeasures should be proposed.

There is a huge amount of work to be done with respect to these agricultural installations in carrying out seismic risk assessment and strengthening of existing soil structures that do not satisfy the current standards. It is important that this work continues. It is also important to develop and implement seismic strengthening technology that is not simply the type of comprehensive seismic strengthening applied to a new facility, but that deals with deterioration with time and poor functionality. The following recommendations are made.

i) The damage to water storage structures such as reservoirs, fill dams, etc., in an earthquake is characteristically of three types: outer-surface cracking in the crest, slip in the dam slopes and water leakage. However, the relationship between the extent of such damage and the margin of safety is not very clear, so it is necessary to develop adequate methods of survey, risk assessment, and evaluation of seismic damage.

ii) It is necessary to propose seismic risk assessment technology and seismic countermeasures specific for water storage structures such as reservoirs, etc., that were not constructed using modern methods.

iii) For water storage structures such as reservoirs, etc., it is important to implement seismic strengthening, but also to implement hazard reduction measures that minimize the damage caused if there is a collapse. Such measures can contribute to area disaster prevention and can include the provision of downstream works to channel floodwater and protect human life in the event of a collapse.

g) Certain hazardous structures built in the past, such as mine tailings dams, must be subject to improved maintenance and enhanced seismic resistance. Measures must be taken against leakage of harmful substances. In particular, it is considered that there is insufficient information disclosure regarding the nationwide implementation of safety measures for mine tailings dams associated with mines that have already closed, and that policy regarding countermeasures is inadequate. It is necessary that this be improved.

h) Subsidence of underground voids in old coalmines and other mines

Overall there is great diversity in the numbers of existing soil structures of various types that do not satisfy current standards, progress in implementing countermeasures, and the history of establishment of design methods and the organizations responsible for them. There is need for a law (like the National Land Management Act) that guarantees ongoing seismic risk assessment and seismic strengthening for soil structures designed and constructed to old standards and for unexamined/untreated natural slopes, in order to mitigate natural disasters due to earthquakes, severe rain, flooding, etc.

3.3.2 Unexamined/untreated natural slopes and cut slopes that could have a major social impact if they collapsed

In general, natural slopes and cut slopes that could have a major social impact if they collapsed are designed against severe rain but not against earthquake. The need to take positive measures against earthquakes has been recognized in the past, but there has been virtually no progress in responding to this matter.

In this earthquake, despite that the number was lower when compared with 2004 Chuetsu earthquake, there were collapses of slopes of weathered volcanic tuff and weathered volcanic deposits mixed with pumice in areas of sedimentary weak rock (such as in Shirakawa City, Fukushima Prefecture, Fig. 3-32). Also, in this case, there were many concerns over possible post-earthquake collapse due to rain.

Fig. 3-32 Failure of a natural slope, Hanokidaira, Shirakawa City (Yasuda, S.)

The following is our recommendations in respect of such unexamined/untreated slopes.

a) Measures are needed to deal with secondary damage due to heavy rain that may occur after an earthquake. In particular, emergency countermeasures to prevent sediment runoff and evacuation procedures based on a “soil damage warning information" system are desirable. Experience has shown that, in the few years following an earthquake, the number of hillside collapses due to rain increases. The danger of flooding is enhanced when trees brought down by such collapses enter rivers and streams. Measures are needed to combat these problems.

b) In the future, it will be necessary to carry out seismic risk assessment and seismic strengthening (existing) and seismic design (new) for important natural slopes and cut slopes at critical locations that might have a major social impact if they collapsed

c) In order to introduce the above procedures, reliable methods will be needed. In particular, it is necessary to re-examine the question of how to evaluate the risk of earthquake-induced collapse taking into consideration geological and topographical conditions. This earthquake occurred over a wide area where the geology included hard rock, soft rock, volcanic areas, and others, so geological and topographical characteristics must be considered in any investigations. For example, in the hilly area of hard rock around the Oshika Peninsula in Miyagi Prefecture, there were many collapses of surface strata. In the Neocene soft rock area of the Ou mountain range, there were few such collapses of surface strata. In the past, there have been many avalanches during inland earthquakes in the volcanic areas of Iwate and Miyagi, but none were reported in this earthquake. It appears that, in addition to geology and topographical characteristics, it is necessary also to take into consideration factors such as earthquake wave properties (acceleration, predominant period, duration, etc.) to explain such phenomena.

d) It is necessary to choose effective countermeasures against earthquake-induced collapse. Overall there were few collapses of cribwork slopes, and in some cases there is evidence that cribwork has had a certain preventive effect against slope collapse. (In one location, collapse did not occur on a slope where cribwork had been completed, but there was collapse and deformation of an adjacent natural slope, with damage to residential land located at the top of the slope.) On the other hand, there was an example of a cut slope treated with sprayed mortar where small-scale collapse had occurred at the top. At one location, a hillside embankment where a slip collapse occurred in the 1978 Miyagi Prefecture Oki Earthquake, further collapse in this earthquake is thought to have been inhibited by carrying out groundwater drainage and implementing steel tubular pile restraints, etc. On the other hand, there were places where deformation occurred again. It is necessary to re-examine the effectiveness of these construction methods.

e) Design in consideration of tsunami effects. There is one example where a masonry retaining wall with a facing of blocks at the toe of a natural slope was scoured away by the tsunami, causing the wall to collapse and accelerating erosion of the slope. On the other hand, there were examples where embankment retaining walls reinforced with geotextiles did not collapse. It is necessary to verify these phenomena, and develop countermeasures based on the results.

f) Development and dissemination of methods of in-ground investigation. Natural slopes and cut slopes are unlike embankments in that ground conditions are often unknown. It is only when a collapse occurs that they become clear. Therefore there is a need for methods of determining the ground conditions before the occurrence of a collapse.

4. Issues for Future Examination and Research

4.1 Issues regarding dissemination of technology

1) Setting a minimum level of technology in accordance with technical standards such as design guidelines

There are great differences in how comprehensive various systems of technical standards are among nationwide organizations, city, town, and village governments, and private organizations. Standards related to soil liquefaction are a good example of this. It is necessary that there be a system (including a legal system) that sets a minimum level of basic technology applicable to the construction of detached houses.

2) Provision of technical support (information, dispatch of specialists, training and education of human resources)

Disaster damage on a large scale is rarely experienced by any one private organization (or individual), small self-governing body (such as a sewage works, detached house permit authority, or authority responsible for developing and maintaining local roads, etc.), small-scale local rail companies, etc. As a result, the technical and financial preparation for disaster within such groups is either inadequate to deal with major disaster or non-existent. Further, it is difficult to maintain a continuous presence of expert engineers. As a result, there is no system for responding to such disasters. The JGS must in future provide appropriate information, dispatch specialists, and provide training and education of human resources. There is also a need to disseminate the concepts of geotechnical engineering at schools and throughout society among engineers engaged in the design, construction, and maintenance of detached houses.

Geotechnical engineers must be in a position to respond to assessments of hazard risk related to residential land development. Therefore, in addition to the existing system of assessors of disaster-damaged residential land, the establishment of a ground quality assessor qualification is proposed. This will enable a comprehensive assessment of risk in the case of residential land that has been damaged by deformation or soil liquefaction, as well as in the case of existing or new residential land. The establishment of a system of liability insurance associated with such assessments will also have to be considered.

4.2 Issues regarding technical development

It is clear that present technology for seismic risk assessment, a-seismic structural strengthening, a-seismic design, and a-seismic construction has shortcomings, so various technical developments are necessary.

a) Application of Level II design seismic motion to soil structures: The necessity for this is clear as a result of this earthquake disaster. The establishment of a highly transparent damage survey system and the information disclosure are also important new issues. How various facilities are operated and what measures are taken to ensure safety in nearby areas when an unanticipated emergency occurs are also important.

b) Seismic damage inspection and assessment technology

It is necessary to develop technology to appropriately evaluate, for example, the soil liquefaction risk of recent artificially developed land such as reclaimed land. At the same time, the aging effect in natural ground, particularly with Holocene Era deposits, also needs to be taken into account.

c) Technology for effectively dealing with secondary damage

The main earthquake of March 11 and subsequent aftershocks destabilized many slopes over a wide area, in particular near the various epicenters. It is necessary to develop techniques to predict possible ground deformation and stability taking based on this damage over a comparatively long time frame (in the order of years), and not just the hazard of landslides in this year's rainy season and typhoon season.

d) Effective prevention measures and restoration measures

Technology is needed for identifying weak points (usually embankments) and suggesting suitable countermeasures for a range of linear structure types comprising different structural types (i.e., RC framework structures, bridges, tunnels, embankments, retaining walls, cut slopes, etc.) constructed on different ground conditions (i.e., railways, roads, sewage installations, river dikes, coastal dykes, electricity transmission lines, etc.). Possible countermeasures might include various types of reinforcing technologies while service continues, ground injection, soil nailing of natural slopes, etc.

e) Railways, roads, etc: Development of technology for rapid restoration as well as strengthened restoration (simultaneous, staged, multi-functional (effective against earthquake, rain, flood) after a disaster

f) Prediction of compound damage (main earthquake + aftershocks, earthquake + tsunami, earthquake + soil avalanche, earthquake + rain, flooding) (simultaneous, consecutive)

- Resistance of embankments and bridges to massive tsunami surges

- Rain and flooding damage after extensive damage to a river dikes at many locations that takes time to repair

- Comprehensive countermeasures against earthquake, heavy rain, and flooding for soil structures, such as embankments and natural slopes (details in report of the 2009 Japanese Geotechnical Society President's Special Committee)

- Development of seismic design methods for river dikes and supporting ground as well as design for simultaneous occurrence of heavy rain and earthquake

- Improvement of resistance to overflow of river dikes: Incorporating a safety margin in width as well as in height, sufficient resistance against over-flow of dyke, for example, paving the crest, rounding of dyke slope tops and use of a gentler slope on landward side of dyke

- Structural forms for embankment type r coastal dykes as tsunami barriers that give them resistance to tsunami surges, overflow, and scouring, as well as seismic resistance

g) Nationwide perspective

In order to prepare for the Tonankai, and Nankai earthquakes, which are anticipated in the near future, and other earthquakes for other parts of Japan, which cannot be predicted, it is necessary to deal with existing soil structures that do not satisfy the current standards. For example, the Nobi Plain may be struck by tsunami if the Tokai and Tonankai earthquakes occur, so it is essential to provide public evacuation structures that will save human life. Also, it is important to express a relevant warning on the likely reduction in function of coastal dykes and river dikes that were constructed on the grounds have settled significantly after their construction. In Ise Bay, where Chubu International Airport is located on an artificial island, it is necessary to carry out geotechnical engineering investigations into the forms of damage that could occur in the event of a large tsunami.

4.3 Issues for the future

The lessons learned and recommendations presented here must form the basis for a specific implementation plan for the future in which specific survey methods, countermeasures, costs, timescales, etc., should be presented. In particular, separate from long-term research and development issues, it is necessary to create a plan for what is can be done on site now using available technology. For this purpose, it is necessary to rapidly incorporate the relevant opinions of practicing engineers in the private sector having a plenty of experiences in practice of planning, design, construction and maintenance into a set of recommendation directly relevant to local residents.

Appendix

On Gigantic Tohoku Pacific Earthquake in Japan

Ikuo Towhata, Professor, University of Tokyo
Hiroyuki Goto, Assistant Professor, Kyoto University
Motoki Kazama, Professor, Tohoku University, Sendai
Takashi Kiyota, Assistant Professor, University of Tokyo
Susumu Nakamura, Professor, Nihon University, Fukushima
Kazue Wakamatsu, Professor, Kanto Gakuin University, Yokohama
Akihiko Wakai, Professor, Gunma University, Kiryu
Susumu Yasuda, Professor, Tokyo Denki University, Saitama
Nozomu Yoshida, Professor, Tohoku Gakuin University, Tagajo

INTRODUCTION

At 2:46 PM of local time on March 11th, 2011, a gigantic earthquake of magnitude Mw=9.0 occurred and affected the eastern half of Japan. Because the seismological aspects of this earthquake have been reported at many web sites and publications, the present report puts emphasis on the damage aspects that have so far been revealed by the post-earthquake investigations. This report is a contribution made by many members of the Japanese Geotechnical Society.

The causative fault of this earthquake is located in the Pacific Ocean off east Japan where an oceanic tectonic plate has been subsiding under the archipelago (Fig. 1). In the area of Sendai City that is one of the biggest cities in the eastern part of Japan, there had been warning about a possible big earthquake in the coming years. It was anticipated that a part of the plate subduction to the east of Japan would cause a big earthquake. The reality was, however, more than that anticipation, the size of the causative mechanism being 500 km in length in the NS direction and the width being 200 km.

In the modern times, two gigantic earthquakes have been known in this part of subduction. The one in 1896 registered the seismic magnitude (M) of 8.2 to 8.5 and the associating tsunami killed 21,915 victims together with 44 missing. The other one in 1933 was of M=8.1 (Mw=8.4) and claimed 1522 victims with 1542 missing. Both earthquakes caused minor intensity of shaking. Another tsunami disaster in the same area was caused by the 1960 Chile earthquake of Mw=9.5 and 142 people were killed. Those experiences encouraged both public and private sectors to be prepared for future tsunami disasters by constructing high sea walls and conducting tsunami evacuation drills, in which the height of future tsunami was decided on the basis of previous tsunamis. Despite those efforts,

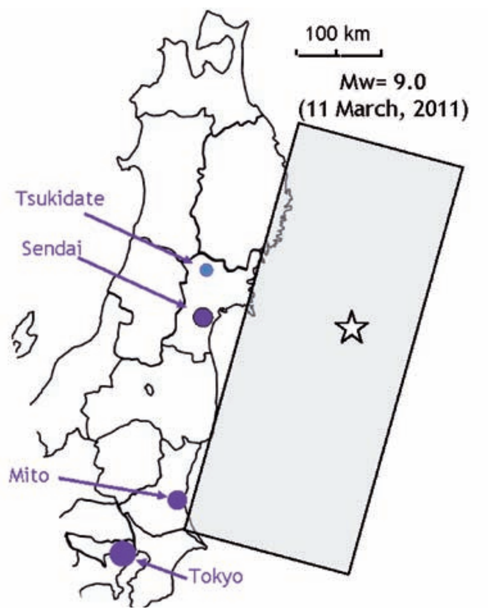


Fig. 1 Location of causative mechanism and major damage areas (Fault model by National Research Institute for Earth Science and Disaster Prevention)

the present earthquake produced much bigger tsunami over the entire coast of east Japan (Fig. 1). It is often said that the 2011 earthquake is of similar size and effect as the *Jogan* earthquake in AD 869 that hit the same area and produced huge tsunami damage.

Geospatial Information Authority of Japan announced that the coseismic displacement of the earth crust in the coastal area was at maximum 5.3 m in the horizontal direction towards the Pacific Ocean and 1.2m in subsidence. Thus, many areas along the affected coastal area got under water, the tsunami effect was made more serious, and the tsunami water remained in the area for a longer time, making the rescue very difficult. Fig. 2 illustrates the coseismic subduction in Sendai area. Note that similar subsidence occurred at many places in the world during past gigantic earthquakes: Kohchi of Japan in 1946 and at several more times in the history, Valdivia and surrounding area in Chile in 1960, South Alaska in 1964, and Izmit Bay of Turkey in 1999. Kohchi and Valdivia came upwards again after the quakes.

(a) Natori City, south of Sendai (b) Gamo of Miyagino Ward, Sendai

Fig. 2 Coseismic subsidence in Sendai (Photographs by Daiken Suzuki, former student of University of Tokyo)

EARTHQUAKE GROUND MOTION

Figures 3 and 4 show the distribution of peak ground acceleration (PGA) and peak ground velocity (PGV) of horizontal components, respectively. PGA values do not simply attenuate from the east coast, but major two clusters are recognized in 1) Miyagi Prefecture (around N38.5^{o} E141.0^{o}), and 2) Tochigi and Ibaraki Prefectures (around N36.5^{o} E140.5^{o}). This implies that the rupture process during the earthquake was not uniform, and contained several asperities radiating strong ground motions. Another point to note is that Tokyo and its surrounding area near the bottom of the figures were subjected to strong shaking. Therefore, damage occurred at many places therein. Fig. 5 illustrates the acceleration records at K-NET Ishinomaki station to the east of Sendai City in Miyagi. It is evident here that there are at least two strong earthquake events that are superimposed on each other. Thus, it is reasonable to assume several asperities in the source mechanism. Another important issue is the long duration time of strong shaking. Increasing the number of seismic loading cycles, this long duration time made the extent of subsoil liquefaction more serious.

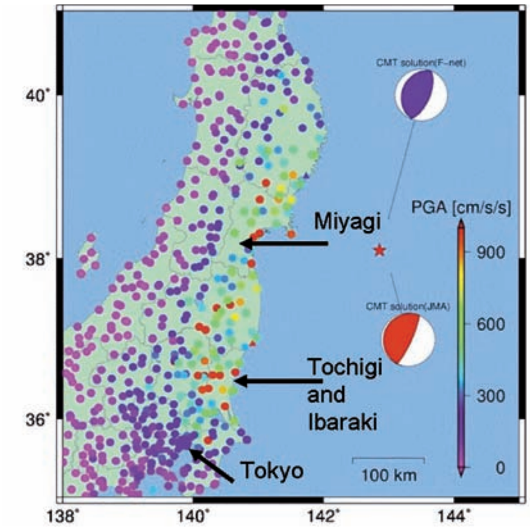


Fig. 3 Distribution of peak ground acceleration provided by NIED, ERI (the University of Tokyo), AIST, and PARI

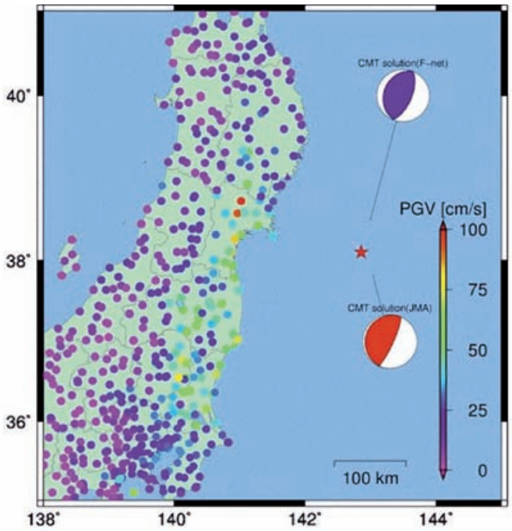


Fig. 4 Distribution of peak ground velocity provided by NIED, ERI (the University of Tokyo), AIST, and PARI

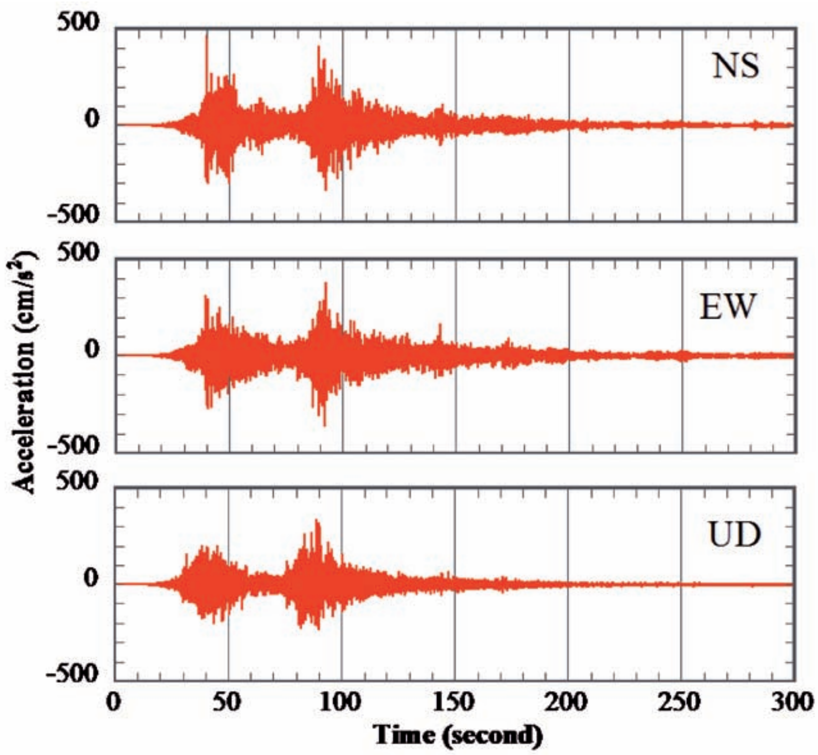


Fig. 5 Strong earthquake motion record at Ishinomaki to the east of Sendai City, Miyagi Prefecture (K-NET MYG010)

DISTRIBUTION OF DAMAGE

Many kinds of damage were caused by the earthquake over a large area in the eastern part of Japan (Fig. 6), ranging over 500 km in NS direction. The number of victims is not yet finalized in the middle of April because tsunami brought many people into sea and also debris of destroyed houses have made searching very difficult. It is anticipated that the total number of victims would be more than 25,000, most of which were killed by tsunami, while the total amount of debris is 26.7 million tons.

The major induced damages are classified into tsunami-related ones, liquefaction of sandy ground, and instability of slope and embankment. It is noteworthy that structural damage was not so significant as in the cases in previous gigantic earthquakes in the concerned region. Fig. 7(a) indicates the central part of Sendai City where many high-rise buildings survived the earthquake without problems. Of particular interest is illustrated in Fig. 7(b) in which Tsukidate Township survived the quake without structural damage despite that the Meteorological Agency issued the highest seismic intensity scale of 7 here. A local dentist was interviewed to mention that the shaking was long and strong, he could not keep standing up, but his old wooden house survived this event without structural damage. Information about lifeline damage is not yet available.

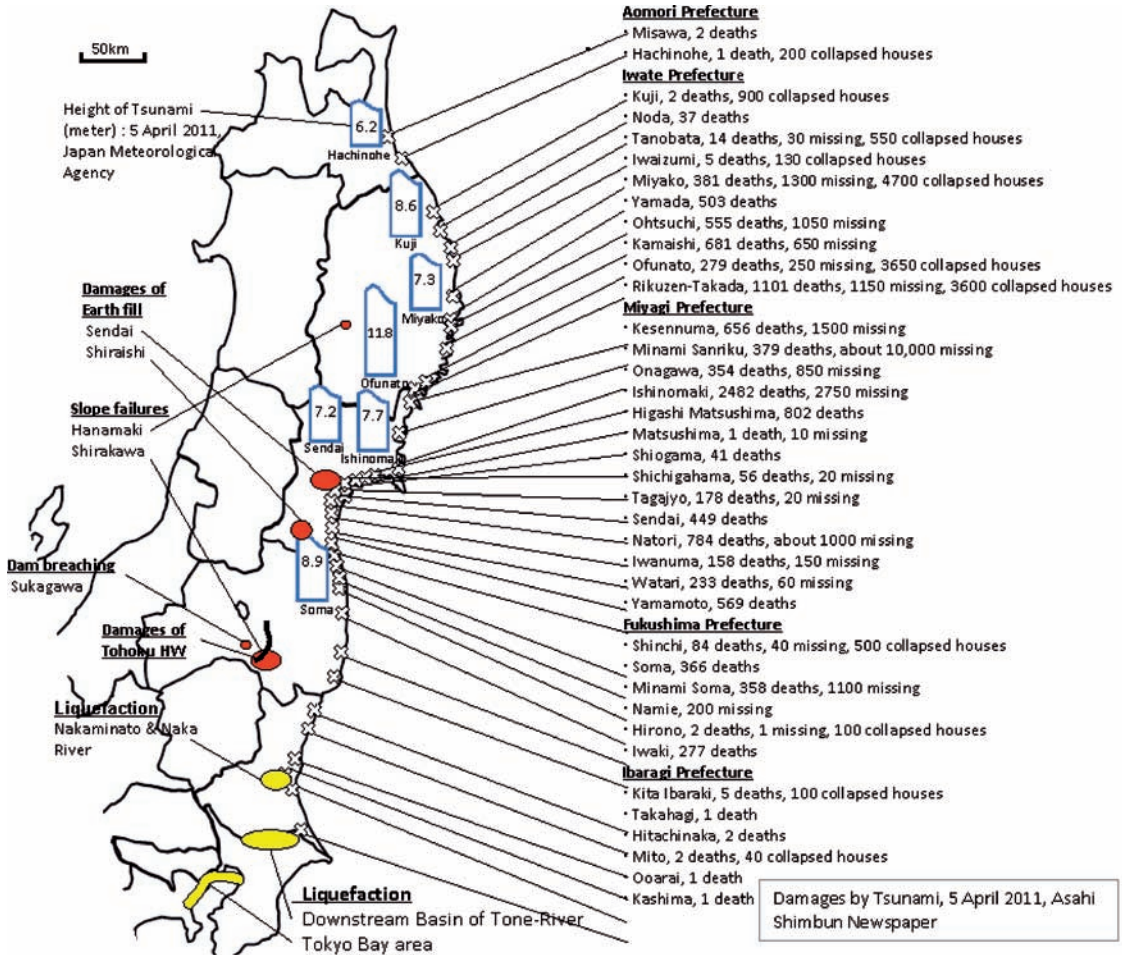


Fig. 6 Distribution of seismic damage

(a) Intact buildings in central Sendai City Township

(b) Houses and shops without damage in Tsukidate

Fig. 7 Good performance of buildings and houses in the affected region

TSUNAMI DISASTER

Tsunami was the most serious type of damage. Because of the sympathy to tsunami victims and their families, engineering societies decided to postpone damage reconnaissance in the affected area unless very necessary. There is, however, minimum information available. First, the height of tsunami was investigated to find that the height was more than 15 m and easily overtopped sea walls that had been constructed against the previously known tsunami height. The destructive power of high tsunami was substantial and removed nearly all the structures in the attacked areas (Fig. 8). This photograph reminds us of Banda Aceh after tsunami disaster in 2004. In this flat land, there is no place for people to evacuate, even if a tsunami alert is issued properly. In some tsunami-affected areas, the sea water remained on shore for many hours and evacuation was made impossible. Prof. Nozomu Yoshida of Tohoku Gakuin University had to take refugee on a pedestrian bridge crossing a street for 12 hours without food and warm overcoat, because the street was inundated until 1 AM. There is a huge amount of debris after tsunami attack (Fig. 9). This debris has to be disposed in an appropriate way, which is a very difficult task.

Fig. 8 Yuriage township near Natori River mouth of Sendai (Photo by Daiken Suzuki)

Fig. 9 Tsunami debris in Tagajo to the south Municipality

(a) Intact quay wall

(b) Erosion in building foundation

Fig. 10 Post-tsunami situation in Ishinomaki Harbor to the east of Sendai

Fig. 11 Erosion of embankment at bridge abutment after tsunami Strike (Iwanuma in Miyagi Prefecture)

Fig. 12 Resuming business of fish restaurants after tsunami strike (Nakaminato Harbor, Ibaraki)

Fig. 13 Destroyed sea wall near Abukuma River mouth

Figure 10(a) shows that the quay wall of Ishinomaki Harbor was intact, although the retreating tsunami water was so powerful to erode sand in building foundation (Fig. 10b). Despite this good seismic performance of the quay wall, the operation of the harbor was stopped for many weeks because facilities for cargo handling were destroyed. Hence, rescue stuffs could not rely on mass transportation by ship. Fig. 11 demonstrates tsunami erosion in bridge abutment. There are local people who are working hard to reestablish the previous life. Fig. 12 shows recovery of fish restaurants in Nakaminato Harbor in Ibaraki Prefecture, 100 km NE of Tokyo, where the tsunami height was 4.2 m, being 1.0 m above the ground surface. The loss of backfill soil behind a coastal levee near the mouth of Abukuma River (Fig. 13) suggests that erosion by the arrival of tsunami was the main cause of the damage, which was more serious than the effect of retreating tsunami.