# Study on the Mechanism of the Damaged Housing Lots during the 2011 Tohoku - Pacific Ocean Earthquake in Japan

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**SUMMARY:**
The Tohoku-Pacific Ocean earthquake caused slope failures and deformation of grounds at many housing lots in Sendai, Sukagawa and other cities because many artificially filled lands have been developed without considering seismic stability in the urban areas. Especially, about 2000 houses and many pipe lines were severely damaged in Sendai City. The authors conducted site investigation and found several patterns of damage. Moreover, soil samples were taken from the damaged slopes and several laboratory tests were carried out to study soil properties of failed slopes. Test results showed the degree of compaction was less than 90% at two damaged housing lots. Based on test results, seismic response analyses and deformation analyses were conducted to demonstrate the effectiveness of these analyses.

*Keywords: slope failure, fill, embankment, housing lot*

## 1. INTRODUCTION

In Japan many artificially reclaimed housing lots have been developed on hills and terraces in big cities such as Tokyo and Osaka from around 1960 due to the increase of population. In the reclamation, soils at hills are cut and filled in valleys as schematically shown in Figure 1. Then both cut grounds and filled grounds are complicatedly distributed in housing lots. Figure 2 shows a schematic soil cross section along a filled valley. The filled zones are apt to slide or deform during earthquakes if the fill is not enough compacted and/or water table is high. In 1968, an artificially filled housing lot at Kiyota district in Sapporo City was severely damaged during the Tokachi-oki earthquake. There were 279 houses in the housing lot. Many houses constructed on the filled ground settled and tilted though no house constructed on the cut ground was damaged. This might be the first experience of the damage to artificially filled housing lots due to earthquakes in Japan.

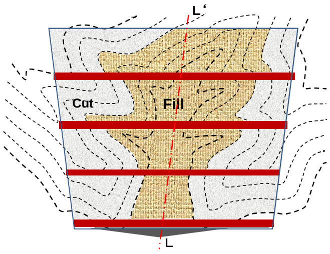


**Figure 1** Cut and filled grounds

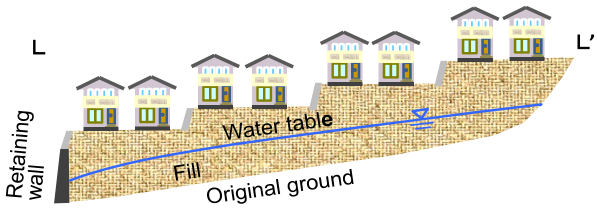


**Figure 2** Typical soil cross section in filled ground

Figure 3 shows earthquakes which caused damage to housing lots after 1968 Tokachi-oki earthquake. Recently almost all big earthquake has caused damage to housing lots because many housing lots have been developed gradually not only in big cities but also in medium dense populated cities. In 1978, several housing lots were damaged during the Miyagiken-oki earthquake in Sendai City. Of them severe slope failures occurred and many houses collapsed at Midorigaoka Ichi-chome housing lot as shown in Figure 4. In 1957 to 1958, this housing lot was constructed by filling a valley. During the reclamation work, trees on surrounding hills were felled and thrown down into the valley. Rocks cut from the hill also were thrown into the valley, then soil cut from the hills was placed as schematically shown in Figure 5. Figure 6 shows a soil cross-section along the slope. The thickness of the fill was 5 to 15 m. The density of the fill was very low with 0 to 10 of SPT *N*-values. It is estimated that buried trees became humus within 30 years. Moreover, as big voids existed between buried rocks, groundwater flowed in the big voids and caused weathering of rocks. Then the bottom of the fill became very loose and caused the slope failure during the Miyagiken-oki earthquake. During restoration, steel pipe piles, 318.5 mm in diameter, were installed to increase resistance against sliding, as shown in Figure 6. The steel pipes were strengthened by filling with steel H sections and concrete. The steel pipe piles were installed in two rows at 2 m centres. A concrete retaining wall and drainage wells were also constructed. The safety factor against sliding during anticipated earthquakes was thereby increased to 1.2.

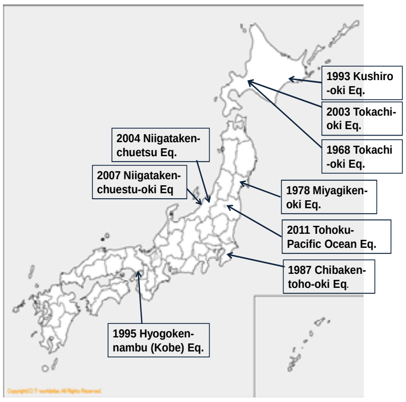


**Figure 3** Earthquakes caused damage to housing lots after Tokachi-oki earthquake

**Figure 4** Damage at Midorigaoka during the 1978 Miyagike-oki earthquake

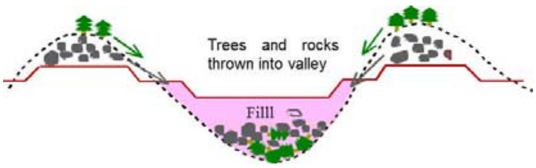


**Figure 5** Procedure of reclamation work conducted at Midorigaoka

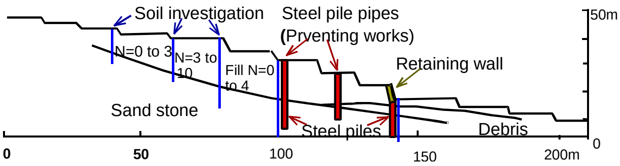


**Figure 6** Soil cross section along failed slope (Tohoku Branch, JSCE)

Based on the experiences of damage during past earthquakes, it can be said that the following fills are unstable during earthquakes:
1) Not enough compacted.
2) Filled soil is liquefiable such as clean sands.
3) Slope is high and/or steep.
4) Ground water table is high due to insufficient drainage system.
5) Trees, glasses and blocks of rock are mixed in filled soil.

Though slope failures in housing lots cause severe damage to houses and loss of lives, much reclaimed land has been developed in urban areas without considering seismic stability in Japan. Then appropriate procedures are needed to evaluate seismic stability of existing reclaimed areas. Recently, this procedure has been discussed and a guideline has been proposed by the Kanto Branch of the Japanese Geotechnical Society (2007), see also Simpson et al. (2009). In the guideline, it is recommended to evaluate the seismic stability by the following five steps.
Step 1: Finding out of filled zone
Step 2: Field investigation to select unstable slopes
Step 3: Soil investigations and laboratory tests
Step 4: Analyses on slope stability or deformation

Step5: Selection of appropriate countermeasures

## 2. DAMAGE TO HOUSING LOTS DURING THE 2011 TOHOKU-PACIFIC OCEAN EARTHQUAKE IN JAPAN

The Tohoku-Pacific Ocean earthquake with a magnitude of Mw=9.0 occurred in the Pacific Ocean on March 11, 2011 in Japan. Though main attention is focused on Tsunami-induced damage, many other damages occurred in a very wide area. In geotechnical field, liquefaction-induced settlement of houses, slope failures in housing lots, landslides, failure of dames, settlement of river dikes occurred. Of them, damage to houses and lifelines in housing lots was very serious because many artificially filled lands have been developed without considering seismic stability in the urban areas as mentioned above. Damaged cities which are Sendai, Shiroishi, Fukushima, Sukagawa, Shirakawa cities and Tokai Village are shown in Figure 7. Among them many housing lots were severely damaged in Sendai City as shown in Figure 8, because the city is surrounded by hills in north, west and south directions and many housing lots have been developed in the hills as shown in Figure 9. According to the investigation conducted by Sendai City Government about two month later the earthquake, numbers of dangerous and semi-dangerous houses were 868 and 1210, respectively among the surveyed 3880 houses. However these numbers have not been confirmed. Figures 10 to 12 show typical damage to houses in Sendai City.

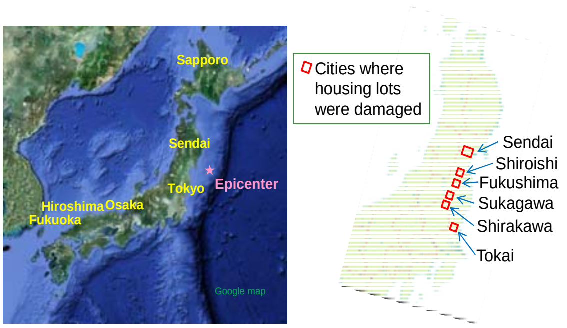


**Figure 7** Damaged cities for housing lots

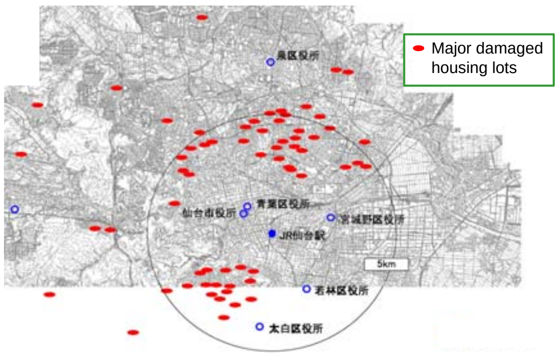


**Figure 8** Damaged housing lots in Sendai City

**Figure 9** Developed housing lots in Sendai City

**Figure 10** Failed slope at Nakayama in Sendai City

**Figure 11** Deformed housing lot at Oritate in Sendai City

**Figure 12** Slid house at Saikaen in Sendai City

The authors conducted detailed site investigation at Nankodai where many filled grounds were constructed for housing lots as shown in Figure 13 to study the patterns of the damage. Based on the site investigation, the following patterns were found:

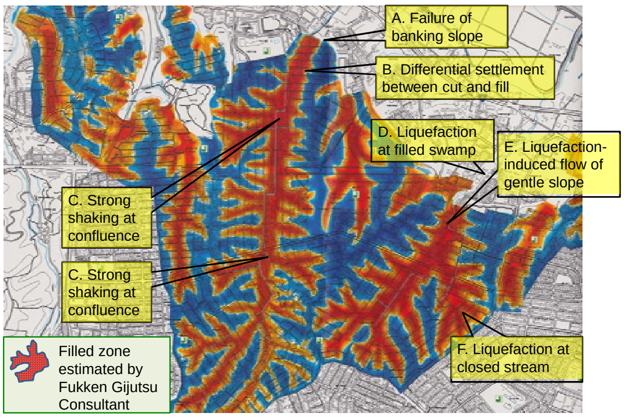


**Figure 13** Six damage patters observed at Nankodai in Sendai City

A. Failure of banking slope: Several houses at the top of the failed slope were damaged as show in Figure 14.
B. Differential settlement between cut and fill: Many houses between cut ground and filled ground were torn as shown in Figure 15.
C. Strong shaking at confluence: Several houses collapsed due to strong shaking because of the concentration of shaking at the confluence of three to four streams.
D. Liquefaction at filled swamp: Filled soils at a swap liquefied and caused settlement and inclination of several houses as shown in Figure 16.
E. Liquefaction-induced flow of gentle slope: Deformation of the ground occurred as shown in Figure 17 due to probably excess pore water because the slope was filled by sandy soils.
F. Liquefaction at closed stream: Liquefaction occurred due to probably high water table because exit of a stream is narrow pass. And several houses settled due to the liquefaction.

**Figure 14** Damaged house at A

**Figure 15** Torn house at B

**Figure 16** Settled house at D

**Figure 17** Deformed ground at E

At Midorigaoka Ichi-chome where severe damage occurred during the 1978 Miyagiken-oki earthquake mentioned above, no damage occurred by the Tohoku-Pacific Ocean Earthquake as shown in Figure 18. Strengthening by steel piles and decreasing of water table conducted after the 1978 earthquake must prevent the damage. On the contrary, Midorigaoka Yon-chome hosing lot where severe damage occurred during the 1978 earthquake but no countermeasure had been applied after the earthquake was seriously damaged as shown in Figure 19.

**Figure 18** No damage at Midorigaoka Ichi-chome in Sendai City

**Figure 19** Sever damage occurred again at Midorigaoka Yon-chome

## 3. SOIL PROPERTIES AND AN ANALYSE OF FAILED SLOPE

The authors took soil samples and conducted several laboratory tests at four failed slopes in Miyagi and Fukushima prefectures to investigate soil properties. Table 1 and Figure 20 show summary of test results and grain-size distribution curves, respectively. Filled soils at three sites in Fukushima are silty sand with 25 to 37% of fines content on the other hand the soil in Sendai is clean sand with no fine. Degrees of compaction *D*c tested at two sites are low as 72.4% and 86.8%. Undrained cyclic strength ratio $R_L$ obtained by cyclic triaxial tests are 0.13 to 0.29. Relationships between degree of compaction and $R_L$ are plotted in Figure 21 together with previous test data. $R_L$ increases rapidly with *D*c in the range of Dc>90%, despite $R_L$ increases slightly with *D*c in the range of 70%<*D*c<90%. Therefore it can be said that the compaction with *D*c=72.4 or *D*c=86.8% must be not enough for stability of slopes if water level is high.

**Table 1** Summary of laboratory test results

| Site | | Fukushima P. | | | Miyagi P. |
|---|---|---|---|---|---|
| | | Shirakawa | Sukagawa | | Sendai |
| | | Misaka | Kinosaki | Midori-gaoka | Midori-gaoka 4 |
| Soil | | Volcanic ash | | | Sand |
| $\rho s$ | $(g/cm^3)$ | 2.680 | 2.714 | 2.649 | 2.687 |
| $\rho_{dmax}$ | $(g/cm^3)$ | 1.244 | 1.732 | 1.693 | 1.874 |
| $w_{opt}$ | (%) | 35.6 | 20.3 | 20.0 | 14.7 |
| $D_C$ | (%) | 72.4 | 86.8 | - | - |
| $F_C$ | (%) | 36.9 | 25.0 | 26.3 | 0.0 |
| $U_C$ | | 132.4 | 524.4 | 412.6 | 3.0 |
| $U_C'$ | | 2.8 | 36.8 | 17.3 | 1.0 |
| $IP$ | | 15.7 | NP | NP | NP |
| $R_L$ | | 0.293 | 0.239 | 0.130 | - |

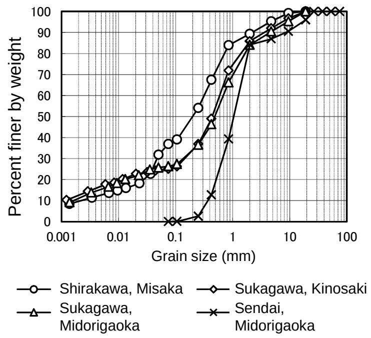


**Figure 20** Grain-size distribution curves

Figure 22 and 23 show photo and a cross section at Midorigaoka in Sukagawa City. Levels of ground surface before and after reclamation were estimated by two sets aero-photos taken before and after reclamation. Then thickness of fill was estimated. The thickness is about 4 to 6 m and the height of the failed slope is 5.7 m. In the site investigation, crack on the ground surface were observed up to about 33 behind the top of the slope. Water table was estimated high because spring water was found at the toe of the failed slope. Then seismic response and deformation analyses were carried out by the following three steps.

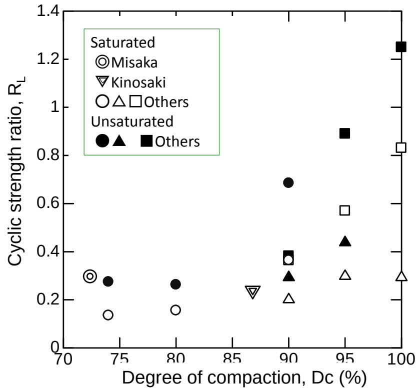


**Figure 21** Relationship between Degree of compaction and cyclic strength ratio

**Figure 22** Failed slope at Midorigaoka in Sukagawa City

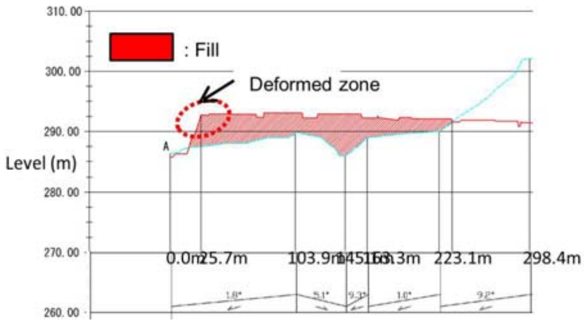


**Figure 23** Cross section

1) Analyse initial static stress and strain before the Tohoku-Pacific Ocean earthquake,
2) Analyse dynamic stress during the earthquake by FLUSH, and
3) Analyse residual deformation after the earthquake by a computer code ALID (Yasuda et al., 1999).
In the analyses water level was assumed as GL-1 m. Figure 24 shows the analysed deformation. The estimated maximum and average settlement of the ground surface are 147.9 cm and 99.8 cm, respectively. On the contrary, measured maximum settlement was about 1.5 m. Therefore estimated deformation is well coincided with the actual deformation.

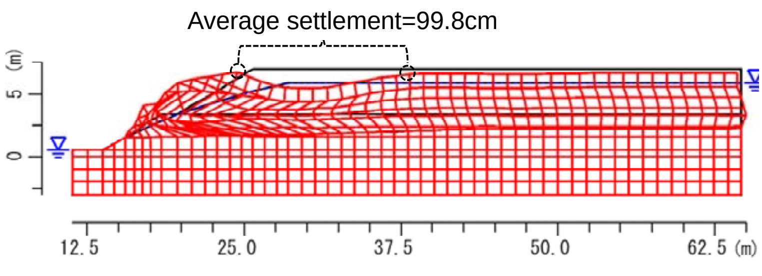


**Figure 24** Analysed deformation

## 4. COCLUSIONS

The authors conducted site survey and at several damaged housing lots during the 2011 Tohoku-Pacific Ocean earthquake and conducted deformation analysis at a site. The following conclusions were derived through these studies.
(1) Many housing lots in hill areas were damaged due to slide and deformation of fill grounds. Especially, about 2000 houses and many pipe lines were severely damaged in Sendai City.
(2) There are several patterns at Nankodai in Sendai City: i) failure of banking slope, ii) differential

settlement between cut and fill, iii) strong shaking at confluence, iv) liquefaction at filled swamp, v) liquefaction-induced flow of gentle slope, and vi) liquefaction at closed stream.
(3) Seismic response and residual deformation analyses conducted were effective to analyse deformation of filled ground.

**AKCNOWLEDGEMENT**
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