Mitigation of liquefaction disaster by grid-wall soil improvement in Urayasu City, Japan

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Earthquake Geotechnical Engineering

Ichiro Ishii, *Deputy Mayor of Urayasu City, Japan*
Ikuo Towhata, *Collage of Science and Engineering – Kanto Gakuin University, Japan*
Shigeru Sato, *Seismic Technology Center – Pacific Consultants CO.,Ltd., Japan*
Shun-ichi Sawada, *Engineering Division – Oyo Corporation, Japan*
Shoichi Tsukuni, *Technology & Production Development Division – Takenaka Civil Engineering & Construction Co., Ltd,Japan*
Akihiko Uchida, *Ground and Foundation Division – Takenaka Corporation, Japan*
Hiroaki Tezuka, *Civil Engineering Division – Maeda Corporation, Japan*
Takahiro Yamauchi, Civil Engineering Division – Maeda Corporation, Japan

ABSTRACT

This paper addresses one of the on-going soil improvement projects that increase the liquefaction-resilience of urban residential environments after huge seismic disasters in 2011. Those projects are characterized by the combination of public sectors and residents who are concerned with the future liquefaction risk. Urayasu City Government decided to install solid underground walls of square geometry under streets and spaces between houses so that cyclic deformation of liquefaction-prone sand may be reduced and excess pore water pressure may not develop significantly. This particular project consists of three parts. The first part carried out detailed soil investigations in which subsoil was found heterogeneous, having high fines content but being still within the knowledge of existing technology. The second part addressed such specifications as size and depth of grid walls. Because of existing houses at the surface, it was impossible to install grid walls with a traditionally-employed narrow spacing. This problem was overcome by centrifuge model tests and numerical analyses that indicated the additional reinforcing effects of the surface unliquefiable soil crust that had not been considered before. The third part made a practical design of underground walls, necessary technical developments, construction plans and cost estimates. Small machines were developed to fit into narrow spaces between houses. Field verification was performed for those machines. Construction plan was elaborated to offer acceptable cost to people. After all of these, efforts were made to reach the agreement between public sectors and residents who are liable to financial contributions to this project

1 PREFACE

A liquefaction disaster occurred in the recent reclamation areas at the time of the 2011 Tohoku earthquake in Japan. Unfortunately, mitigation technologies of the liquefaction disaster were not enough for private residential area and underground lifelines.

Low-rise houses which were constructed on a shallow foundation suffered differential settlement and tilting (Fig. 1) due to liquefaction. Underground lifelines and particularly the sewage pipes stopped service due to uplifting of the manhole, the breakage of pipes, and inflow of liquefied sand, and the normal urban life fell into great confusion. Damaged buildings and low-rise houses were more than 9,000 in number in Urayasu City. In Japan where earthquakes occur frequently, it is significant for existing residential areas to reduce liquefaction damage in order to maintain safety of communities.

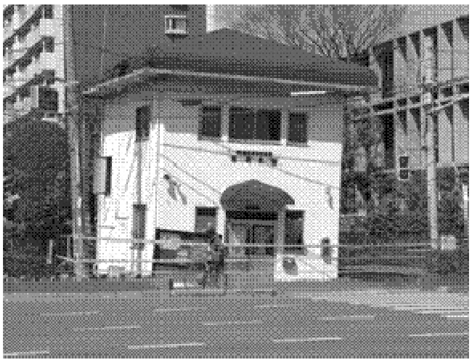

Figure 1. Building with shallow foundation tilted due to liquefaction

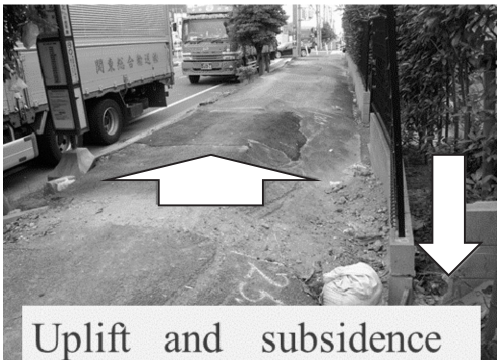

Figure 2. Example of the deformation of the road due to the liquefaction and subsidence of private land.

In this report, the authors introduce the integrated liquefaction mitigation which is composed of soil improvement under existing roads and private residences. This project is now on-going in Urayasu City under the frame work of “A system of liquefaction mitigation in urban area” by Japanese Government for revival from earthquake disaster.

2 LIQUEFACTION DISASTER REDUCTION PROJECT IN URAYASU CITY AND THE METHOD OF UNDER GROUND WALL CONSTRUCTION

“A system of liquefaction mitigation in urban area” that was launched by the Japanese Government founded after the 2011 Tohoku earthquake combines liquefaction mitigation for public facilities such as roads and sewages with private facilities like residential area. It is noteworthy that it is funded partly by the National Government liquefaction mitigation for private residential area.

In order to prevent the damage of roads (public facility) and underground lifelines in a big reclamation island, it is not sufficient to provide soil improvement to each facilities because roads deform easily due to liquefaction in private residential area adjacent to public road (Fig.2). It is necessary to reinforce the entire reclamation land including private residential area integrally by utilizing the system mentioned above.

It is important to carry out the soil improvement in a huge area integrally under the leadership of Government were the followings are essential;

- Need for the agreement of the private owner
- To apply the soil improvement method which is already verified effective for wide area
- To select the soil improvement method which is able to construct without removal of existing houses

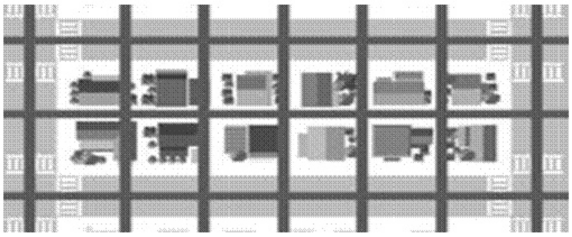

Figure 3. A plan for grid-wall soil improvement for roads and existing residential houses.

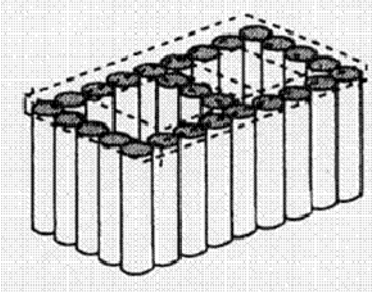

Figure 4. Concept of grid-wall soil improvement.

The grid-wall soil improvement method was adopted as the project of Urayasu City by from viewpoints. The grid-wall soil improvement method inhibits a liquefaction by suppressing the shear deformation of soil during earthquake by soil improvement wall (Fig.3). The grid-wall is made of cement mixing which is made of overlapped independent columns constructed by mechanically mixing or high pressure injection method (Fig.4).

3 CHARACTERISTICS OF SOIL IN URAYASU CITY

Urayasu City is located in the innermost part of Tokyo Bay. This area is the mouth of the former Tone River and Edo River flowing down the Kantou plain. The sediment from the rivers deposits in Urayasu City area to produce thick Alluvial clay and Pleistocene. At the surface of these soil layers is a reclaimed sandy material constructed by sea-bed dredging (Fig.5) .

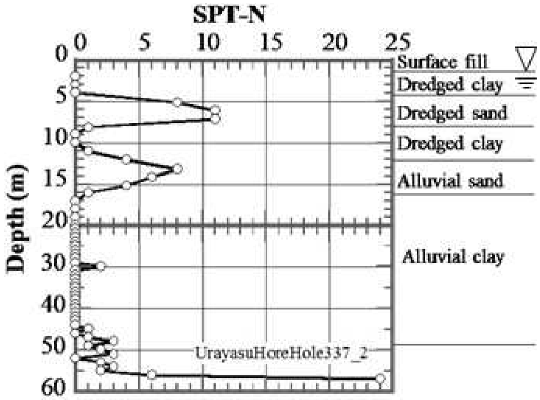

Figure 5. Example of boreholes in liquefaction damage area in Urayasu City

The liquefaction damage in Urayasu occurred mainly in this reclaimed sand layer. Reclamation work of Urayasu City started in 1960’s and was completed in 1980. The consolidation settlement in thick Alluvial layer continued even in 1990’s. This made it difficult to adopt ground water lowering as one of the liquefaction mitigation become further subsidence due to the ground water lowering was feared.

Prior to the implementation of soil improvement project, Urayasu City organized residents meeting through the resident’s associations. Consequently, residents’ organization for project examination was established in 22 districts.

The total number of meetings with residents and the city government exceeded 200. These meetings were held to discuss to initiate working on soil conditions, detailed designs of soil improvement and cost evaluation in 20 districts having 4103 residential lots. It was thus aimed to help residents make the final decision whether or not to join the soil improvement project.

The soil investigation consisted of dynamic cone penetration tests at 360 sites with boring investigation, soil sampling, and liquefaction test at 119 points in addition to the examination of the existing soil investigation data in the city. According to the investigation, it was found that the thickness of reclaimed sandy layer varies from place to place because of the sand bar and channels of sea currents prior to the reclamation. The distribution of grain size also changes depending on the distance of discharge point during reclamation (Fig.6). On such heterogeneous ground, it is essential for the design of liquefaction measures to be site specific.

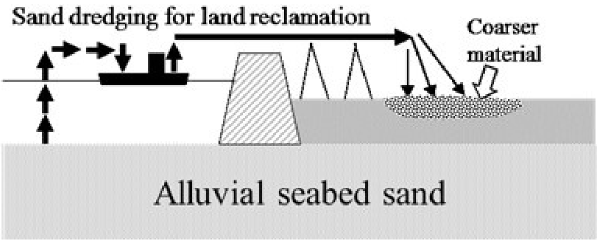

Figure 6. Effect of the discharge point and size on reclamation material (the longer distance, the smaller particle)

The dredged sand included non-plastic fines more than 50%. The existing liquefaction risk evaluation method does not take into account such high fines content (*F*c). In order to verify the effectiveness of existing evaluation methods, we compared the experimental result of liquefaction resistance force of undisturbed samples with estimated values (using SPT-N and F_C) based on the Recommendations for Design of Building Foundations (AIJ2001). There was a good agreement between them (Fig.7).

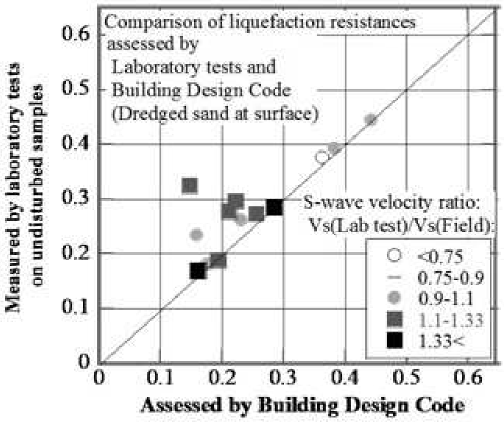

Figure 7. Comparison of experimental results and assessed liquefaction resistance

4 SELECTION OF LIQUEFACTION MITIGATION

The aim of present liquefaction mitigation project is to minimize the damage in residential land under the same magnitude of earthquake as in 2011. Further, there should be no severe damage if a strong earthquake occurs in the proximity of the city (in the Northern part of Tokyo Bay).

In the examination of subsoil response caused by 2011 earthquake, we produced the seismic waves using an observed record at Tokyo Yumenoshima Site adjacent to Urayasu City (Fig.8).

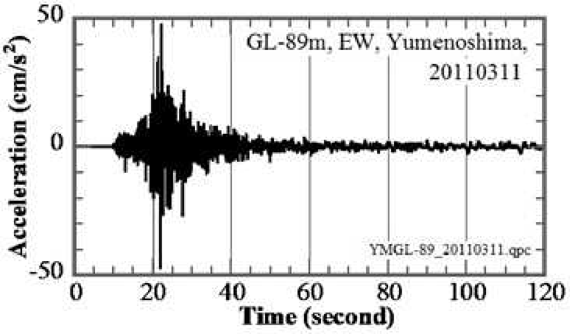

Figure 8. Seismic acceleration record observed at Tokyo Yumenosima Site (2011)

This input motion was prepared as follows;

An observed seismic record was converted to an outcrop motion at an engineering base considering the subsoil condition of the observation site and then put in the soil profiles in Urayasu City. The amplitude of waves were adjusted to fit maximum acceleration of the actual record obtained at several points (143-197Gal) in Urayasu area. These seismic waves were utilized for the judgement of liquefaction and design of liquefaction mitigation. The vertical distribution of the factor of safety against liquefaction (F_L) was assessed by the Recommendations for Design of Building Foundations mentioned above. The relation between thickness of the unliquefiable subsoil at the surface (H_1) and the index of settlement due to liquefaction based on the Recommendation for Design of Building Foundations (*D*cy) calculated by integration of the shear strain in each subsoil layers is plotted in Fig.9.

Fig.9 illustrates procedures used for evaluation of quality from the viewpoint of liquefaction vulnerability (Towhata et al., 2015). The data of target area were judged as middle (B) to large (C), and the results coincided with the actual damages in 2011.

There are two candidates of soil improvement method. The one is construction of an impermeable underground wall surrounding the target area and lowering of ground water level inside. The other is to construct rigid walls in grid pattern in a target area to constrain shear deformation of soil, in order to minimize the rise of excess pour water pressure.

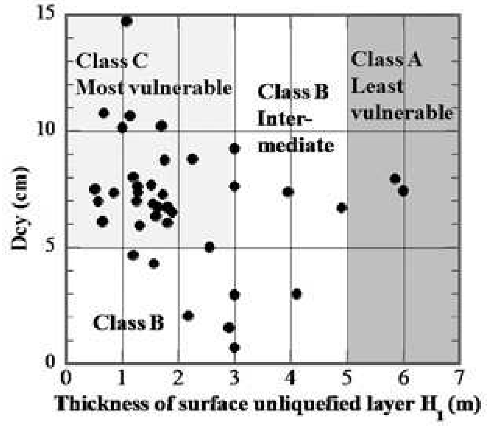

Figure 9. Comparison Thickness of surface unliquefiable layer (H_1) and *D*cy parameter

The former method is inexpensive in construction and operation and Amagasaki city in Hyogo Prefecture adopted this method. At present, several projects started using this method. This method, however, was not selected by Urayasu City due to fear of additional settlement by during lowering of ground water level.

The latter was utilized for the foundation of a hotel in Kobe Harbor and prevented liquefaction during the 1995 Kobe earthquake. This method is more expensive and has been recognized effective only when the size of the grid is smaller than 80% of the thickness of the liquefiable subsoil. In the case of Urayasu City, the thickness of the liquefiable subsoil is about 6-10m, thus, this method seemed not applicable. Because the size of each house was about 10m, this length is also the minimum size from the viewpoint of construction of grid size. However, the previous study of this method, it did not take into account the effect of the restriction of soil deformation by about 1.5m unliquefiable layer at the surface. We found that the grid-wall soil improvement was able to work efficiently dynamic centrifuge model tests and numerical analysis (Tsukuni et al., 2015). Consequently, grid-wall soil improvement method was selected (The typical grid-size was 16×13m, the effective width of the grid-form wall was 0.85m).

Table. 1 shows the requirement for performance-based design of grid-wall soil improvements. The main target earthquake for the design is of the same level as the main shock observed in 2011 in Urayasu. For this main design earthquake, it is required that no obvious damage occurs for a residential house by achieving either FL exceeding 1.0 in all loose sandy layers or Dcy within 5 cm and H1 greater than 5.0 m. Additional consideration is made of a very rare and stronger earthquake. For this situation, the requirement that the induced stress level in the improved grid-wall should not exceed the allowable level.

Table1 Requirement for performance based-design of grid-wall soil improvements

Design earthquake	Requirement performance	Performance guideline
Main target earthquake	Occurrence of no obvious damage due to liquefaction	①FL > 1.0 in all liquefied strata or ②Dcy ≦ 5 cm and H1 ≧ 5 m
Level 2 earthquake	Maintaining effectiveness of counter measures	Induced shear stress ≦ allowable stress (in improved soil)

Various problems were faced in actual design. First, it is ideal that the top of the soil improvement wall is located at the ground surface as liquefaction mitigration. In the construction area, however, various underground pipelines exist near the surface. The ground water level is about GL-1.5m. Thus, design of the top of the soil improvement wall was set at GL-1.5m to avoid the underground pipelines. When underground pipeline is located at much deeper elevation, the soil improvement is not implemented partly. In such a case, centrifuge model tests were carried out to verify the effectiveness of this method. Second the depth of the liquefaction layer is locally very deep in an abandoned river channel, and construction cost of soil improvement becomes seriously high. In this case, this method was proved by model tests to be still effective although the soil improvement wall does not reach the bottom of liquefaction layer (Takahashi et al. 2006).

5 SUBJESTS OF THE CONSTRUCTION OF GRID-WALL SOIL IMPROVEMENT

The biggest problem in the construction of the grid-wall soil improvement is the minimum 1.0m spacing between houses (Fig 10). In addition, there is often a fence along the border of land. To install underground walls in such a narrow space, we developed a middle-size high-pressure jet mixing equipment which can improve soil from an elevated platform over a border fence. This machine can form an oval-shaped improvement columns shown in Fig.11 by directionally changing jet pressure. The grid wall

Figure 10. Example of the narrow space between houses

Figure 11. Oval shaped soil improvement columns (result of test construction)

Figure 12. Small size equipment for high pressure jet mixing

is constructed by overlapping these soil improvement columns. Fig.12 shows a further downsized equipment.

The employed soil improvement method inevitably blow-out muddy material from underground during construction (Fig 13). If the waste material could be recycled as backfilling material after proper treatment in the construction field, it would contribute to the cost reduction of construction. In reality, however, the waste material has to be transferred to a disposing company because there was no big recycling company near the site. Otherwise it is expensive to install temporary disposal facility that can treat the waste material sufficiently in accordance with the strict environmental rules.

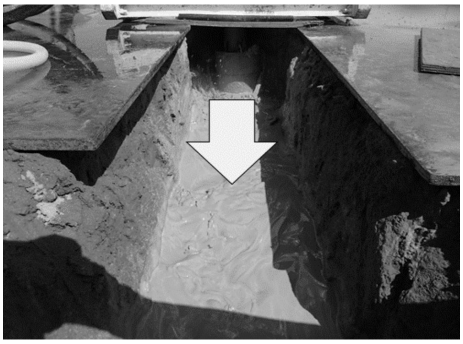

Figure 13. Blowout of muddy material during soil improvement

To minimize the construction cost, working time per day was extended upon the agreement of residents. During the construction, deformation of ground was monitored under the temporary construction management criteria (10mm deformation => warning, 15mm deformation => stop working) to prevent damage in existing houses.

6 ACTION FOR AGREEMENT WITH RESIDENTS

After the abovementioned process, we decided the use the grid wall soil improvement method, made detailed designs based on site investigation and calculated construction cost.

Public fund is introduced into ground improvement in private land because liquefaction in private land induces damage in such public sectors as road and lifelines. Obviously, this is a ground improvement over a substantially big area and residents in the area have to achieve a unanimous agreement to join the project.

The national government will provide 50% of the ground improvement cost in the private residential land and the city government will make additional support. Despite this, residents still have to make significant payment, although the precise amount is not yet clear. It is necessary for several hundreds of families to be in favor of the project implementation.

Therefore, in order to build up the general agreement of resident that become the key for project implementation, the technical committee for liquefaction measures organized by city invited three resident members who are private land owner in addition to experts and executive officers. This committee answered all of question relating to this project. This committee meeting was held 6 times open for public, discussed engineering issues and cost in front of more than several hundred residents.

At the same time, city office organized explanation meeting of this project to resident about 170 times in total and tried to build agreement by answering even trivial questions. To date, the technical examination and cost estimation are finished. Three areas consisting of 471 families have reached the agreement that started the preparation for implementation of the project.

7 CONCLUSION

In 2011, substantial damage occurred due to liquefaction in private residential areas. Because of cost requirement, private housing did not have a field left behind by the development appropriate liquefaction measures. The damage of the public facilities such as road by a big earthquake disaster is closely related to liquefaction in private residential area. Considering this issue, Japanese Government launched a new system that can fund the integrated liquefaction mitigation in both public road and private residential area. This paper introduces the case of Urayasu-City as an example of this system.

Major conclusions of this paper are as follows;

- The reclaimed land in Urayasu city is heterogeneous reflecting the original topography and reclamation process using the dredging material. We carried out a huge amount of soil investigation to capture the actual subsoil condition.
- Selected grid-wall as the liquefaction mitigation method prevents liquefaction by restricting the cyclic subsoil deformation during earthquake. As compared to ground water lowering, this method is expensive, but can avoid settlement of land.
- The narrower spacing of grid is able to prevent liquefaction more effectively. It is difficult, however, to reduce the spacing between grids because the houses exist on the ground surface. Based on the centrifuge model test, the unliquefiable layer at the surface provide the restraint effect although the space of grid is wider.
- It became possible to apply the grid-wall soil improvement method in existing residential area due to development of small size equipment that can work in a narrow space.
- At this moment, upon the detailed survey, investigation, design and cost estimation, three areas reached agreement and started the soil improvement project.

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