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Effectiveness of Surface Gravel Replacement for Liquefaction Damage Mitigation at Soma LNG Terminal during 2022 Fukushima Earthquake

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ABSTRACT

The replacement of ground surface material with gravel is a possible method of mitigating damage caused by liquefaction. It was developed after the 2011 Tohoku Earthquake. The concept is to quickly discharge excess porewater pressure caused by liquefaction through gravel drains installed just below the surface, thereby preventing sand boiling and resulting uneven settlement. However, since the method was developed, its effectiveness in actual large earthquakes could not be confirmed until two later earthquakes occurred. These were the similar M7.3 and M7.4 earthquakes with epicenters off the coast of Fukushima Prefecture that occurred in succession in 2021 and 2022. Following liquefaction damage at the Soma LNG Terminal during the 2021 earthquake, mitigation work using this new method was begun. The 2022 earthquake occurred as the work was in progress. In this paper, liquefaction damage caused by the two similar earthquakes is compared, leading to two main conclusions. First, regarding on-site roads, the work effectively suppressed sand boiling at pavement interfaces. Second, regarding piping foundations, the work had the effect of suppressing sand boiling in the vicinity of the foundations and preventing uneven settlement.

Keywords: Liquefaction, Gravel drain, Sand boiling, Landfill ground, Off-the-Coast-of-Fukushima earthquake

BACKGROUND

The 2011 Off the Pacific Coast of Tohoku Earthquake caused severe liquefaction damage to detached houses, structural foundations and roads that had not been provided with protection against liquefaction. To reduce this problem in future earthquakes, we have developed a technique known as surface gravel replacement [1] that can significantly reduce liquefaction damage to structures such as roads and foundations for on-site equipment (Figure 1) for which conventional liquefaction countermeasures are not cost-effective. The method entails constructing drainage channels filled with fine-grained crushed stone at surface level where sand boiling is expected. These prevent sand boiling by discharging the water component to the surface, thereby significantly reducing uneven settlement of foundations due to liquefaction [1], [2].

In 2021 and 2022, earthquakes exceeding M7 occurred with epicenters off the coast of Fukushima Prefecture. Following the 2021 earthquake, the Soma LNG Terminal implemented surface gravel replacement in areas where sand boiling and uneven foundation settlement had occurred. In this paper, we report on liquefaction damage observed after both the 2021 and 2022 earthquakes, focusing on the mitigation effect of the newly developed method.

RESEARCH SITE AND GROUND MOTIONS

Outline of site

The Soma LNG Terminal is an L-shaped site with the longer (western) section situated on an old landfill (completed around 2000) and the shorter arm on a new landfill to the east (completed in 2016). Figure 2(a) is an aerial photograph of the site taken before reclamation of the eastern section began. The area investigated in this paper is the old landfill under the western section of the terminal.

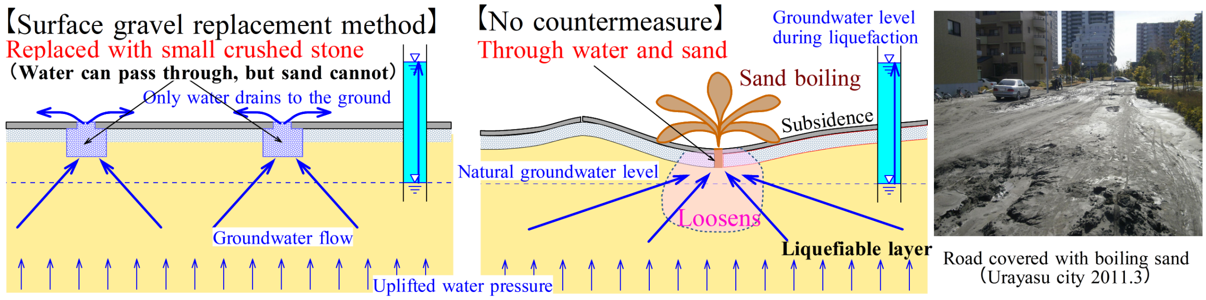
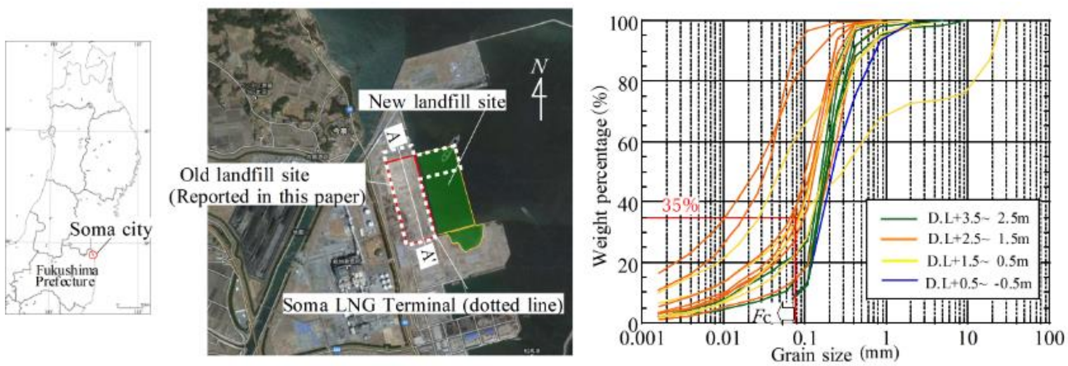


Figure 1. Concept of surface gravel replacement



(a) Aerial photo before new reclamation on the east side (b) Grain size distribution curves for Fs layer of western landfill
Figure 2. Aerial photo of site and grain size distribution curves for Fs layer [3]

Figure 3 shows a north-south cross section through the old reclaimed ground (marked as cross section A-A' in Figure 2(a)). The upper layer of the reclaimed soil consists of sandy soil (F_s) and the lower layer is cohesive soil (F_c), for a total thickness of about 10 m. Below the reclaimed soil, there is a dense sand layer with a high N value (A_{s1}), a clay layer with a small N value (A_{c2}), a sand layer (A_{s2}) and a hard Neogene Pliocene Yamashita layer (T_{ms}). The groundwater level was about D.L+2.7m to +3.2m, which was confirmed by the ground survey and during installation of gravel for the pipe foundation group. Liquefaction is thought to have occurred in the F_s layer deposited near the surface of the landfill.

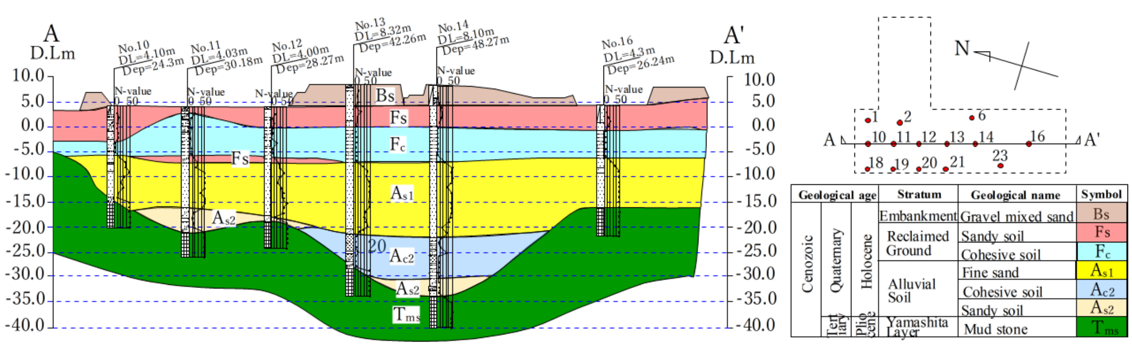


Figure 3. Geological section of the construction site

Figure 2(b) shows sample grain size distribution curves for the F_s layer in the western landfill. Many of the samples have a fine particle content F_c of around 35 %. Liquefaction is assumed to occur at locations where the fine particle content is less than 35 %. In fact, during the 2021 and 2022 earthquakes, sand boiling occurred only in certain area of the reclaimed land. According to the Architectural Institute of Japan's "Guidelines for Designing Building Foundation Structures (2019)", slight liquefaction is predicted in an earthquake with a maximum horizontal surface ground acceleration α_{max} = 350 cm/s^2 and an earthquake magnitude M=7.5. For this reason, no liquefaction measures were taken for structures such as roads and pipe foundations prior to the 2021 earthquake.

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Comparison of ground motions in 2021 and 2022 earthquakes

The 2021 and 2022 earthquakes were similar, both having epicenters off the coast of Fukushima Prefecture. The 2021 earthquake occurred at 23:07 on 2021/2/13 with Magnitude 7.3 and seismic intensity 6 lower at Soma City. Then the 2022 earthquake occurred at 23:36 on 2022/3/16 with Magnitude 7.3 and seismic intensity 6 upper at Soma City. As shown in Figure 4, the epicenters of two earthquakes were nearby at about 67 km distance from Soma LNG Terminal.

Table 1 and Figure 5 show the seismic motion data observed at the K-NET Soma site of the National Research Institute for Earth Science and Disaster Resilience during the 2021 and 2022 earthquakes. K-NET Soma is located about 4 km southwest of the Soma LNG Terminal (Figure 4). The maximum acceleration in the 2022 earthquake was 728 cm/s^2 and the maximum velocity was 73 cm/s for the EW component, and the magnitude was 7.4 (Table 1). This is comparable with the 2021 earthquake, where the magnitude and duration of the seismic motion were almost the same, but the EW component was 1.3 times larger in maximum acceleration and 1.9 times larger in maximum velocity.

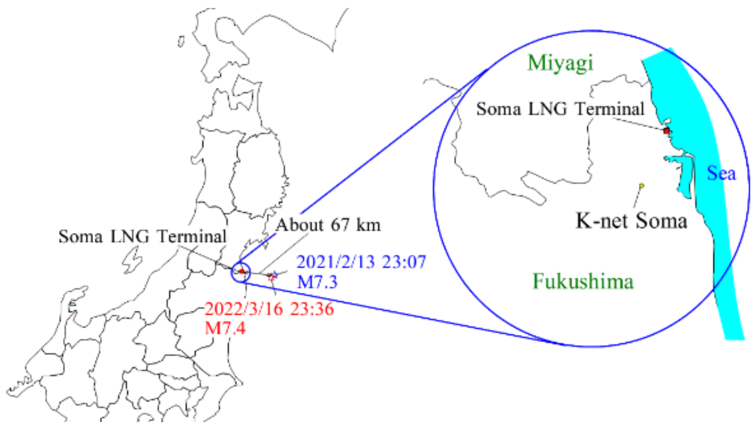

Figure 4. Epicenters of 2021 and 2022 earthquakes and location of Soma LNG Terminal

Table 1. Seismic motion in 2021 and 2022 earthquakes

Earthquake Occurrence	Maximum Acceleration【cm/s/s】			Maximum Velocity【cm/s】			Magnitude	Seismic Intensity at Soma city
	NS	EW	UD	NS	EW	UD		
2021/2/13 23:07	586	555	507	43	38	15	7.3	6 lower
2022/3/16 23:36	566	728	618	28	73	25	7.4	6 upper

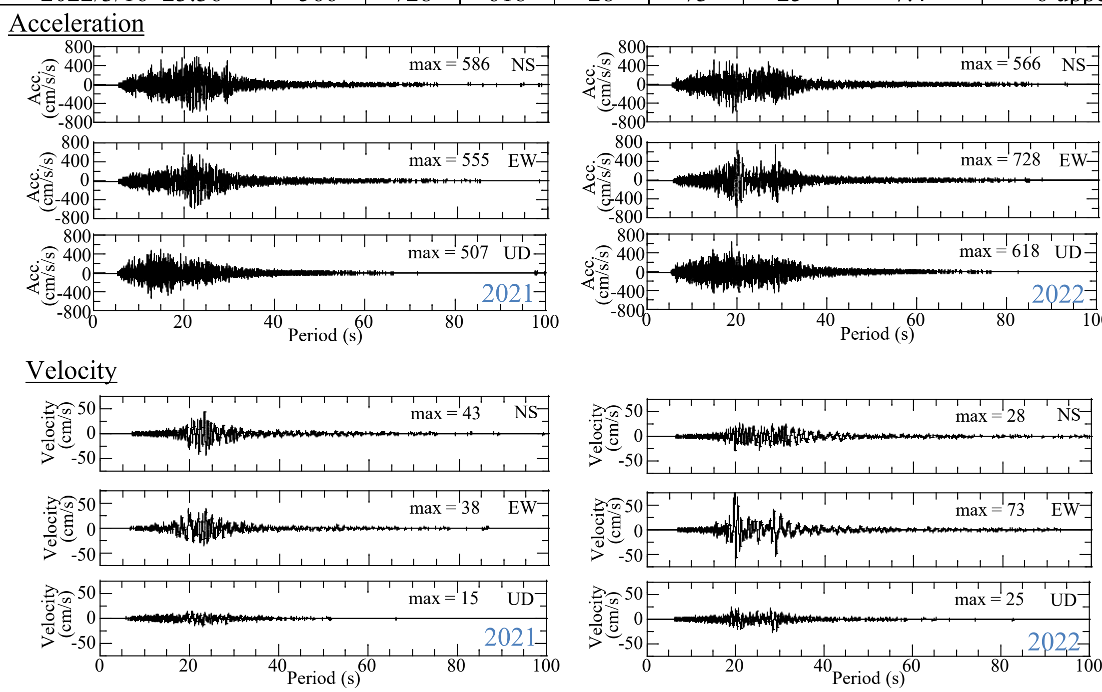

Figure 5. Acceleration and velocity waveforms observed at K-NET Soma in 2021 and 2022 earthquakes

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IMPLEMENTATION OF SURAFACE GRAVEL REPLACEMENT AND ITS EFFECT

On site roads

Investigation of sand boiling and design of countermeasures

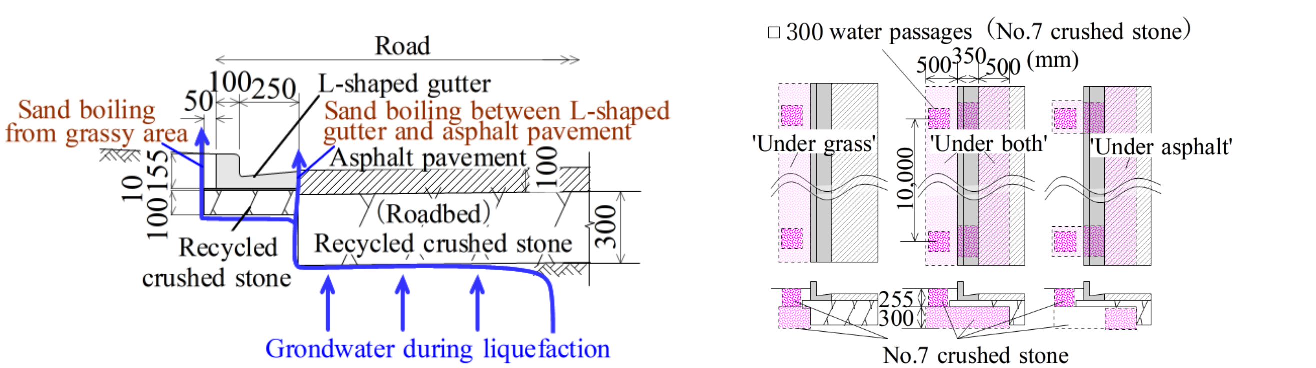
The 2021 earthquake caused sand boiling in some areas of the landfill, but not all. The assumed reason for the localized sand boiling is that the reclaimed soil layer has varying fine particle content and only liquified where the content was low. Due to liquefaction, subsidence of pipe foundations was observed in many places.

Looking at the on-site roads, sand boiling occurred at the gap between L-shaped gutters and asphalt pavement as shown in Picture 1(a), with sand in some places also extending onto the grassy area beyond the L-shaped gutter as in Picture 1(b).

(a) Sand boiling from interface between L-shaped gutters and asphalt pavement *(b) Sand boiling from grass beyond L-shaped gutter*

Picture 1. Sand boiling along on-site roads

Figure 6(a) explains the assumed mechanism of sand boiling in this situation. In the post-liquefaction process, groundwater rises up and forces whole areas of road upward, spewing out at the edge of the road where the crushed-stone roadbed is thinner and avoiding the thicker roadbed under the asphalt pavement. This phenomenon was also observed in the 2011 Off the Pacific Coast of Tohoku Earthquake [4]. Based on this understanding, we assumed that countermeasures based on improvement with cement would simply induce sand boiling at other locations where countermeasures were not implemented. Instead, we implemented surface gravel replacement in three patterns as shown in Figure 6(b) depending on where the sand boiling occurred in the 2021 earthquake. The 'Under grass' pattern was to prevent sand boiling from grassy areas. 'Under asphalt' was to prevent sand boiling between L-shaped gutters and asphalt pavement. 'Under both' was to prevent both. In each case, a layer of No. 7 crushed stone (crushed stone with grain size adjusted from 2 to 5mm) with a thickness of 0.3m was laid along the axis of the road and water conduits leading to the ground surface in the grassy area were constructed at a pitch of 10m. By discharging the rising groundwater alone to the surface, these structures should prevent sand boiling.



(a) Assumed mechanism of sand boiling *(b) Three patterns of surface gravel replacement implementation*

Figure 6. Mechanism of sand boiling and measures for the road

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The three patterns of surface gravel replacement were used at the positions shown in Figure 7. The effect of these liquefaction countermeasures is described in the following based on photographic observations.

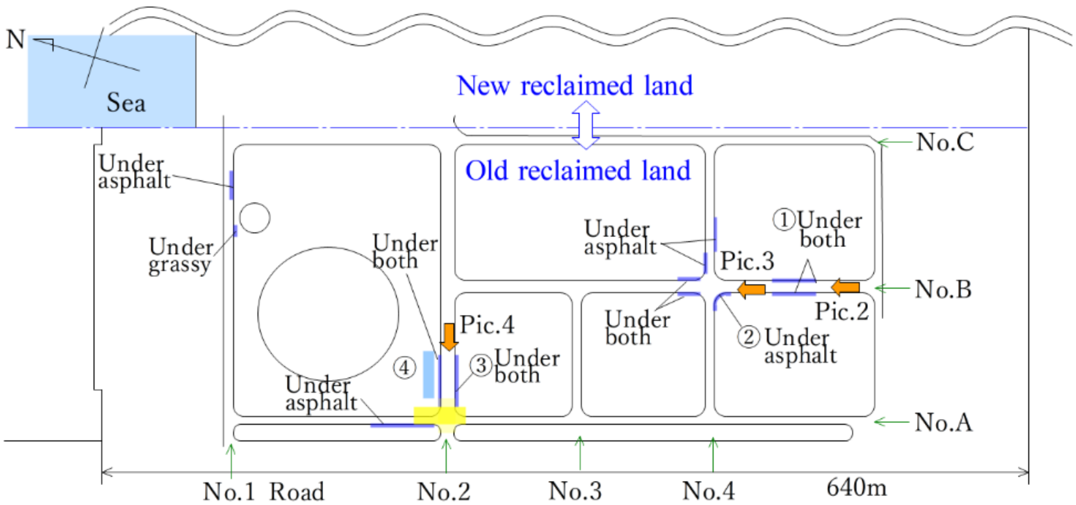

Figure 7. Locations of surface gravel replacement

Effects of surface gravel replacement countermeasures against 2022 earthquake

Both sides of Road B (*Figure 7①: 'Under both' type*)

After the 2021 earthquake, cracks and unevenness were observed in the L-shaped gutters and the pavement surface, and there was evidence of sand boiling from the interface between the L-shaped gutters and the asphalt pavement. The white circled areas in Picture 2(a) indicate cracks caused by the strong seismic motion. Differences in motion amplitude between the liquefied and non-liquefied parts would influence the occurrence of cracks in the road. On the other hand, after the 2022 earthquake, no significant unevenness was observed in the L-shaped gutters nor did sand boil from the interface between the L-shaped gutters and the asphalt pavement. Note that the 2022 earthquake occurred before the asphalt pavement was restored, as shown in Picture 2(b).

(a) After 2021 earthquake *(b) After 2022 earthquake*

Picture 2. Road B (Figure 7①: 'Under both' type)

Intersection of Road B and Road 4 (*Figure 7②: 'Under asphalt' type*)

During the 2021 earthquake, sand boiling occurred at the interface between the L-shaped gutters and the asphalt pavement. In the 2022 earthquake, there was no sand boiling from the interface or damage to the L-shaped gutters. Sand boiling did

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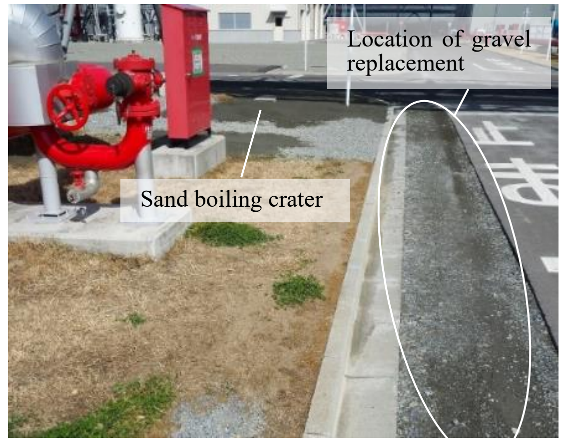
occur on an unprotected grassy area about 2-3m away from the road intersection. The 2021 earthquake did not cause this sand to boil, so no measure was taken in this area. It would have been caused by the stronger motion of the 2022 earthquake.

(a) After 2021 earthquake

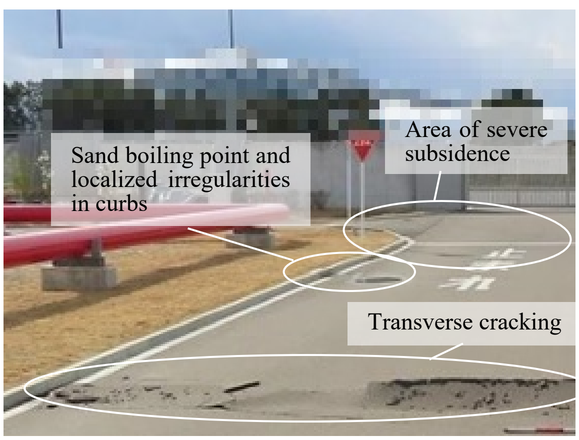


(b) After 2022 earthquake

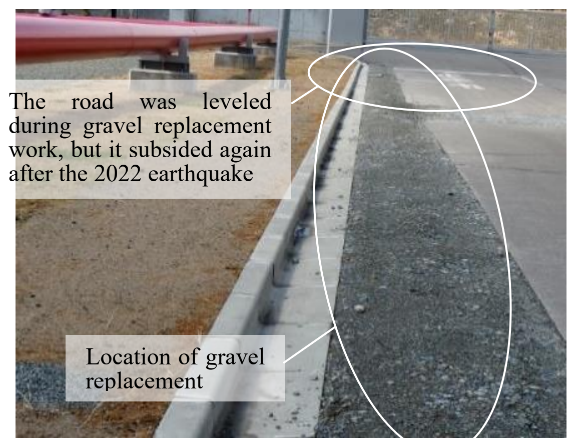
Picture 3. Intersection of Road B and Road 4 (*Figure 7②: 'Under asphalt' type*)

Road 2 (*Figure 7③: 'Under both' type*)

After the 2021 earthquake, there was evidence of cracks in the asphalt pavement, a sand boiling crater and depressions in the asphalt pavement, and irregularities in the L-shaped gutters. The area in the background of the picture (shaded yellow in Figure 7) suffered severe overall subsidence while the L-shaped gutters and road surface also subsided slightly in response. Although the L-shaped gutters were made level during the replacement work, overall mild subsidence happened again in the 2022 earthquake. This type of mild settlement would be caused by relatively heavy liquefaction in this area. The severity of liquefaction depends on exact location, because the soil type and fine content of reclaimed land varies.



(a) After 2021 earthquake



(b) After 2022 earthquake

Picture 4. Road 2 (*Figure 7③: 'Under both' type*)

The overall effects of using surface gravel replacement along these on-site roads are summarized below.

- No sand boiling occurred at the interface between L-shaped gutters and asphalt pavement in the 2022 earthquake, although it was seen in the 2021 earthquake. Application of this new method had a significant effect in terms of suppressing sand boiling.
- The 2022 earthquake caused no damage to the asphalt pavement and no irregularities were observed in the L-shaped gutters. On the other hand, in the 2021 earthquake, the asphalt pavement cracked in locations with severe liquefaction damage.
- Even with the countermeasures, there were places where overall mild settlement occurred in the 2022 earthquake, as shown in Picture 4. This new method allows liquefaction to occur, so this type of gradual settlement may be unavoidable. But it reduces damage caused by liquefaction, such as sand boiling and severe localized uneven settlement.

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Pipework foundations

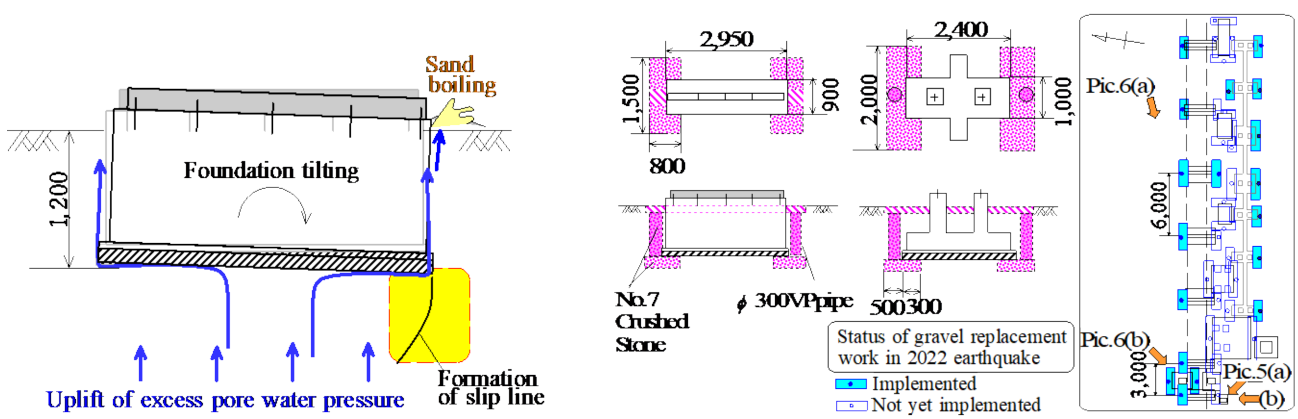
Investigation of the cause of foundation damage and countermeasures

At position ④ in Figure 7, there is a group of foundation structures that support various pipework. Sand boiling occurred in this vicinity in the 2021 earthquake. Picture 5 shows one pipe foundation that tilted in the direction of the nearby sand boiling adjacent to the foundation.

(a) Sand boiling adjacent to foundation *(b) Uneven settlement of foundation with adjacent sand boiling*

Picture 5. Condition of pipework after the 2021 earthquake

Figure 8(a) shows the mechanism by which sand boiling causes uneven foundation settlement. Gaps form around the foundation due to the difference in response between ground and foundation, allowing sand boiling to occur adjacent to the foundation. Uneven settlement leads to tilting of the foundation as the ground is progressively damaged. The tilting phenomenon progresses gradually as ground near the surface continues to liquefy. This gradual tilting occurs during liquefaction over a period of a few minutes to 10 minutes during and after shaking. Loosening of the soil under the edge of the foundation as a result of sand boiling increases the tilting of the foundation [1], [2]. This is what is thought to have occurred with these foundations. This understanding leads to the conclusion that liquefaction damage may be reduced by ensuring the ground remains strong by quickly draining only water and not sand from immediately below the foundation. Based on this conclusion, surface gravel replacement was implemented as shown in Figure 8(b) to achieve this. A 300mm-thick layer of No. 7 crushed stone was laid with a width of 300mm under the foundation and 500mm outside both sides of the foundation. Groundwater is drained to the surface through φ300 pipes filled with No. 7 crushed stone.



(a) Assumed mechanism of sand boiling *(b) Surface gravel replacement implementation*

Figure 8. Mechanism of sand boiling and implementation of surface gravel replacement for pipework foundations

Effects of gravel replacement countermeasures against 2022 earthquake

At the time of the 2022 earthquake, gravel replacement work had already been implemented for some of the foundations. The blue colored areas in Figure 8(b) are the locations where the work had been completed. Picture 6 shows the situation around the foundations after the 2022 earthquake. The sand boiling that occurred around the foundations in the 2021

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earthquake was not seen in the 2022 earthquake. Although gravel replacement work was still in progress at the time, the measures were seen to have a certain effect in suppressing sand boiling around the foundations. Further, in contrast with the 2021 earthquake, there was no noticeable sinking of the foundations or uneven settlement. After the earthquake, No. 7 crushed stone from within the drainage pipes was found spilled over the ground surface. This was observed at almost all the drainage pipes. Because the 2022 earthquake occurred at night and was not directly observed, the flow of groundwater to the ground surface, driven by the excess porewater pressure, is assumed to have flushed some of the crushed stone out of the pipes. This phenomenon can be taken as evidence that the crushed stone layers have fulfilled their function and the installed gravel drain reduced liquefaction damage by dissipating excess porewater pressure promptly.

(a) Group of pipework foundations *(b) Crushed stone ejected from ϕ300mm drainage pipe*

Picture 6. Pipework foundations after 2022 earthquake

CONCLUSIONS

Surface gravel replacement as a countermeasure against liquefaction damage was implemented at the Soma LNG terminal after a 2021 earthquake off the coast of Fukushima. The effects of these measures were investigated after the subsequent 2022 earthquake. The following conclusions were reached:

- Regarding on-site roads, the sand boiling seen at the interface between L-shaped gutters and asphalt pavement in the 2021 earthquake did not occur in 2022 after surface gravel replacement was implemented. In terms of suppressing sand boiling, the effect of these countermeasures was remarkable. There was no evidence of damage to the asphalt pavement or irregularities in the L-shaped gutters, which were observed after the 2021 earthquake and attributed to liquefaction. On the other hand, slight non-uniform settlement was observed in multiple locations; this is thought to result from different degrees of liquefaction in different areas. Although this type of uneven settlement is inevitable when the new method is used, since it does not prevent liquefaction itself, the function of the road was sufficiently maintained.
- Regarding foundations for pipework on the site, the sand boiling that was seen around the foundations after the 2021 earthquake did not occur in the 2022 earthquake. Although gravel replacement work was still in progress at the time of the second earthquake, where completed it had the effect of preventing sand boiling. The 2022 earthquake caused, no noticeable uneven settlement of the foundations. Some crushed stone that had been used to fill the drainage pipes was found to have been flushed to the ground surface under pressure from the upward flow of groundwater during liquefaction. The installed drain reduced foundation damage by dissipating excess porewater pressure promptly.

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