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DAMAGE TO RESIDENTIAL AREAS CAUSED BY LIQUEFACTION-INDUCED LATERAL FLOW DURING THE 2024 NOTO PENINSULA EARTHQUAKE AND SELECTION OF APPROPRIATE COUNTERMEASURES

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ABSTRACT

In Japan, the Mj7.6 Noto Peninsula Earthquake occurred on January 1, 2024, causing severe damage over a wide area. In mountainous areas, natural slopes slid and road embankments collapsed in many places, cutting off traffic and leaving 3,345 people stranded in 24 districts, creating a critical situation. In the plains, liquefaction occurred in many residential areas, causing severe damage to houses, lifelines, and roads. This liquefaction caused the lateral flow of gently sloping ground at the inland edge of sand dunes. From Uchinada Town to Kahoku City, lateral flow of up to 2 to 3 meters occurred in various places over an area of about 10 km x 0.1 km, causing serious damage to low-rise houses, roads and lifelines. Not only did the low-rise houses settle and tilt, but they were also pushed or pulled horizontally and distorted so much that they had to be demolished. The road curved horizontally due to lateral flow and rose by up to 1 meter at the end of the flow. In Japan, during the 2011 Tohoku Earthquake, liquefaction occurred in the Tohoku region of northeastern Japan and in the Kanto region surrounding Tokyo, and about 27,000 low-rise houses were damaged due to liquefaction. After the Tohoku Earthquake, a new project to protect residential areas against liquefaction was established in Japan. Ten cities affected by the 2024 Noto Peninsula Earthquake have also begun to consider the possibility of using this project to lower groundwater levels over a wide area as a countermeasure, and soil investigations have been carried out since six months after the earthquake. However, in areas where liquefaction-induced ground flow occurred on gently sloping ground, new problems have arisen, such as how to avoid blocking the flow of groundwater.

KEYWORDS: Liquefaction-Induced Lateral Flow; Noto Peninsula Earthquake; Countermeasures

INTRODUCTION

In Japan, the Noto Peninsula Earthquake occurred at around 16:10 on January 1, 2024 in the northeastern part of the Noto Peninsula, as shown in Figure 1. Strong shaking throughout the Noto Peninsula caused extensive damage to low-rise houses and other structures, roads in many areas were cut off due to failures of slopes and embankments, and coastal areas were hit by a tsunami. In some areas, the coast rose by up to four meters, making ports unusable. With transportation and lifelines cut off over such a wide area, recovery has been extremely difficult, and even 8 months later, restoration work is still in progress. Therefore, the extent of the damage caused by liquefaction on the Noto Peninsula is still not clear. However, liquefaction can occur far from the epicenter when the seismic intensity is V- or higher in the JMA scale, so the extent of liquefaction damage occurring outside the Noto Peninsula is becoming clear. Cities that suffered widespread liquefaction damage in residential areas are shown in Figure 1. Liquefaction occurred in the following geomorphology in each city:

1) Inland edges of sand dunes: Uchinada Town, Kahoku City, Kanazawa City, Hakui City Niigata City,
2) Old river channels: Niigata City, Hakui City, Toyama City
3) Sandbars: Himi City, Imizu City
4) Artificial fill: Takaoka City

In the 2011 Tohoku Earthquake, a lot of damage was caused by the liquefaction of artificially formed land in residential areas, but there was little artificially formed land on the Noto Peninsula. Nevertheless, according to the Ministry of Land, Infrastructure, Transport and Tourism (MLIT), the number of homes

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damaged by liquefaction is estimated to exceed 17,000. Among the liquefied areas, some areas of Niigata City experienced liquefaction 60 years ago during the Niigata Earthquake, and areas in Uchinada Town were liquefied 133 years ago during the Nobi Earthquake. It is thought that after many years of soil deposition, the aging effect makes soil less likely to liquefy, but these cases show that liquefaction can reoccur over long periods of time.

Though it has only been several months since the Noto Peninsula Earthquake, and soil investigations have just begun, projects to lower groundwater levels and implement district-wide measures have already begun in ten cities. The damage and the status of countermeasures being considered are described below.

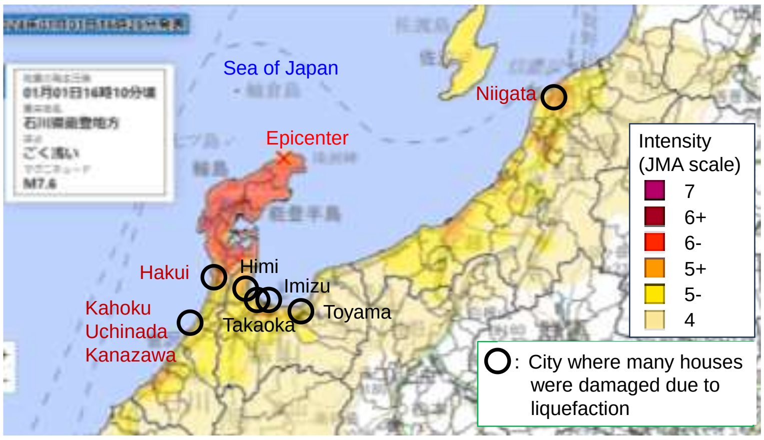


Fig. 1 Cities that suffered widespread liquefaction damage in residential areas (Base diagram: JMA, 2024)

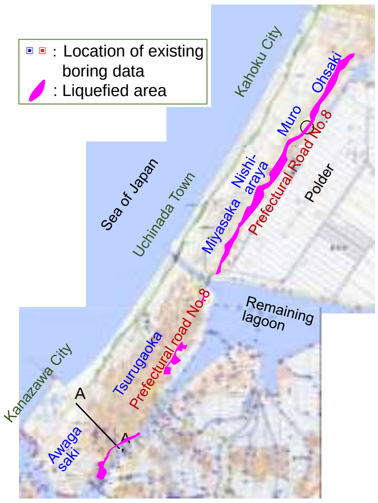


Fig. 2 Liquefied area and locations of sites of borings in the Uchinada Sand Dunes of this area (Base diagram: NGICJ, 2024)

DAMAGE CAUSED BY LATERAL FLOW IN GENTLY SLOPING GROUND AT THE EDGE OF UCHINADA SAND DUNES

Some areas of Uchinada Town, Kahoku City, and Kanazawa City in Ishikawa Prefecture suffered not only liquefaction but also large lateral flow, causing extremely severe damage to houses, roads, and lifelines. In these areas, the Uchinada Sand Dunes are formed between the Sea of Japan and the Kahoku Lagoon. Liquefaction and associated lateral ground flow occurred on the inland edge of the sand dunes (Kahoku Lagoon side) in a narrow area approximately 10 km long and 0.1 km wide, stretching from the Ohsaki district of Kahoku City to the Awagasaki district of Kanazawa City, as shown in Figure 2. In terms of altitude, liquefaction occurred in the range of approximately EL. +2 m to +6 m. Particularly serious damage was caused by liquefaction and flow over a wide area between the Miyasaka district and the Ohsaki district along the northern part of the Uchinada Sand Dunes. Figure 2 also shows the locations of sites of borings in this area before the Noto Earthquake. Data acquired from these borings was published by the National Geo-Information Center (NGICJ, 2024). Prefectural Road No. 8 passes through the inland edge of the sand dunes. The following study was carried out using only the data acquired from the dune side of Prefectural Road No. 8.

First, the cross section of the sand dune was estimated from the boring data (NGICJ, 2024). Ideally, a cross-section of the sand dunes passing through the Uchigata district is desired, but since there are only a few boring data from that district, a cross-section passing through the Awagasaki district, where there are more data, was drawn, as shown in Figure 3. In the cross section, alluvial clay is deposited beneath the dune sand layers, and the boundary between them is approximately EL. -5 m in the center of the dune and approximately EL. -1m on the inland edge. The higher the dune, the more the clayey soil layer appears to have settled due to consolidation. The SPT N-value of the clayey soil layer is close to zero at the inland edge and is soft, but at the center of the dune it is around 10, suggesting that its strength has increased due to consolidation or that sand from the dune has been mixed in. The sand layer appears to be divided into a loose upper layer with an N value of around 5 to 10, and a slightly denser lower layer with an N value of 10 or more. According to Fuji (1976), in around 8000 BC, when sea levels rose to their present elevation, sandbars and sand spits developed in this area, which is thought to have triggered the formation of sand dunes later. The sandbar must have sunk into the sea in around 6000 BC, when sea levels were about 5m higher than at present, and then as sea levels dropped, the sandbar emerged above sea level, and sand dunes began to form rapidly. Based on the process of sand dune formation, Fuji distinguishes between the old sand dunes on the Sea of Japan side and the new sand dunes that formed on top of them on the Kahoku Lagoon side. It is not sure whether the same is true for the line in Figure 3, but since the N values differ between the upper and lower parts, the boundary line in Figure 3 can be considered the boundary between the old sand dune and the new sand dune. However, further investigation is required.

In general, the groundwater level is higher in the center of a sand dune cross section and lower at both edges, as schematically shown in Figure 4. If there is a lowland between the dunes near the top of the dunes, the groundwater level may be shallow even if the elevation is high, but there is no lowland in the Uchinada Sand Dunes. Therefore, it is thought that the groundwater level of the Uchinada Sand Dunes is distributed as shown in Figure 4. Using the boring data that included the groundwater level, the ground surface elevation and depth to the groundwater table were plotted, as shown in Figure 5. The line in the Figure is an approximation using the least squares method, assuming it passes through the origin, and the results show that the groundwater level is shallow at the edges of the sand dunes, where the ground surface elevation is low.

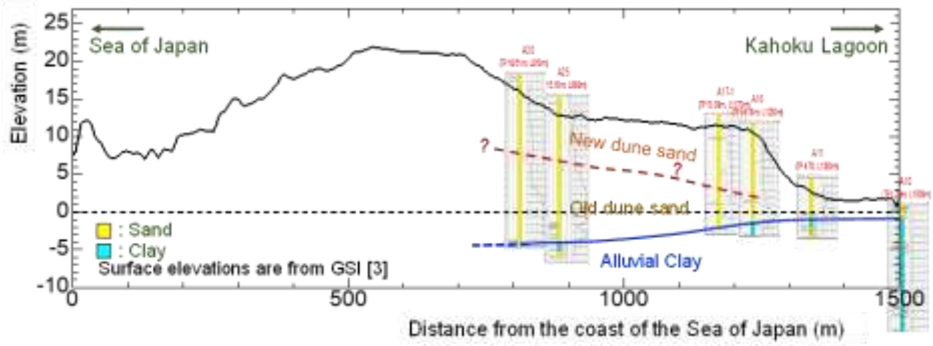


Fig. 3 Cross-section passing through the Awagasaki district

Fig. 4 Schematic diagram of groundwater level distribution in a sand dune

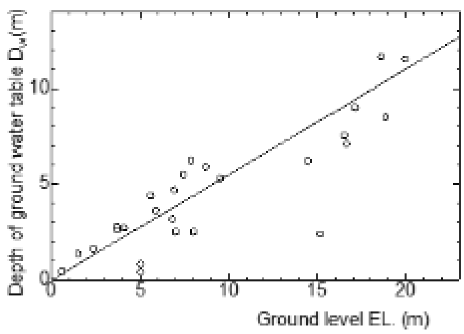


Fig. 5 Relationship between the ground surface elevation and depth of the groundwater table

DAMAGE IN THE NISHI-ARAYA DISTRICT WHERE LATERAL FLOW WAS PARTICULARLY SEVERE

The section of the area shown in Figure 2 that suffered the most damage was the northern half between Ohsaki in Kahoku City and Miyasaka in Uchinada Town. The Nishi-Araya district is located in the center of this section, and a cross section of the sand dunes passing through this district is shown in Figure 6.

Liquefaction and lateral flow occurred in the zone indicated as the liquefied zone in the Figure. Figure 7 shows a topographical map from the Nishi-Araya district to the Muro district. This area is divided into three, designated by colors: below 2 m above sea level, above 5.5 m above sea level, and in between. The old road is at an altitude of about 2 m, which is thought to have been the border between the sand dunes and Kahoku Lagoon. As will be described later, in this area, liquefaction and associated large ground flow occurred over an area roughly between EL. +2 m and +5.5 m.

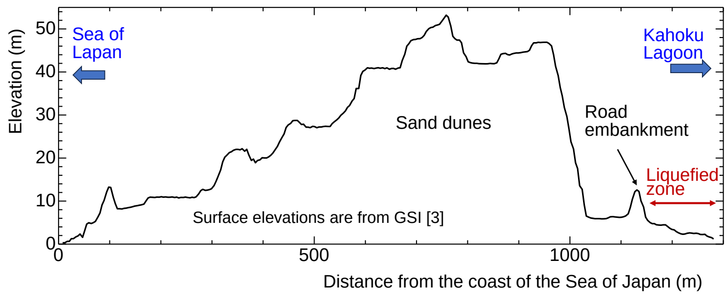


Fig. 6 Cross section across the sand dunes in the Nishiaraya district

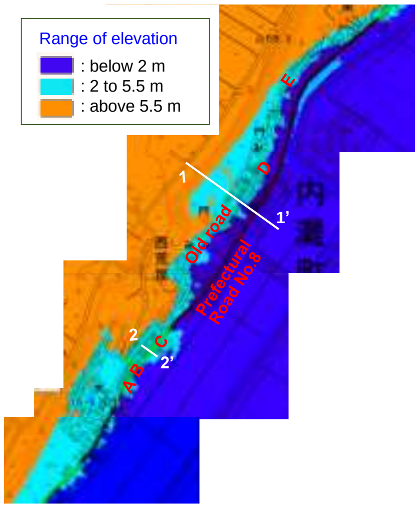


Fig. 7 Topographical map from the Nishi-Araya district to the Muro district

A cross section along the 2-2' survey line is shown in Figure 8 with photographs of damage taken at four locations within the cross section. Since there is no previous boring data from this district, the groundwater level is estimated based on Figure 5. The horizontal distance along this line is approximately 120 m, the elevation difference is approximately 3.5 m, and the average gradient is only 1.7°, making the ground very slightly inclined. Photo a) was taken on the road one block west of Prefectural Road No. 8. A large tensile crack was observed between residential areas, suggesting that the flow began in this vicinity. Photo b) shows the alley between that road and Prefectural Road No. 8, where several cracks had appeared, indicating that the ground had been pulled toward the prefectural road. Photo c) shows the damage to Prefectural Road No. 8. The road surface was significantly raised and tilted, and the floor of the garage in the photo had risen, making it impossible to get the car out. In the downstream Photo d), cracks were also seen in the ground and wall.

Figure 9 shows a cross section along the 1-1' survey line, located 600 m northeast of the 2-2' survey line. As can be seen in photo e), there were several large tensile cracks, indicating that lateral flow had occurred from these points. The ground had flowed up to the area between the old road and Prefectural Road No. 8, and some residential land along the old road was jutting out onto the road, as shown in photo f). The elevation where the tensile cracks appeared and the flow began was approximately EL. +5.5 m, and the flow stopped at an elevation of approximately EL. +2 m. Liquefaction and flow occurred in a similar elevation range in Uchinada Town. Based on the relationship shown in Figure 5, the groundwater level at an altitude of EL. +5.5 m is estimated to be about 3 m deep. According to Ishihara's diagram showing the relationship between the depth of groundwater table and damage caused by liquefaction, if the groundwater table is deeper than 3m, no damage will occur to the ground surface even if the layers below that depth liquefy (Ishihara, 1985). It is unclear whether the same approach can be applied to the occurrence of lateral ground flow, but the authors would like to investigate this further using analysis.

The slope in Photo e) is the slope of a sand dune, but this slope was cut artificially. In the Uchinada Lagoon, reclamation work along the coast was carried out between 1961 and 1964. The sand used for fill was mainly from the sand dune cliffs behind each residential zone. Additionally, sand from the sand dunes in the Osaki district was used for the western polder dike and housing lots inside the polder. Since the ground surface elevation was significantly lower in the areas where these sand dunes were cut, it is estimated that the groundwater table was relatively shallow at the time of the Noto Peninsula Earthquake.

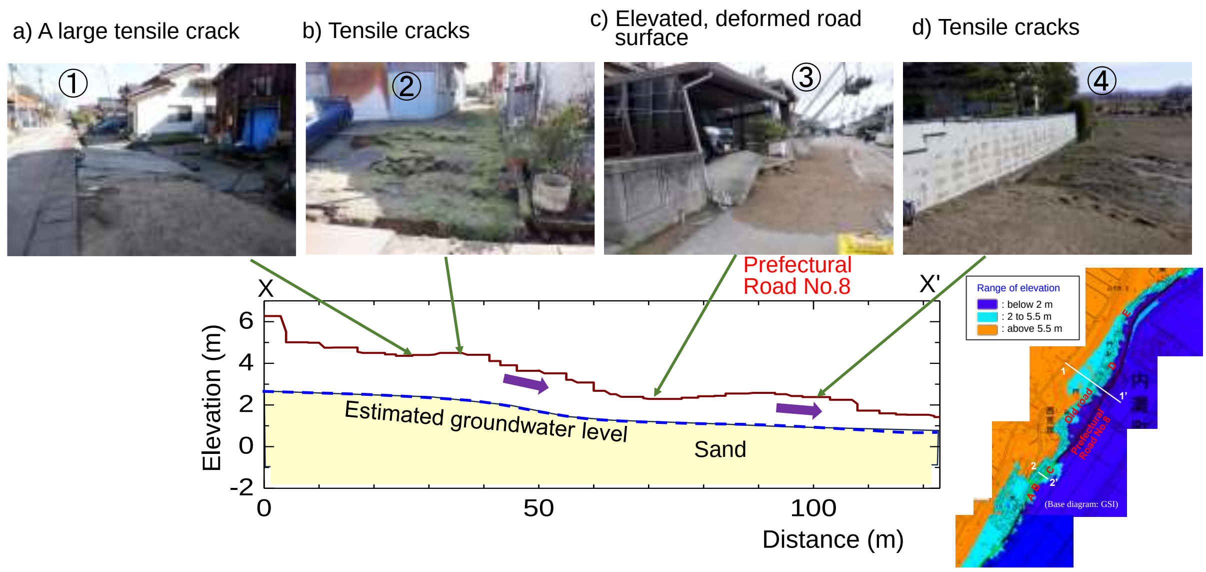


Fig. 8 Cross section along the 2-2' survey line and photos of damage along this cross section

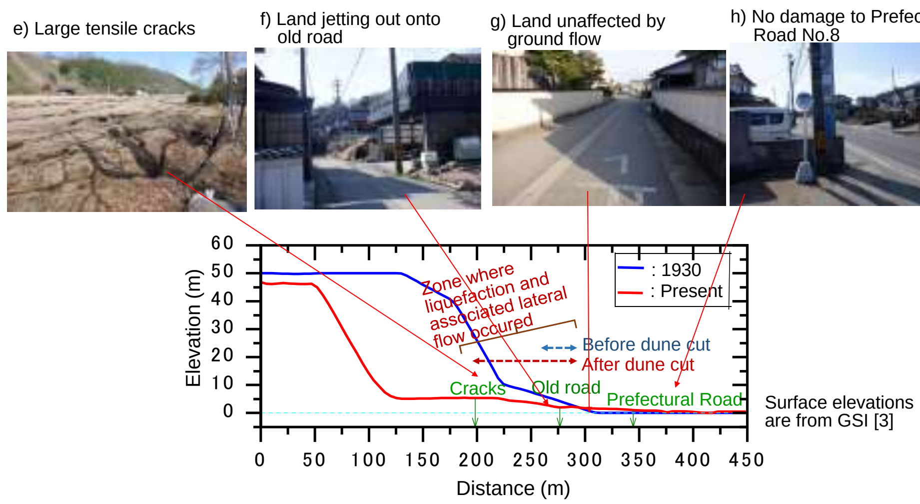


Fig. 9 Cross section along the 1-1' survey line and photos of damage along this cross section

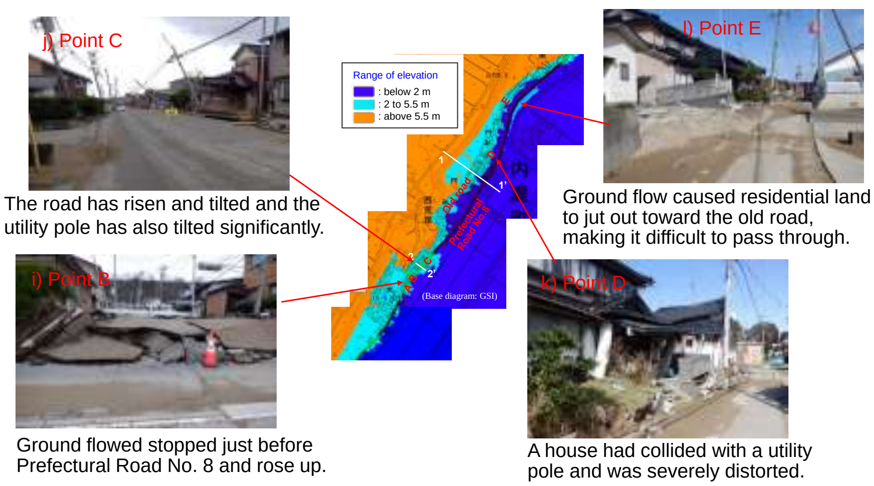


Fig. 10 Photographs of damages in other parts of the Nishi-Araya and Muro areas

Figure 9 also shows the shape of the ground surface in 1930, before the sand dunes were cut. Assuming that liquefaction and associated lateral flow occurred in the zone with elevation of EL. +2 to EL. +5.5 m, it is estimated that if the sand dunes had not been cut, this area would have been too narrow for large flow to occur.

Figure 10 shows photographs of damage in other parts of the Nishi-Araya and Muro districts. Point B, shown in Photo i), is about 60 m southwest of the site shown in Figure 8, where the ground that had flowed out stopped just before Prefectural Road No. 8 and rose up, blocking traffic. Point C, shown in Photo j), is 50 m northeast of the 2-2' line, facing south. The road has risen and tilted significantly due to flow from the sand dune on the right, and the utility pole has also tilted significantly. Furthermore, as shown in Photo k) at Point D, a house had collided with a utility pole and was severely distorted. At Point E, lateral flow caused residential land to jut out toward the old road, making it difficult to pass through, as shown in Photo l).

SOIL CROSS SECTION ESTIMATED BY SIMPLE SOIL INVESTIGATION

In the areas where liquefaction occurred in the Uchinada Sand Dunes, houses and roads remain damaged even six months after the earthquake. Plans are underway to implement liquefaction countermeasures throughout these areas, similar to the restoration work carried out in Chiba City and other cities after the 2011 Tohoku earthquake (Yasuda et al., 2020). A ground survey for this purpose is about to begin, but since the ground condition is still unknown, the authors carried out a simple ground survey. For this purpose, Screw Weight Soundings (SWS) were conducted to measure not only the penetration resistance but also the groundwater level and sample collection, as shown in Figure 11. The investigation was conducted in the Osaki district along a line perpendicular to the sand dunes, as shown in Figure 12. Along this line, no sand boiling or lateral flow occurred at point No. 1, but from point No. 2 downstream, sand boiling and cracks in the ground, suggesting lateral flow, occurred, as shown at point F), causing damage to houses. The $W\mathrm{sw}$ and $N\mathrm{sw}$ obtained by SWS were converted to SPT N-values using the following Inada's formula.

$$N=2\times W\mathrm{sw}+0.067\times N\mathrm{sw}\ , \quad \text{where, unit of } W\mathrm{sw} \text{ is kN} \qquad (1)$$

The results are shown in Figure 13. The authors also conducted microtremor array observations and plan to use these to determine the soil layer boundaries in the future. For the time being, the soil layer boundaries estimated from the SWS data alone are shown in Figure 13. This reveals the following:

1) At undamaged No. 1, there is a dense alluvium sand layer at a depth of 1 to 2 m.
2) From No. 2 to No. 6, where liquefaction and flow occurred, a very loose dune sand layer with a converted N-value of around 5 is deposited.
3) Downstream from No. 2, the groundwater level was very shallow at about 1 to 2 m, and became shallower the further downstream.

Fig. 11 Screw Weight Sounding (SWS), groundwater level measurement, and sampling equipment

Fig. 12 Locations where SWS surveys were conducted in the Ohsaki district [Base photo: GSIJ (2024)]

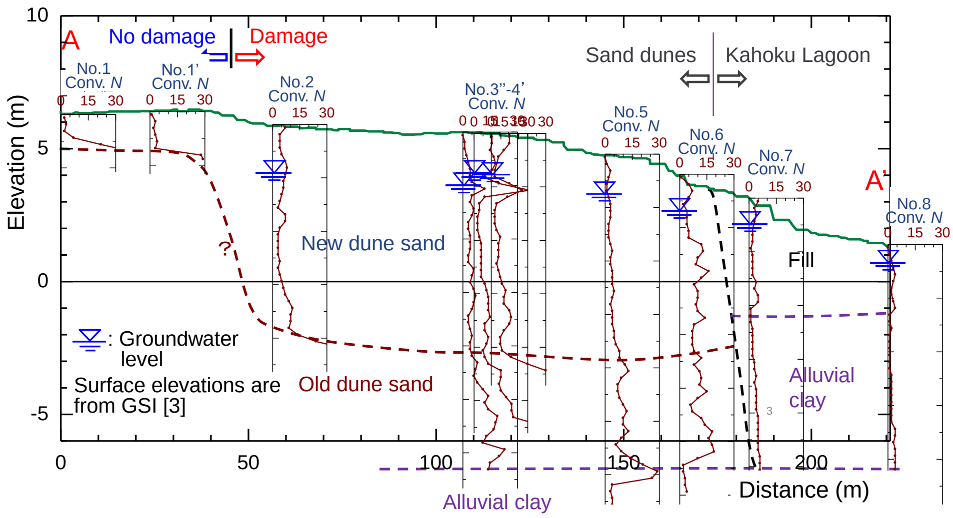


Fig. 13 Cross section estimated by SWS

HISTORY OF RESEARCH INTO THE MECHANISM OF DAMAGE TO LOW-RISE HOUSING CAUSED BY LIQUEFACTION (PARTIALLY QUOTED FROM YASUDA ET AL., 2020)

Japan has high seismic activity and widely distributed soil that is prone to liquefaction, so liquefaction occurs every one or two years. Therefore, almost all large structures, such as bridges and mid-rise buildings, are now being designed with liquefaction in mind, and these structures have suffered almost no damage in recent earthquakes. On the other hand, it is not mandatory to take liquefaction into consideration in the design of low-rise housing, and damage has occurred to such housing every time there has been an earthquake. In particular, the 2011 Tohoku earthquake damaged about 27,000 houses, and since then, several studies have been conducted on the mechanism of damage caused by liquefaction to low-rise housing.

On flat land with a liquefied layer of uniform thickness, uniform subsidence occurred due to the change in volume of the liquefied layer and houses penetrated into the ground at some inclination due to the loss of bearing capacity or due to a decrease in the shear modulus of the liquefied layer, as shown in Figures 14 and 15. Two months after the Tohoku Earthquake, the Japanese Cabinet announced a new standard for the evaluation of damage to houses based on two factors, settlement and inclination. Houses tilted at angles of more than 50/1,000, of 50/1,000 to 16.7/1,000, and of 16.7/1,000 to 10/1,000 were judged to be totally collapsed, large-scale half collapsed and half collapsed houses, respectively, under the new standard, because in the steeply tilted houses, inhabitants felt giddy and nauseas and could not live in their houses after the earthquake, though the walls, pillars and windows of the houses had no damage.

The author and his colleagues conducted model tests using a large shaking table and a soil container owned by the Building Research Institute in Japan to demonstrate the mechanism of the penetration settlement of houses due to liquefaction Kaneko and Yasuda (2014). Figures 16 (a), 16 (b) and 16 (c) show the behavior of the model house and surrounding ground at 26, 34 and about 70 seconds, respectively. As shown in Figure 16 (a), water started spewing out of the ground at 26 seconds at the edge of the model ground. However, water did not spew out of the ground until the end of shaking around the model house, but spewed out several seconds after the end of shaking, as shown in Figure 16 (c). On the contrary, the penetration settlement accelerated at about 15 seconds, and, at 34 seconds, reached about 8 cm, which is about 80% of the settlement at the end of shaking. Figure 17 summarizes the timing of the occurrence of liquefaction (A), penetration settlement accelerated (B), water spewing out at the edge of the ground (C), the end of shaking (D), and water spewing out at the edge of the house (E), with the time histories of the ground and penetration settlements. As shown in this sequence, penetration settlement occurred first, then ground water spewed out around the model house. The ground surface settled gradually after the occurrence of liquefaction. Based on the model tests, the author concluded that a structure such as a building or a house did not sink into a hole that was produced by water spewing out, but penetrated into the ground due to a decrease in the shear modulus of the surface layer following the outside lateral flow of the ground under the house and the heaving of ground surrounding the house, as schematically shown in Figure 18. The ground surface settled slowly because the liquefied layer under and around the house densified gradually due the spewing out of the pore water.

Fig. 14 Settled and tilted houses in Urayasu City

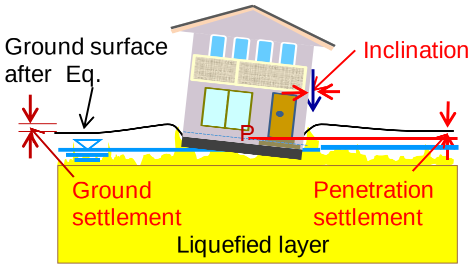


Fig. 15 Schematic diagram of a settled and tilted house

(a) Spewed water at the edge of the ground at 26 sec.

(b) Penetration settlement at 34 sec.

(c) Spewed water at the edge of house around 70 sec.

Fig. 16 Photographs of penetration settlement, heaving, and spewed water

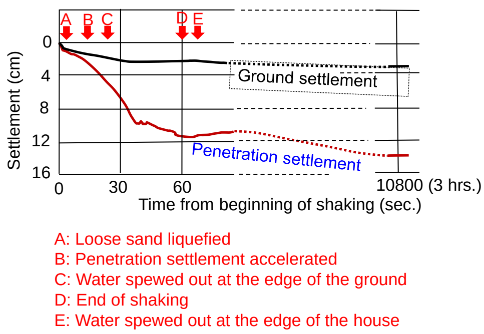


Fig. 17 Time histories of penetration settlement and ground settlement

The tilting of houses is derived from non-uniform settlement. According to the author's previous study on the non-uniform settlement of houses, several factors affect non-uniform settlement. Among them, the effect of adjacent houses was dominant, as schematically shown in Figure 19. If two houses are close to each other, they tilt inward toward each other, and if four houses are close, they tilt toward their common center. Figures 20 (a) and 20 (b) show the actual relationship between the penetrating settlement and the inclination of houses in two cities in which the houses are clustered close together and in two other cities in which the houses are scattered, respectively. Though these data are scattered, inclination increases with penetrating settlement in each Figure. And the relationships are different in two sets of cities.

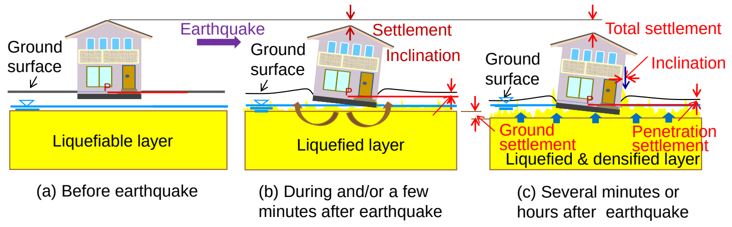


Fig. 18 Mechanism of liquefaction-induced settlement of a house and ground

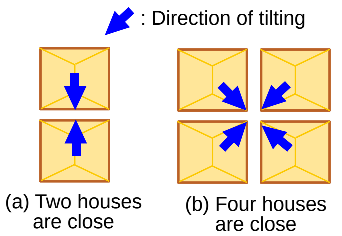


Fig. 19 Effect of adjacent houses on the inclination of houses

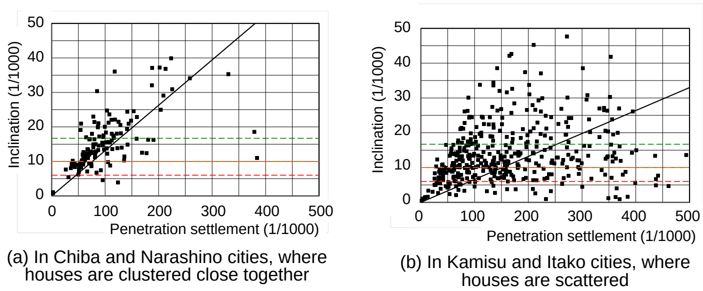


Fig. 20 Relationship between penetration settlement and inclination of houses caused by the 2011 Tohoku Earthquake (Yasuda et al., 2020)

The author and his colleagues measured the exact depth of the water table at the sites of about 28 damaged houses of Urayasu City. The measured depths are classified by the level of damage to wooden houses and plotted in Figure 21. As shown in this Figure, a water table of about 1.7 to 2.0 m below the ground surface was the critical depth to cause damage to houses. So, the author assume that the upper non-liquefied layer affects the damage to wooden houses as follows. When a liquefied layer is of uniform thickness and the upper non-liquefied layer is thin, houses penetrate into the ground, often at an angle, due to the lateral flow of the liquefied layer. In addition, uniform subsidence occurs due to the densification of the liquefied layer. However, if the non-liquefied layer is thick, penetration settlement and tilting is limited, though uniform subsidence due to the densification of the liquefied layer occurs. For the non-liquefied layer, it must be noted that the water table is not stable but increases during shaking for two reasons: i) the inflow of water from the lower liquefied layer due to liquefaction-induced densification, and ii) the spewing out of water due to excess pore water pressure induced in the liquefied layer. The inflow of water from the lower liquefied layer increases the water level by 1 m or less if the thickness and the volumetric strain of liquefied layer is several meters and about 5%, respectively. The water spewed out from the liquefied layer occasionally reaches a few meters above the ground surface, but it flows through narrow spaces, such as cracks in the ground, and lasts for a short time. Therefore, the ground water level usually increases by only a meter or so. Considering this increase in the water table due to liquefaction, a water table of about 2 to 3 m below the ground surface must be the critical depth to prevent damage to a house, as schematically shown in Figure 22.

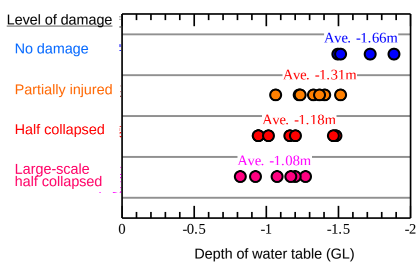


Fig. 21 Measured depth of water table at sites of damaged and undamaged houses in Urayasu Yasuda et al. (2020)

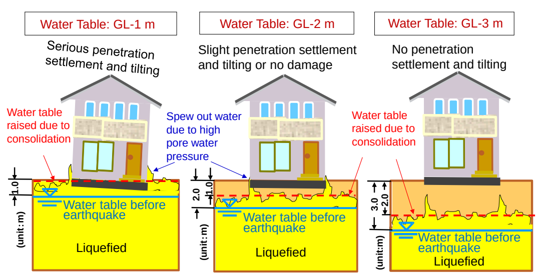


Fig. 22 Illustration of the impact of the water table on the liquefaction-induced settlement and tilting of a house

URBAN LIQUEFACTION COUNTERMEASURE PROJECT APPLIED TO SEVERAL CITIES WHERE SEVERE DAMAGE OCCURRED BY THE TOHOKU EARTHQUAKE [PARTIALLY QUOTED FROM YASUDA ET AL., 2020, YASUDA & HASHIMOTO, 2016]

Soon after the 2011 Tohoku Earthquake, the repair of tilted houses by lifting their superstructures, reconstructing their footings, and placing the superstructures on the new footings started. However, this kind of repair does not prevent re-liquefaction during a future earthquake. The ground beneath the houses must be improved to prevent liquefaction. There are four patterns to improve the ground in areas where houses have been damaged, as illustrated in Figure 23 and explained below:

(1) **Pattern 1**: If many damaged houses in a residential area are demolished, the best option is to improve the ground in the entire area and rebuild houses.

(2) **Pattern 2**: If a damaged house is demolished, an appropriate countermeasure against liquefaction must be applied before reconstruction.

(3) **Pattern 3:** If all or many settled and tilted houses are repaired by uplifting, the ground in the whole area, including lifelines and roads, must be treated.

(4) **Pattern 4**: If a settled and tilted house is repaired by uplifting, the ground beneath it must be treated.

Pattern 3 is the most favorable because the ground beneath houses and roads and around buried pipes can be treated simultaneously. The MLIT established a new project eight months after the earthquake, the "Urban liquefaction countermeasure project". In this project, a wide residential area of more than 3,000m^2, including roads, buried pipes and more than 10 houses, is treated by an appropriate countermeasure and its costs are shared by the government and inhabitants.

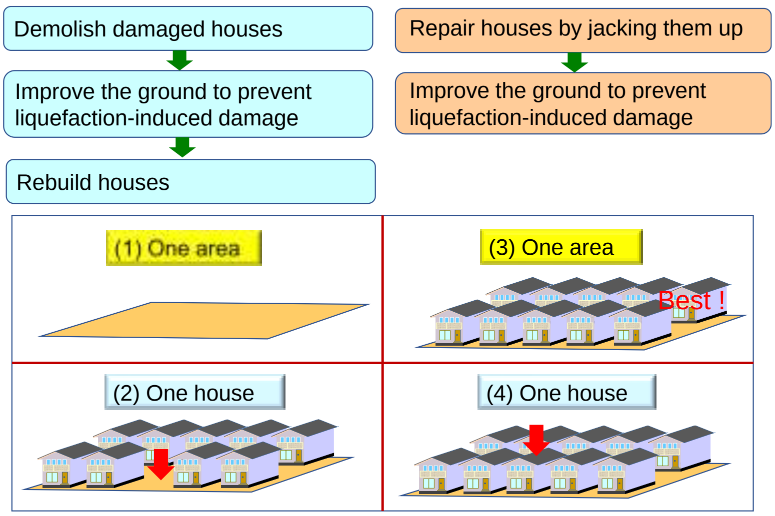
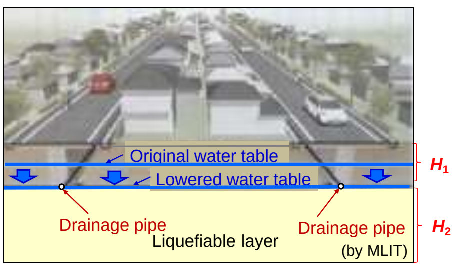
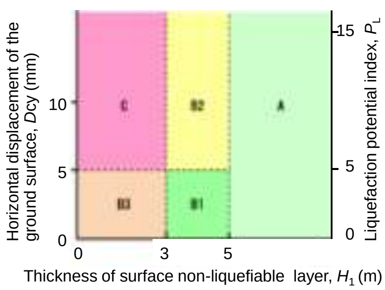


Fig. 23 Four patterns to strengthen the foundation ground of residential areas against liquefaction





Evaluation results	Potential for liquefaction damage
C	The potential for severe damage is high.
B3	Potential for severe damage is relatively low.
B2	
B1	
A	Potential for severe damage is low.

Fig. 24 Lowering of ground water table (MLIT)

Fig. 25 A new method to estimate the liquefaction-induced damage to wooden houses (MLIT)

Two methods, lowering the ground water table and surrounding the foundation ground with lattice-type underground walls, have been selected. In six cities, the method of lowering the ground water table, schematically shown in Figure 24, has been selected as the most promising. For the method of lowering the water table, it was necessary to decide i) how much to lower the water table, ii) how to lower the water table, iii) how much subsidence occurs accompanying the lowering of the water table, and iv) the cost of each method of lowering the water table. The project decided that a water table of about 3 m below the ground surface was appropriate to prevent liquefaction damage to wooden structures in most cities based on a comparison of the water tables where structures had been damaged and the water tables where structures had not been damaged and based on the criterion proposed by MLIT shown in Figure 25

In Chiba City, a residential area of about 3 km x 10 km was constructed by reclaiming the coast of Tokyo Bay. Liquefaction occurred over a wide area in this reclaimed land, causing serious damage to many low-rise houses, roads and lifelines. Then a technical committee was organized in 2012 to select an appropriate countermeasure to liquefaction as part of the urban liquefaction countermeasure project. Three districts were nominated first, then, the applicability of two methods, lowering the ground water table and surrounding the foundation ground with lattice-type underground walls, was investigates by conducting borings and analyses. Then, it was decided that two districts, Isobe 4-chome and Isobe 3-chome, would lower the ground water table. Figure 26 shows the layout of drainage pipes in Isobe 4-chome. 260 low-rise houses exist in an area of about 7.1 ha. The depth of the drainage pipes was designed with a slope of

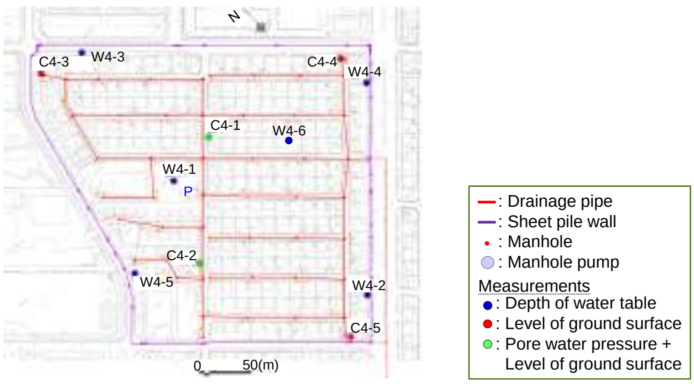


Fig. 26 Layout of drainage pipes in Isobe 4-chome in Chiba City Yasuda et al. (2020)

Fig. 27 Installation of a drainage pipe from the shaft

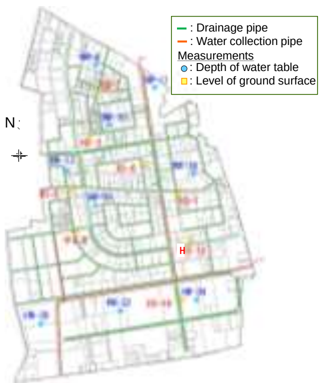


Fig. 28 Layout of drainage pipes in Hirai-tohbu in Kashima City (Yasuda et al., 2020)

Fig. 29 Excavation work in Hirai-tohbu

2 mm/1000 mm from northwest to southeast because there is a small river in the southeast direction. Drain water flows through the drainage pipes into two manholes located at the southeast boundary of the area, then the water is pumped up and into a pipe connecting to the river. The drainage pipes were placed by a special shield method. Vertical shafts of about 2.5 m in diameter were constructed at intervals of about 50 m, and then specially made drainage pipes of 30 cm in diameter were installed from the shafts, as shown in Figure 27. The distance between drainage pipes was planned as 40 m, and the planned depth of the pipes was GL-3 m. Sheet pile walls were installed to a depth of about 6 m around the district to prevent water flow from outside the area. Many sensors were installed to measure the depth of the water table, the settlement of the ground surface, the pore water pressure during and after the construction of drainage pipes. The ground water table decreased to about GL-2.2 m to -2.9 m in one year due to the drainage from an original ground water level of about GL-1.2 m to -1.6 m. The settlement of the ground surface due to

lowering the ground water level was very small, from 3 mm to 6 mm. The total cost of lowering the ground water level in this area was about US $15 million.

Kashima City faces the Pacific Ocean. Liquefaction occurred on the coast, in part of the sand dunes, in the filled area on the alluvial lowland and in the filled area on the slope of the terrace. Six districts were nominated first, and borings and analyses were conducted. Then, it was decided that three districts, Hirai-tohbu, Kashimajingu-ekinishi and Hachigata, would lower the ground water table. Figure 28 shows the layout of drainage pipes in the Hirai-tohbu district. 245 wooden houses existed in an area of about 68.5 ha. This area is located on sand dunes, and the ground surface slopes gently toward the coast from west to east. As the dune sand is suitable for construction material, it has been extracted and backfilled with other sandy soils at many spots historically. So, filled sandy soil is deposited from the ground surface to the depth of 5 m to 15 m, irregularly. The depth of the drainage pipes was designed at a slope of 1 to 48 mm/1000 mm from west to east and with the depth of about 3 m below the ground surface. Drained water flows into water collection pipes, then flowed to ocean naturally. Drainage pipes were constructed by a standard method because wooden houses were being constructed in the area and existing houses were scattered. First, groundwater level was lowered by well-point method, trenches were excavated, as shown in Figure 29, then drainage pipes of 200 mm to 300 mm in diameter were placed inside the trenches using permeable sheets and the trenches were backfilled with gravelly sand. The ground water table decreased to about GL-3.0 m to -4.0 m in two years from an original ground water level of GL-0.5 m to -2.0 m. The total cost of lowering the ground water level in this area through this method was about US $32 million.

LAUNCH OF URBAN LIQUEFACTION COUNTERMEASURE PROJECTS IN TEN CITIES AFFECTED BY THE NOTO PENINSULA EARTHQUAKE

In ten cities that suffered damage from liquefaction in the Noto Peninsula Earthquake, the urban liquefaction countermeasure project began six months after the earthquake. The project began with an appraisal of the damage, and soil investigations are currently being conducted. Based on these survey results, most cities are considering measures to lower groundwater levels, as was done in six cities after the Tohoku Earthquake.

Figure 30 shows liquefied zone and locations of soil investigations conducted approximately eight months after the earthquake in the Awagasaki district of Kanazawa City [KCDATRC, 2024]. Figure 31 shows the soil cross-section estimated based on the results of these soil investigations. As shown in this cross section, a layer of loose dune sand is deposited on the surface. Plans are underway to conducting 3D analysis of groundwater flow and to determine the layout of an effective network of underground drainage pipes for lowering the groundwater level as schematically shown in Figure 32.

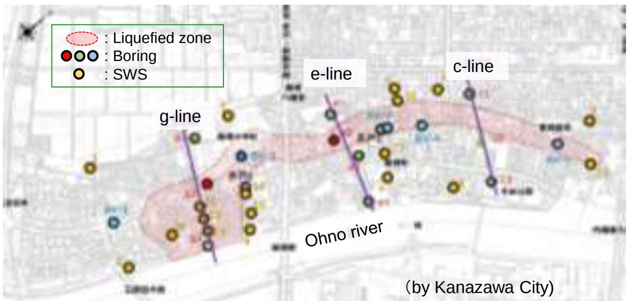


Fig. 30 Liquefied zone & locations of soil investigations in the Awagasaki district, Kanazawa City [KCDATRC, 2024]

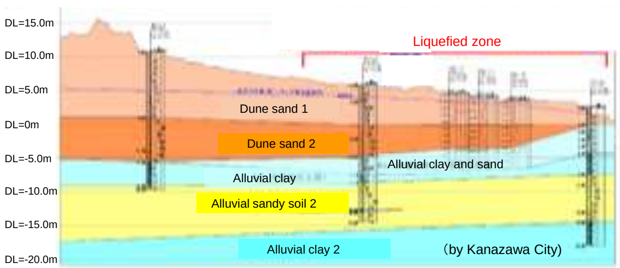


Fig. 31 Soil cross-section estimated based on the results of soil investigations [KCDATRC, 2024]

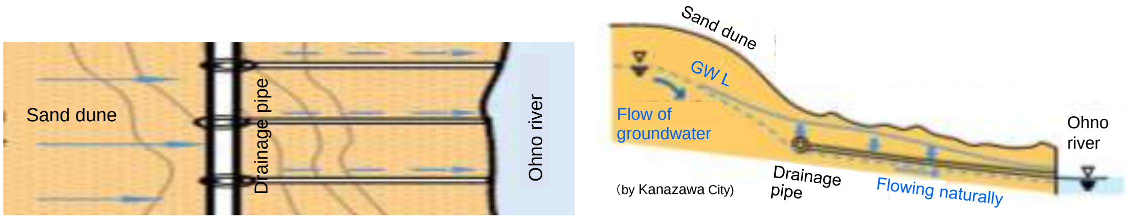


Fig. 32 Idea for the layout of an effective network of underground drainage pipes [KCDATRC, 2024]

The grounds in the area shown in Figures 26 to 29 are almost flat, and no horizontal ground flow due to liquefaction has occurred. However, as mentioned above, in Uchinada Town, Kanazawa City, Kahoku City, Hakui City, and Niigata City, gently sloping ground on the edge of sand dunes liquefied, causing large horizontal flows. Therefore, consideration of the following three items is required for the entire area:

(1) In areas where flow occurred, houses have been severely deformed and have had to be demolished. In addition, the ground has shifted horizontally by about 1 to 3 meters, causing the surface to become wavy. Therefore, as shown in Figure 23 (1), all the houses must be demolished and the land must be readjusted and leveled first. If restoration is to be carried out after that, it may be more reasonable to improve the ground, such as compacting it, rather than lowering the groundwater level.

(2) Because groundwater flows horizontally, lattice-type improvement works would raise the groundwater level upstream, making the upstream side more susceptible to liquefaction. In the case of the groundwater level lowering method, surrounding the area with sheet piles will similarly raise the groundwater level upstream. Therefore, it is necessary not to surround the area with sheet piles or to drive sheet piles only on lateral sides. However, since the groundwater table is sloping, the groundwater can be allowed to flow naturally and released into rivers, etc. as shown in Figure 32.

(3) It is necessary to verify that lowering the groundwater level also reduces the amount of horizontal displacement due to ground flow. However, there has only been one case in which the amount of reduction was examined through analysis. The analysis was carried out during the restoration work after the gently sloping ground in Tokai Village liquefied during the Tohoku earthquake, causing the ground to flow as shown in Figure 33. The analysis was carried out using the simple residual deformation analysis code ALID Yasuda et al. (2017), and it was found that, as shown in Figure 34, if the groundwater level remained unchanged, a maximum displacement of 28 cm would occur, whereas if the groundwater level was lowered to GL-2m or GL-3m this would decrease to 12 cm or to 8 cm, respectively. Then, as shown in Figure 35, underground drainage pipes were installed to lower the water level to about GL -3m.

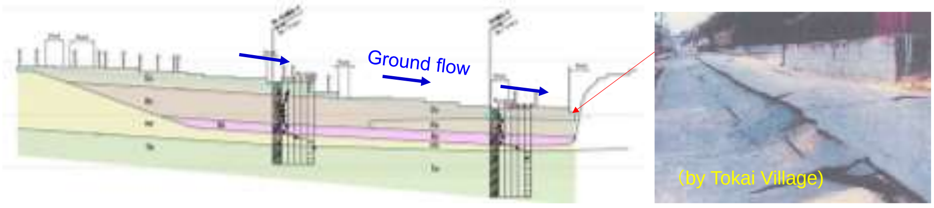


Fig. 33 Soil cross-section and upward thrust of a road surface caused by liquefaction-induced ground flow in Tokai Village during the Tohoku Earthquake

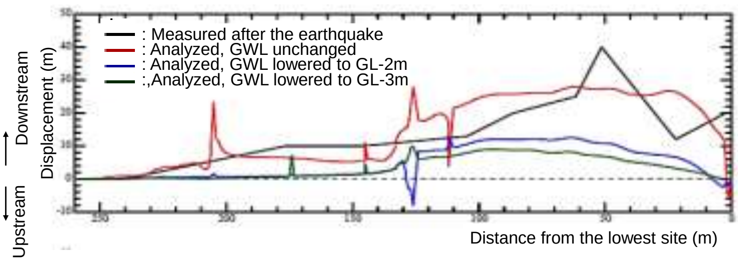


Fig. 34 Horizontal displacement obtained by residual deformation analysis

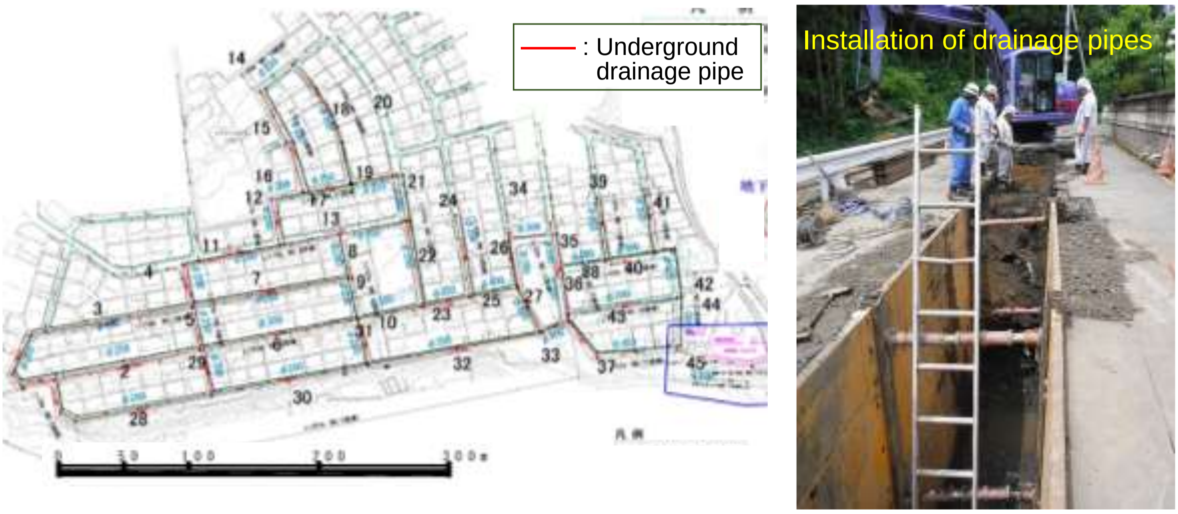


Fig. 35 Layout diagram of underground drainage pipes Yasuda and Hashimoto (2016)

CONCLUSIONS

The damage caused by liquefaction-induced lateral ground flow that occurred in the 2024 Noto Peninsula Earthquake was introduced. Next, the urban liquefaction countermeasure projects that were started in seven cities six months after the earthquake were introduced and the problems that arose in areas where the ground had flowed were pointed out. The main conclusions derived from these studies are as follows:

1) In the Noto Peninsula Earthquake, liquefaction and associated ground flow occurred in the gently sloping ground on the inland edges of sand dunes in Ishikawa and Niigata prefectures, causing severe damage to low-rise houses, roads, and lifelines.
2) After the 2011 Tohoku Earthquake, an "Urban liquefaction countermeasure project" to protect residential areas against liquefaction was established in Japan. Lowering the ground water table was proposed as a suitable measure and applied to six cities.
3) The ten cities affected by the Noto Peninsula Earthquake have also begun considering whether such measures are possible. However, in areas where liquefaction-related ground flow has occurred on gently sloping ground, new issues have arisen, such as how to avoid blocking the flow of groundwater, and further consideration is required.

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