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Damage to residential areas caused by liquefaction-induced ground flow during the 2024 Noto Peninsula Earthquake and subsequent recovery

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ABSTRACT: In Japan, the Mj7.6 Noto Peninsula Earthquake occurred on January 1, 2024.　In the plains of this peninsula, liquefaction occurred in many residential areas, causing severe damage to houses, lifelines, and roads. This liquefaction caused the flow of gently sloping ground at the inland edge of sand dunes. From Uchinada Town to Kahoku City, ground flow of up 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. In Japan, during the 2011 Tohoku Earthquake, liquefaction occurred over a wide area, 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. Several 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. It was necessary to verify that lowering the groundwater level also reduces the amount of horizontal displacement due to the ground flow. The authors applied the simplified residual deformation analysis code ALID to the site where they had conducted soil surveys. They found that, if the groundwater level remained unchanged, a maximum displacement of about 1.8 to 3.3 m would occur, whereas if the groundwater level is lowered, this would decrease to about 0.1 to 0.3 m.

KEYWORDS: Liquefaction, Noto Peninsula Earthquake, recovery.

1 INTRODUCTION

Japan has high seismic activity and much of the ground is prone to liquefaction, meaning that earthquakes causing liquefaction occur once every one to two years. During the 1983 Nihonkai-chubu Earthquake, liquefaction occurred on the gently sloping ground at the edge of sand dunes in Noshiro City, causing horizontal displacement of up to approximately 5 m, as shown in Figure 1, which became the catalyst for the recognition of liquefaction-induced ground flow. Furthermore, a re-examination of the damage caused by the 1964 Niigata Earthquake revealed that horizontal displacement of up to 10 m had occurred in the ground behind river revetments. In the 1995 Kobe Earthquake, liquefaction caused the revetments of the coastal reclaimed lands to bulge, causing lateral flow of the ground behind them. These inflicted extensive damage to the pile foundations of bridges and buildings, which prompted proposals for design methods of pile foundations to deal with the lateral flow of the ground behind revetments, and countermeasures were also started. However, no design methods or countermeasures have been developed for flow on gently sloping ground.

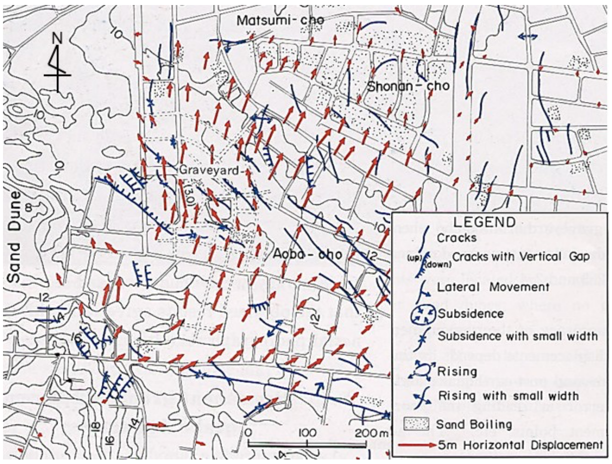

Figure 1. Liquefaction-induced flows occurred on gently sloping ground during the 1983 Nihonkai-Chubu Earthquake.

In the Noto Peninsula Earthquake that occurred in Japan in 2024, liquefaction-induced flow occurred on the gently sloping ground at the edge of the sand dunes, with horizontal displacements of up to 3 m, causing serious damage to low-rise houses with spread foundations, roads, and lifelines. In areas where the horizontal displacement was small, houses simply settled and tilted, so they are being restored by using jacks to lift them back to level, but in areas where the horizontal displacement was large, houses became so distorted that they were unusable and are being demolished. Plans are underway throughout the affected areas to rebuild by lowering groundwater levels or compacting the ground to prevent damage from liquefaction and ground flow in future earthquakes. This paper describes the damage caused by the ground flow that occurred during the Noto Peninsula Earthquake, the results of ground investigations, and the state of reconstruction.

2 LIQUEFACTION AND FLOW OCCURRENCE ON GENTLY SLOPING GROUND DURING THE 2024 NOTO PENINSULA EARTHQUAKE

The Noto Peninsula Earthquake of *M*j=7.6 occurred on January 1, 2024. Strong shaking 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 addition, widespread liquefaction occurred in residential areas, causing extensive damage to approximately 17,000 low-rise houses, lifelines, and roads. In particular, liquefaction and subsequent flow occurred on the gently sloping ground on the inland edges of the Uchinada and

Niigata Sand Dunes, causing very serious damage to many low-rise houses. In Uchinada Sand Dunes, liquefaction and associated lateral ground flow occurred in a narrow area approximately 10 km long and 0.1 km wide, stretching from the Osaki 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 TP. +2 m to +6 m. According to earthquake data recorded in this area, the maximum surface acceleration was approximately 200 cm/s^2. Figure 2 also shows the locations of sites of existing borings data in this area (National Geo-Information Center). In general, the groundwater level is higher in the center of a sand dune cross section and lower at both edges. 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 3. Ishihara (1985) has shown that if there is a non-liquefaction layer of about 3 m on the surface, there will be no damage on the surface even if the lower part liquefies. Looking at Figure 3, the elevation at which the groundwater level is 3 m deep is approximately TP + 5.5 m, which is consistent with the actual liquefaction range.

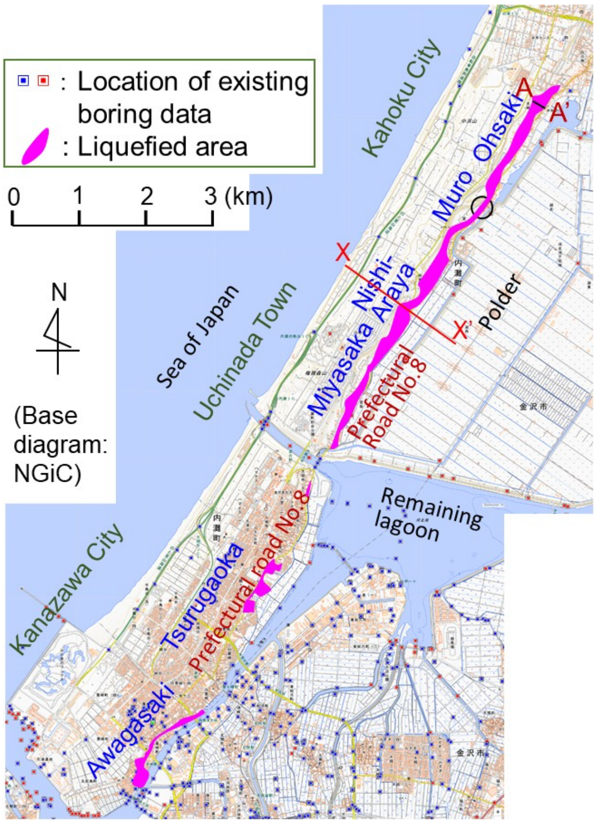

Figure 2. Liquefied area and locations of sites of borings in the Uchinada Sand Dunes.

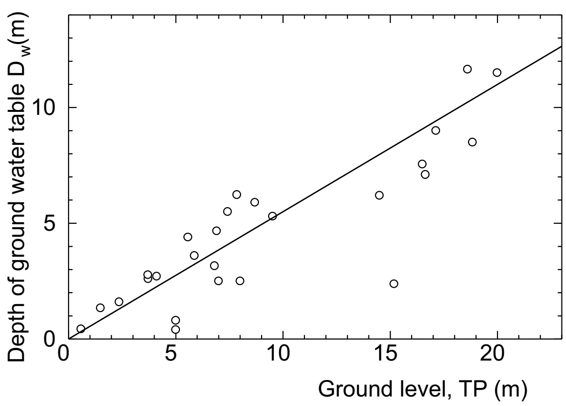

Figure 3. Relationship between the ground surface elevation and depth of the groundwater table.

Within the area shown in Figure 2, the damage was particularly severe in the Nishi-Araya district of Uchinada Town. A cross section (X-X' line in Figure 2) of the sand dunes passing through this district is shown in Figure 4. Liquefaction and ground flow occurred in the zone indicated as the liquefied zone in the figure. Figure 5 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. A cross section along the 2-2' survey line in Figure 5 is shown in Figure 6 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 3. 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.

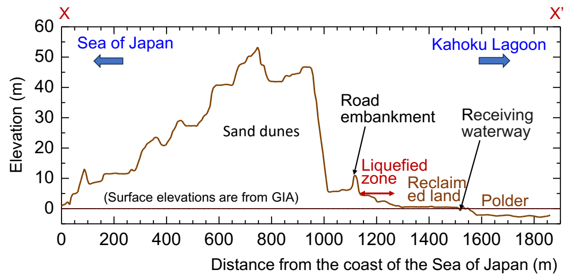

Figure 4. Cross section of the sand dunes in the Nishi-Araya district.

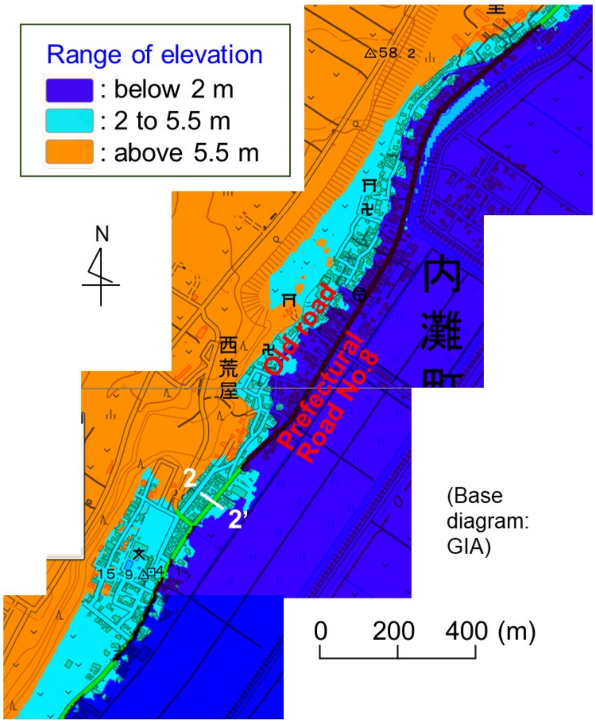

Figure 5. Topographical map from the Nishi-Araya district to the Muro district.

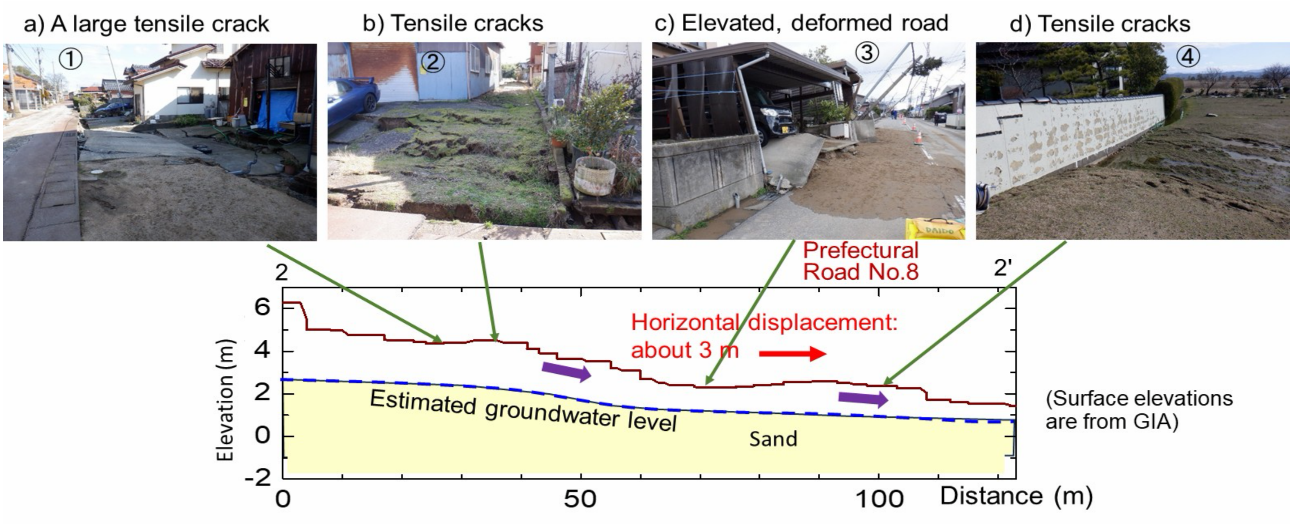

Figure 6 . Cross section along the 2-2' survey line in Figure 5 and photos of damage along this cross section

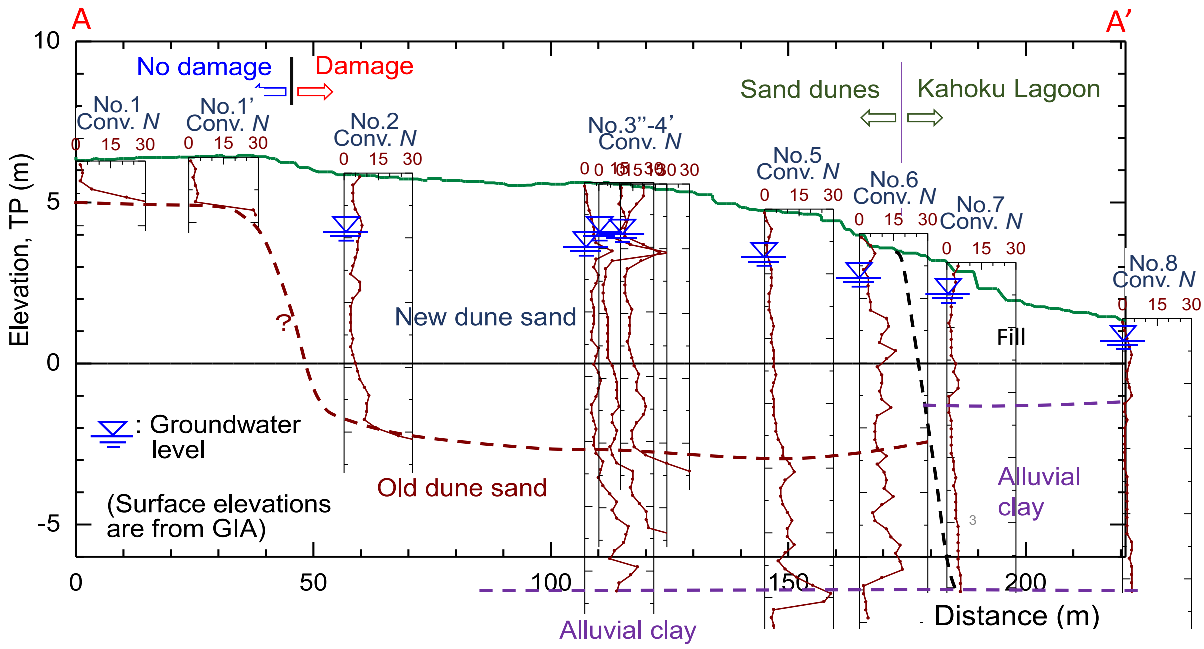

Figure 7. Cross section along the A-A' survey line in Figure 2 estimated by SWS in the Ohsaki district.

In Uchinada Town, many areas have gently sloping ground because the sand dunes were cut and the sand was used for land reclamation projects. 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. A horizontal displacement of 2 to 3 m occurred in this area. Damage similar to that shown in Figure 6 occurred widely from Kahoku City to Kanazawa City.

3 ESTIMATION OF A CROSS-SECTION FROM SOIL INVESTIGATIONS AND PATTERNING OF THE DAMAGE TO LOW-RISE HOUSES CAUSED BY GROUND FLOW

In order to investigate the ground conditions in the areas where liquefaction and ground flow occurred, Screw Weight Soundings (SWS) and microtremor array observations were conducted along the A-A' line shown in Figure 2, in Osaki, Kahoku City (Ishikawa et al., 2024). In SWS, not only the penetration resistance but also the groundwater level was measured, and soil samples were collected. The *W*sw and *N*sw obtained by SWS were converted to SPT *N*-values using the following Inada's formula (1960) for sandy soils.

$$N = 2 \times W_{sw} + 0.067 \times N_{sw} \quad (1)$$

where *W*sw is the weight (kN) and *N*sw is the number of half turns.

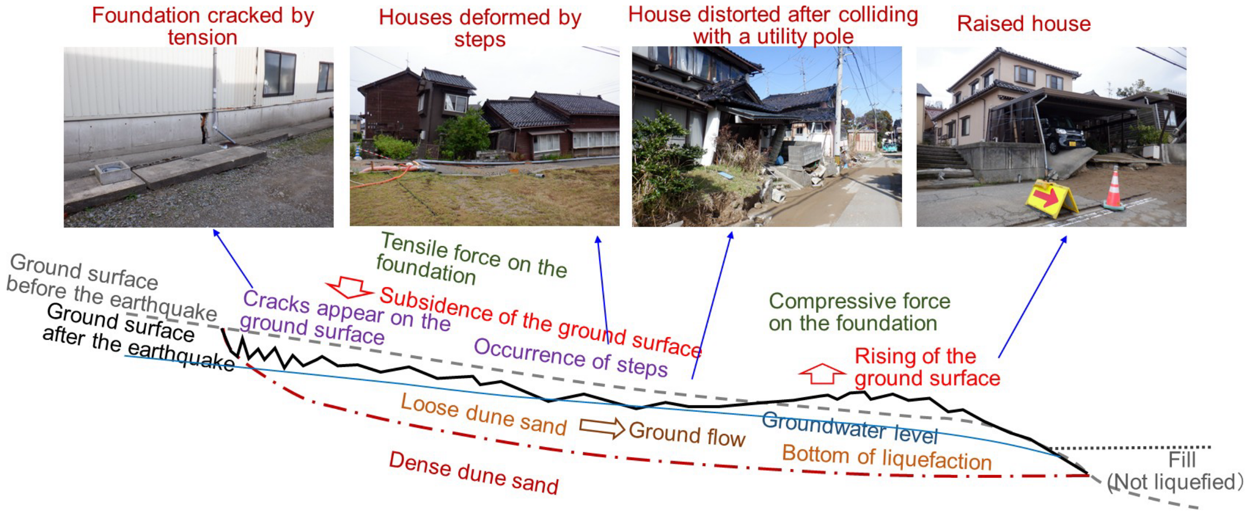

Figure 8. Patterns of ground deformation and damage to houses caused by liquefaction-induced ground flow.

The cross section estimated from the soil investigations is shown in Figure 7. This reveals the following:

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

Based on the above survey results, Figure 8 shows the patterns of ground deformation caused by liquefaction-indued ground flow and the resulting damage to houses. As shown in this figure, houses not only settled and tilted due to liquefaction, but were also pushed and pulled horizontally, and even thrust upward, causing severe distortion and resulting in serious damage.

4 RECOVERY OF RESIDENTIAL AREAS AFFECTED BY LIQUEFACTION-INDUCED GROUND FLOW

Land that has liquefied in an earthquake is at high risk of re-liquefying in future earthquakes and suffering damage again. Therefore, after an earthquake, urban areas affected by liquefaction must be treated in two ways: i) they are not used as residential areas, or ii) they continue to be used as residential areas while taking measures. As an example of the former, in Adapazari, Turkey, which suffered severe damage from liquefaction and shaking during the 1999 Kocaeli Earthquake, plans were being considered to relocate the entire city to a neighboring area. However, they were not carried out. On the other hand, in Christchurch, New Zealand, which has been hit by frequent earthquakes since 2010 and has experienced liquefaction several times, mass relocations of areas affected by liquefaction have actually been carried out.

Proposals have been made for collective relocation in urban areas affected by liquefaction in the Noto Peninsula Earthquake, but Japan's high population density means it is difficult to find land for relocation. Investigations are currently underway into the possibility of continuing to use the site as residential land while taking measures against liquefaction. In these cases, there are two options: i) demolishing the damaged houses and clearing the land, and then building new houses on ground that has been treated for liquefaction prevention, or ii) using jacks to lift up damaged houses that have settled and tilted and leveling them out, and then taking measures against liquefaction for the entire area. One example of the second option is the Yamamoto housing complex in Kashiwazaki City, which was affected by the 2007 Niigataken Chuetsu-oki Earthquake, where measures were taken to lower the groundwater level by installing underground drainage pipes. During the recovery efforts following the Tohoku Earthquake in 2011, drainage pipes were laid in six cities as a measure to lower the groundwater level to approximately 3 m below the ground surface (Yasuda and Hashimoto, 2016). Since then, measures have been taken to lower groundwater levels during recovery efforts following the 2016 Kumamoto Earthquake and the 2018 Hokkaido Iburi-tohbu Earthquake.

Therefore, in the recovery efforts following the Noto Peninsula Earthquake, the second option is being considered in several cities. However, in some areas where houses have suffered serious damage from ground flow, as shown in Figure 8, and most of the houses have been demolished, measures such as ground densification by the first option are also being considered. In the Awasaki district of Kanazawa City, the southernmost part of the Uchinada Sand Dunes shown in Figure 2, plans are underway to lower the groundwater level by installing underground drainage pipes, as shown in Figure 9 (1) (Kanazawa City). This figure is a plan view, but an example of a cross-section across the sand dunes is shown in Figure 9 (2). A three-dimensional seepage analysis was conducted under the condition that a drainage pipe was installed approximately 4 m beneath the road, and it was estimated that the groundwater level would drop on both the upstream and downstream sides of the sand dunes.

However, even if lowering the groundwater level in this way prevents houses from settling or tilting, it is unclear whether it will also prevent ground flow. Then, for the cross section in Figure 7, the authors analyzed the possibility that the lowering the groundwater level would reduce the amount of ground flow, using the residual deformation analysis method we developed named ALID (Yasuda et al., 2017). In the analysis, the maximum surface acceleration was assumed to be 200 cm/s^2 based on nearby earthquake records, and the groundwater level was analyzed in two cases: one set based on the results of the SWS survey, and one in which the groundwater level is lowered. In the former, the difference in groundwater levels between the upstream and downstream is 3.2 m, while in the latter, assuming that the groundwater level will be significantly lowered at the upstream road, the gradient

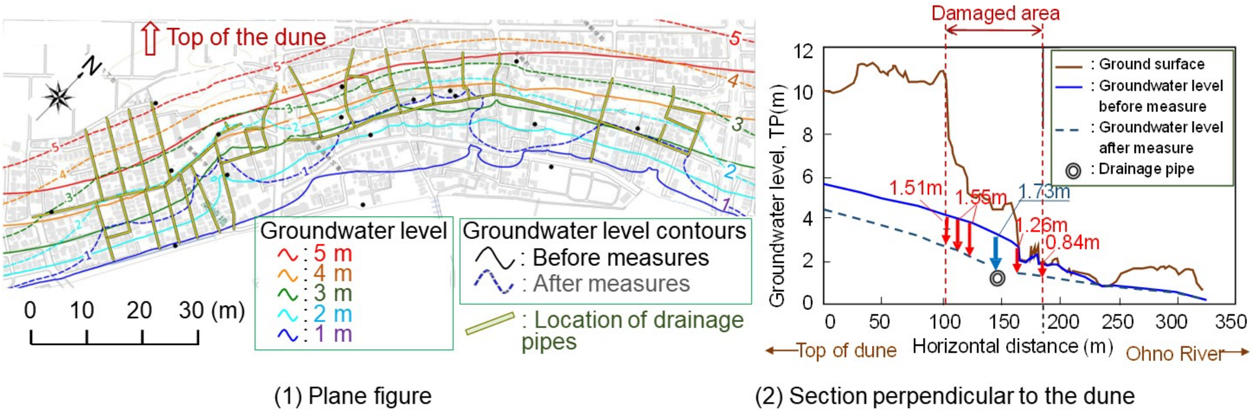

Figure 9. Drainage pipe layout plan in Kanazawa City and estimated results of resulting drawdown of groundwater level.

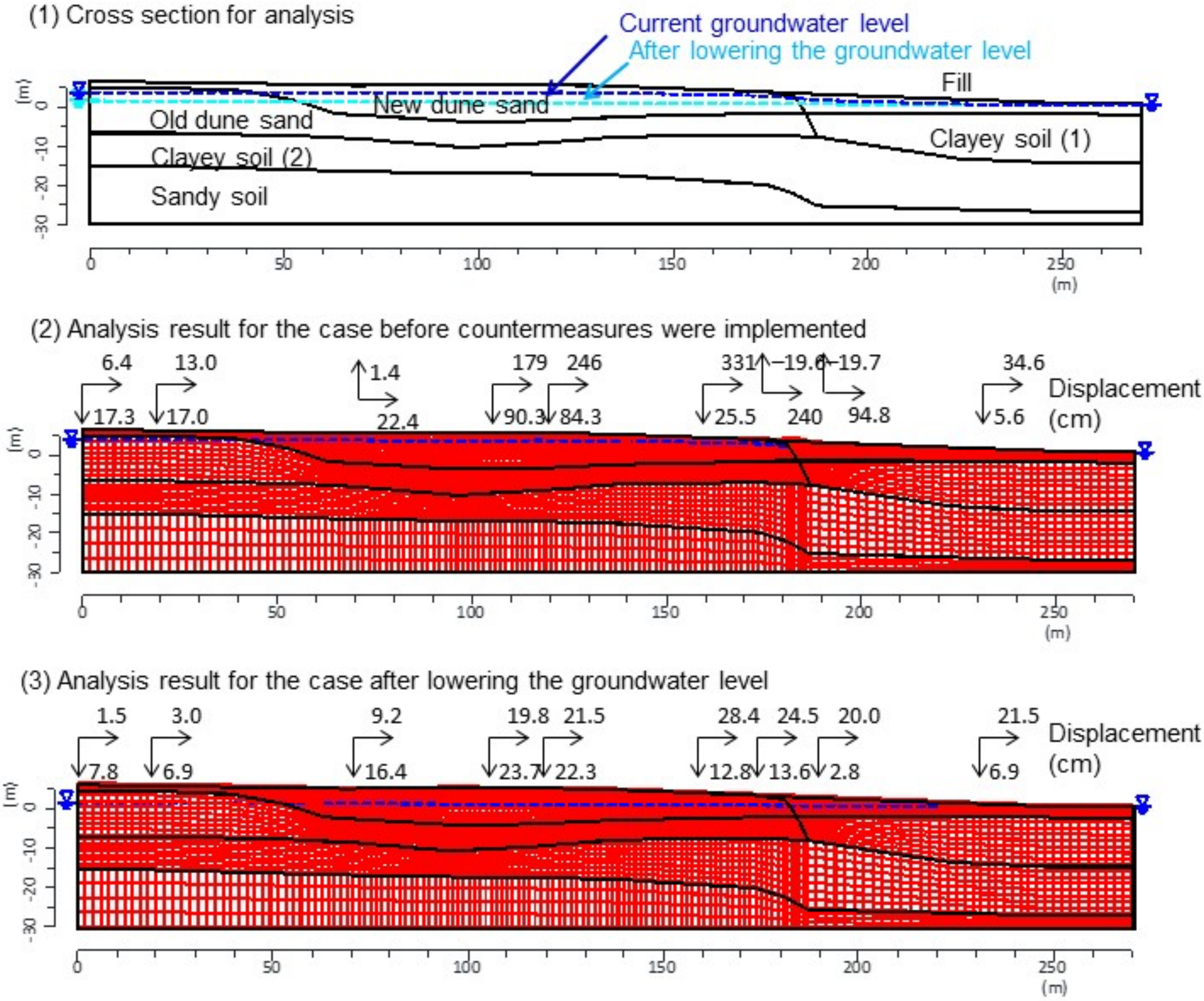

Figure 10. Analysis results of the effect of groundwater level lowering on flow displacement suppression at the Ohsaki 2-2' line.

is assumed to be 1/200, resulting in a difference in groundwater levels between the upstream and downstream of 1.15 m. The analysis procedure was as follows: i) the shear stiffness of each mesh of the ground was estimated from the converted *N*-value, and this was used to perform initial stress analysis using the static finite element method; ii) the converted *N*-value and fines content were used to determine the distribution of safety factor against liquefaction (F_L) using the method in the Japan's Highway Bridge Specifications; iii) analysis was performed again using the static finite element method using the shear stiffness reduced according to F_L to determine the amount of deformation caused by liquefaction. As a result of the analysis, as shown in Figure 10, in the case before countermeasures were implemented, the horizontal displacement was 1.8 m to 3.3 m, whereas in the case where the groundwater level was lowered, this was reduced to a maximum of 0.1 m to 0.3 m, demonstrating that the countermeasures were effective. The horizontal displacement that occurred in this area during the Noto Peninsula Earthquake is estimated to have been 2 to 3 m, which is consistent with the analysis results before countermeasures were implemented.

Among the cities affected by the Noto Peninsula earthquake, Kanazawa City has been making the most progress in considering countermeasures. The countermeasures policy shown in Figure 9 has been decided, and field demonstration experiments are currently being carried out. Based on this, construction work on countermeasures is scheduled to begin approximately two years after the quake occurred.

5 CONCLUSIONS

The authors investigated the damage resulting from liquefaction and flow on gently sloping ground due to the Noto Peninsula Earthquake that occurred in Japan in 2024, and explained the current recovery efforts while taking measures. The conclusions reached are as follows:

(1) Liquefaction occurred in a narrow area on the inland margins of two sand dunes. In addition, ground flow occurred with a maximum horizontal displacement of 3 m, causing the upstream side to subside and the downstream side to rise.

(2) In areas where ground flow occurred, low-rise houses not only settled and tilted, but were also pushed and pulled horizontally, and even thrust upward, causing the houses to suffer severe damage and large distortions.

(3) It is estimated that approximately 17,000 low-rise houses have been damaged by liquefaction, and as a countermeasure, it is planned to lower the groundwater level throughout the city to approximately 3 m below the ground surface. A residual deformation analysis showed that this level of groundwater level drop not only prevents settling and tilting of houses, but also reduces the amount of flow displacement in gently sloping ground. Therefore, for gently sloping ground or ground behind sea walls where liquefaction-induced ground flow can cause large horizontal displacement, it is desirable to carry out such analyses to quantitatively analyze the impact of the ground flow on structures and take measures. It is also necessary to develop countermeasures against liquefaction-induced ground flow other than the lowering of groundwater levels.

6 ACKNOWLEDGEMENT

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7 REFERENCES

GIA (Geospatial Information Authority of Japan: GSI Maps. https://maps.gsi.go.jp/#15/38.045742/140.912683/&base=english&ls=english&disp=1&vs=c1g1j0h0k0l0u0t0z0r0s0m0f0&d=m

Hamada, M., Yasuda, S., Isoyama, R. and Emoto, K.: Observation of permanent ground displacements induced by soil liquefaction, *Japanese Journal of JSCE*, No. 376/III-6, pp.211-220, 1986. (in Japanese)

Inada, M.: Use of Swedish Sounding Test Results, *Tsuchi to Kiso*, JGS, pp. 13-18, 1960. (in Japanese)

Ishihara, K.: Stability of natural deposits during earthquakes, *Proc. of the 11th ICSMFE*, Vol.1, pp.321-376, 1985.

Ishikawa, K., Yasuda, S., Kasahara, S. and Senna, S.: Analysis of liquefaction-induced flow characteristics along the Uchinada sand dues caused by the 2024 Noto Peninsula Earthquake, *Japanese Journal of JSCE, Special Issue (Earthquake Engineering)*, 2024. (in Japanese, in press)

Kanazawa City: Materials for a technical meeting to study restoration techniques for areas affected by the Noto Peninsula Earthquake, 2025. (in Japanese) https://www4.city.kanazawa.lg.jp/soshikikarasagasu/kikikanrika/gyomuannai/2/27002.html

NGiC (National Geo - Information Center): National Land Information Database. (in Japanese) https://ngic.or.jp/

Yasuda, S. and Hashimoto, T: New project to prevent liquefaction-induced damage in a wide existing residential area by lowering the ground water table, *Soil Dynamics and Earthquake Engineering*, 91, pp.246–259, 2016.

Yasuda, S., Yoshida, N., Adachi, K., Kiku, H. and Ishikawa, K.: Simplified evaluation method of liquefaction-induced residual displacement, *Journal of Japan Association for Earthquake Engineering*, Vol.17, No.6, pp.1-20, 2017.