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Liquefaction Problems in the 21st Century

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ABSTRACT: This paper concerns liquefaction problems that were not solved in the 20th Century. Most of the problems lie in inexpensive structures and existing structures that were out of scope in the past. Efforts are going on to overcome the problems in spite of the imbalance of the required cost and the financial capacity. Seismic performance design is one of the future directions but there are again problems to tackle. It is stressed that qualification of the properties and lands are important because people can recognize the lying hazards and can prepare for the future safety.

KEYWORDS: Liquefaction problems, Seismic performance design, Lying hazards, Future safety

1. INTRODUCTION

The construction community recognized seismic liquefaction as a big threat after the 1964 Niigata earthquake when sandy subsoil, which had been considered good because of its small consolidation settlement and reasonable bearing capacity, suddenly changed to an extremely soft material. As a consequence of reduced rigidity of soil, many structures subsided, floated or displaced laterally and lost their functions. Since then many technical developments have been achieved for practice of disaster mitigation and their basic principles can be summarized as what follows. Note that this summary does not pick up all the past achievements due to insufficient knowledge of the author.

a) Liquefaction-prone soil condition:
   i) Loose, water-saturated cohesion less young soil in seismically active regions.
b) Causative mechanism of liquefaction:
   i) Dislocation of soil grains under cyclic shear stress and consequent volume contraction (negative dilatancy),
   ii) Limited permeability of soil that does not allow quick drainage of pore water during the seismic shaking.
c) Assessment of liquefaction vulnerability:
   i) Determination of design seismic action with due consideration of local earthquake activities.
   ii) Evaluation of liquefaction resistance of subsoil by subsurface exploration that is in most practices SPT although efforts have been made to use CPT, S-wave velocity and others.
   iii) Calculation of factor of safety against liquefaction, FL, by comparing the seismic action and soil resistance.
   iv) As an alternative, more advanced numerical technology only when it is feasible.
d) Mitigation of liquefaction disaster:
   i) Prevention of liquefaction by achieving the factor of safety, FL, greater than unity.
   ii) Densification, promotion of drainage and grouting in most practices.

Towards the end of the 20th Century, the above-mentioned practice had been well established in most major construction projects. Nevertheless, there were limitations therein as well and they started to be recognized during the earthquake events in the 21st Century. The author attempts to address those limitations in this article and also wishes to show efforts that are being made to overcome those limitations. By doing this, the author likes readers to understand the following issues:

(1) Types of natural disaster changes with the change of our life style.
(2) People desire more safety under the threat of natural disaster than in the previous times.
(3) Accordingly, what was good enough in the past may not be so good in future.

2. LIMITATIONS OF 20TH CENTURY LIQUEFACTION TECHNOLOGY

The technologies to mitigate liquefaction disasters were developed in the 20th Century for the safety of such important infrastructures as harbors, bridge foundations, energy facilities, dams and big buildings among others. Because those important structures were constructed by public sectors and big industries that were able to provide sufficient funding, the established mitigation technologies were rather expensive, although they are reliable as verified by many earthquake events. As a consequence, those infrastructures that cannot afford the high cost of liquefaction mitigation are left unprotected today. Examples of those “poor” structures are residential house foundations, embedded lifelines and river levees (Photos 1 to 3 taken after the 2011 gigantic earthquake in east Japan).

Photo 1 Liquefaction damage of house

Noteworthy is that most 20th Century liquefaction mitigations are executed in an open land where there is no structure. Therefore, big construction machines can easily improve vulnerable subsoils at a reasonable cost. In the 21st Century, the increased desire for safety has raised the intensity of design earthquake actions and many structures that were once safe under less intense design actions started to be considered unsafe. Because those structures already exist on the ground surface and owners do not want to demolish them, such a difficult soil improvement as grouting or installation of drainage pipes under existing structures is now required. Note that densification under existing structures is not recommendable because it causes ground subsidence that seriously affects the existing super-structures on the ground surface. The situation of people’s house is very complicated. Because of the financial restrictions, foundations of most houses are not prepared for subsoil liquefaction. Because of the shortage of structural strength, soil improvement under existing houses requires special care. Conditions of houses and foundations are different from house to house and therefore soil improvement under existing houses cost significantly in spite of the house size and limited financial resource. With these in mind, the present paper is going to review the current situations of unprotected structures in more details.

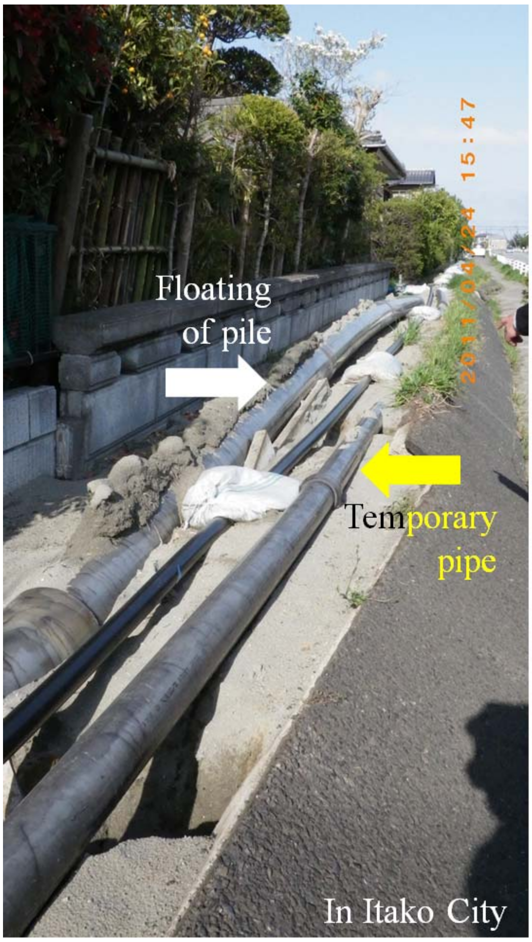

Photo 2 Liquefaction damage of lifeline

Photo 3 Liquefaction damage of river levee

3. LIQUEFACTION PROBLEMS IN RIVER LEVEES

The gigantic earthquake of magnitude = 9 in 2011 in east Japan caused many liquefaction damages in river levees. Being situated along river channels, many river levees are underlain by soft sandy soils that fill abandoned river channels. These soils are young and water-saturated without densification, and their liquefaction vulnerability is high. The problem is that the subsurface soil conditions are highly variable from place to place and therefore it is difficult to recognize the range of liquefaction soil precisely. This problem is related with the cost of current soil investigation by means of SPT, because river levee is a very long structure and the budget for unit length is low. Therefore, less expensive equipment is desired. In addition, the three-dimensional image of the heterogeneous subsoil condition should be captured at a reasonable cost. Most river levees have been expanded and enlarged many times through the history (I, II and III in Photo 4). Often there is no record of the previous construction history. As a consequence, we do not know the cross section of a levee, although we need to assess its seismic behaviour and safety. Investigation inside a levee is not easy due to the above-mentioned financial reasons.

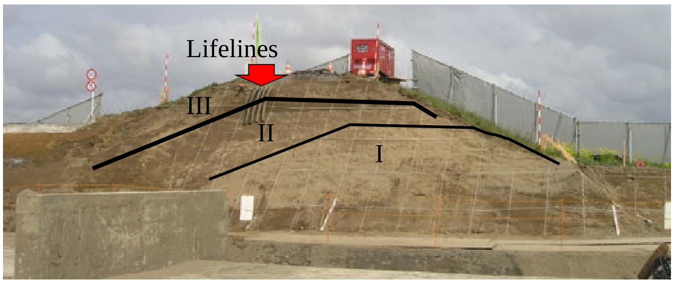

Photo 4 Excavation of Tone River Levee at Iijima

Traditionally liquefaction issues of river levees concerned the foundation soil under a levee body. However, one of the recent problems is the liquefaction inside a levee. This remark may sound strange because a levee is located above the ground surface and, therefore, above the ground water table and also because a levee is considered to be compacted. Photo 5 illustrates a typical damage caused by liquefaction inside a levee. Noteworthy is the profound distortion of the levee slope that is in The mechanism of the levee's internal liquefaction is discussed as what follows;good contrast with the intact shape of the unliquefied ground surface. Consolidation settlement is induced in the soft clayey subsoil under the weight of a constructed levee.

As a consequence, the lower part of a levee becomes submerged underground water table.

More water is supplied from the surface during rain and the levee body becomes more water-saturated.

Sometimes the levee is not well compacted when situated on very soft clay. There are such experiences that compaction disturbed the sensitive subsoil and significantly reduced its bearing capacity. Therefore, it is technically desired to develop

(1) to detect liquefaction-prone parts of existing levees, less expensive three-dimensional investigation technology that has at the same time a reasonable sensitivity to mechanical properties and types of soil, and
(2) inexpensive soil improvement of the liquefiable parts of an existing levee under the ground water table.

(a) Overall deformation (b) 2-m subsidence at the top

Photo 5 Levee that was damaged by internal liquefaction during the 2011 East-Japan gigantic earthquake (Naruse River)

4. LIQUEFACTION DAMAGE IN EMBEDDED LIFELINES

Modern community relies substantially on the operation of such lifelines as electricity, communication, water supply and sewage. Because the total length of a lifeline network is huge, it is not an easy task to improve the seismic resistance of a lifeline network. This is particularly the problem of an embedded lifeline that is affected by liquefaction of backfill soils. Photo 2 illustrated a floating of a sewage lifeline during the 2011 earthquake in Japan. Floating is caused by liquefaction of backfill soil around the embedded pipe. Therefore, lifeline damage is possible in areas of any kind of natural soil, irrespective of its liquefaction resistance. Although compaction of backfill soil has been specified, site engineers are reluctant to do it in fear of possible damage to a pipe. As a consequence of liquefaction, not only floating but also disconnection of pipes and flow-in of liquefied backfill sand (Photo 6) stopped the operation of sewage service for months after the 2011 earthquake. One of the efficient mitigation measures for embedded pipelines is the use of cement-mixed backfill sand. Being liquefiable, this kind of sand has been proved to function properly during earthquakes. It seems to the author, however, that the cement-mixed backfilling makes future excavation and pipe maintenance difficult. Also, improved backfilling is possible practically only upon new pipeline construction and, from the financial and time viewpoint, it does not suit the improvement of existing lifeline system. The author proposed several mitigation measures that overcome the above-mentioned limitations (Otsubo et al., 2014). Photo 7 indicates crushed glass beads for backfilling. This material is obtained from recycling of waste glass bottles etc. Because its grain size is large (typically 3 mm), permeability is high and the developed excess pore water pressure dissipates quickly during earthquakes. Moreover, the uniform gradation makes emax-emin smaller than that of well-graded materials. Hence, the volume contraction during cyclic loading is small and the extent of liquefaction becomes less significant.

The second idea aims to improve the backfill soil without overall excavation so that liquefaction resistance of “existing” embedded pipelines might be improved more easily. For example, Figure 1 schematically shows a columnar structure embedded between the top of a pipeline and the base of surface pavement. This structure is supported by the rigid pavement and is able to efficiently prevent the floating of a pipe during the possible liquefaction of backfill. Note that the excavation that is needed for the installation of this column is significantly less than that of the overall excavation.

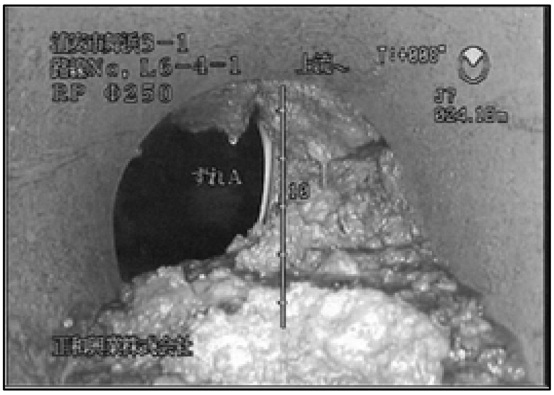

Photo 6 Clogging of embedded sewage pipe by flow-in of liquefied backfill sand from pipe disconnection (provided by Urayasu City Government)

Photo 7 Glass beads for backfilling

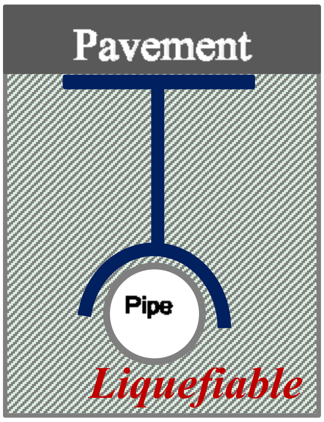

Figure 1 Installation of columnar structure that requires a limited amount of excavation

5. EARTHQUAKE VULNERABILITY OF PEOPLE'S HOUSES

The 2011 earthquake demonstrated two types of earthquake problems in people's houses. Photo 8 indicates failure of residential fill that led to the total demolition of an overlying house. Because this residential area was constructed in a hilly area by cutting high places and filling valleys, there occurred a significant difference in seismic performance among places and only the filled parts experienced fatal damages during the earthquake. The problem from the people's viewpoint is that customers are not aware of the seismic risk of land that they are going to purchase and are shocked to see the consequence after a big earthquake. It is unfortunate that efforts of seismic experts to disseminate knowledge have not been efficient to date. Photo 1 illustrated liquefaction-induced damage of a house that was essentially subsidence and tilting while no significant structural damage happened. The significant subsidence led to breakage of embedded lifelines that were connected from free field to the subsiding house foundation. Most of such liquefaction damage were reported in young sandy ground that was constructed by reclamation of former seas, lakes and river channels. The problem is that the residents were not aware of the liquefaction risk when they purchased the land despite that concerning rules and regulations state that land owners themselves are responsible for the risk. It is important that liquefaction technology has not paid or could not pay much attention to the safety of private properties, while much has been done to protect infrastructures from liquefaction problems. Another problem is that efforts to disseminate people about liquefaction problem have not been very effective.

6. TO HELP PEOPLE'S HOUSES FROM NATURAL DISASTERS

Earthquake is not the only one kind of natural disaster that produces a fatal damage to a private house. Photo 9 illustrates an area near Hiroshima where a heavy rain in August, 2014, caused debris flow in a residential area, destroyed many houses and killed 74 people during mid night. The problem was that a residential development took place on an alluvial fun that was formed by deposits of debris and that people did not pay attention to the risk of natural disasters. Similar to the aforementioned earthquake problems, it is very difficult to reduce the risk by reconstruction, soil improvement, relocation etc. after people have constructed houses and started living. Such a problem in existing structures is profoundly more difficult than that of new construction. Relocation requires people to purchase another land despite that their previous land and house are still under unfinished mortgage payment.

Apart from the mortgage problem, the engineering community should do something to help people from natural disasters. The essential issue is that people, who have no knowledge on soil mechanics and applied geology, should be provided with appropriate information on the risk of disasters. In this regard, the Japanese Geotechnical Society dispatched a qualification project by which to produce experts who can interpret geology, geomorphology, soil conditions, history of land reclamation, construction methods etc. and let people know about the possible extent of risk. Although this qualification is yet to be well established, it is aimed to achieve the following goals;

Qualified engineers study the available data and, if necessary, carry out subsoil investigations in order to show the quality of the clients' land from the viewpoint of natural disaster risk.

All major projects of residential land development require official approval of qualified engineers.

The price of residential land is affected by its safety quality. This situation will be a good incentive for land developers to produce good and safe residential land and sell it at a higher price.

7. PROBLEMS YET TO BE SOLVED

Efforts are going on to mitigate the natural disasters of the afore-mentioned inexpensive structures. However, many things have to be achieved further with a certain extent of success. Most of them come from the fact that those inexpensive structures cannot afford the cost of risk mitigation program.

(a) In earth-filled former valley (b) In cut parts

Photo 8 Failure of residential land during the 2011 earthquake

Photo 9 Consequence of debris flow caused by heavy rain (Hiroshima, 2014)

7.1 Soil investigation

The tradition of soil mechanics and geotechnical engineering relies on the subsoil investigation by which both spatial/geometrical information and those on material properties are obtained. More elaborate investigation costs more than what inexpensive construction affords. In case of a river levee, the problem is not only that the subsoil is variable at a spatial scale of 30 m or so but also that the inside of a levee itself is highly heterogeneous. It is not rare that there is no information about the cross section and soil properties because many levees have been constructed and expanded several times in the past hundreds of years (Photo 4). Because of the significant heterogeneity, desirably subsoil investigation should be carried out on a cross section of a levee at every 10 meters or so along the levee axis. Therefore, some efforts have been made in the recent times to use geophysical methods of investigation. However, the obtained resolution is not good enough from the geotechnical viewpoints.

Most probably, mechanical soil properties (strength or liquefaction resistance) can be obtained only by such mechanical methods as in-situ sounding or soil sampling. Because of the financial restrictions, it is attempted, first, to screen more vulnerable sections of levee by referring to past disaster histories and geomorphologies, and, second, to conduct subsoil investigations on the selected more vulnerable sections at such a short interval as 20 meters. A device in Photo 10 is a dynamic cone penetrometer with pore water pressure measurement that can obtain information on the soil stiffness and the location of the ground water table (Sawada and Towhata, 2011). It is attempted in this device to assess the fines content from pore water pressure response during dynamic penetration and finally to determine the liquefaction resistance of soil.

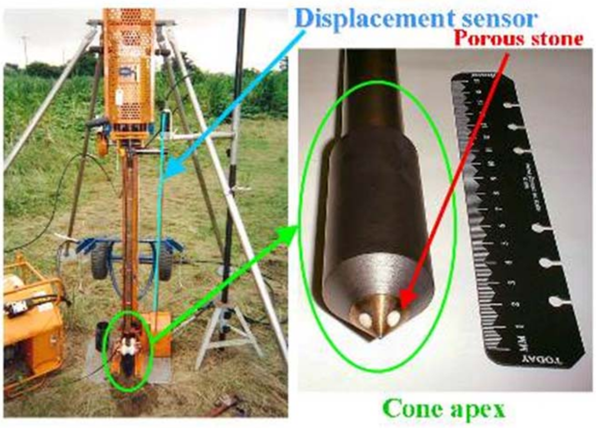

Photo 10 Piezo Drive Cone for quick soil investigation

7.2 Soil improvement under existing houses

In principle, soil improvement in a private residential land is a responsibility of house owners. However, the scale of house damage during the 2011 gigantic earthquake was extremely huge and the national government decided to provide a certain public aid to private properties, which is an integrated soil improvement package by which both public streets and private lands are worked on together. It was thought therein that the safety of streets and embedded lifelines against liquefaction is achieved by soil improvement not only under the public spaces but also in private lands; hence the public fund should be added to the personal money in order to improve private subsoil. Photo 11 shows a case in which liquefaction in a private land induced subsidence of the building and the subsided soil was pushed out to the public sidewalk where significant uplift happened. Note that pipelines are often embedded under sidewalk.

The integrated projects for soil improvement have been planned in many municipalities in and around the Tokyo Metropolitan area where residential lands have been constructed in young reclaimed islands or in former river channels and swamps. The issues to be considered in the projects are as what follows:

Photo 11 Uplift of public sidewalk as a consequence of liquefaction-induced subsidence of private building

There are many houses on the ground surface and they cannot be demolished or removed for soil improvement.

Therefore, soil has to be improved under existing houses.

Hence, densification is not possible because big machines cannot come in and also because the induced soil deformation is not allowed by fragile houses.

Grouting is too expensive for people, although it can be executed under existing houses.

The public sectors do not want to recommend to people those new technologies that have not been validated.

Consequently, only two choices have been chosen as the candidate soil improvements, which are ground water lowering in most municipalities and square grids of underground walls in Urayasu City.

Ground water lowering was executed in Amagasaki City near Osaka after the 1995 Kobe earthquake, while the same earthquake proved the reliability of the underground grid wall in Kobe Harbor.

Ground water lowering produces unsaturated and unliquefiable soil crust at the surface, while underground grid walls constrain cyclic shear deformation of soil to reduce the excess pore water pressure.

Installation of ground water lowering mechanism is much less expensive than construction of grid walls, although it needs maintenance cost of pumps and electricity.

Urayasu City chose the more expensive grid walls because there is a very thick soft clay layer under liquefaction-prone sand and it was feared that consolidation settlement may be reactivated by the lowered ground water level. Certainly, construction of underground walls requires further efforts to reduce the cost, while maintaining the seismic performance.

7.3 Seismic performance-based design

Because low-cost construction is a key issue in safety of inexpensive structures, it has been discussed to introduce the performance-based design principle. This principle attempts to achieve reasonable safety at reasonable cost during strong earthquakes by allowing the factor of safety less than unity but keeping the residual deformation reasonably small. It appears, however, that there are many difficulties to overcome prior to the practice of the performance-based design.

First, the assessment of residual deformation needs more input data on soil properties, subsoil stratification (geometry), and design earthquake motion. Particularly, the first two issues require more detailed soil investigation and the needed cost cannot be always afforded by people. Although many studies have been made on the constitutive models of soils and good constitutive models can help assess the deformation, more soil data and more expensive soil investigation are needed. Second, tools for deformation analysis have to be decided. To date there are many programs/theories that suggest different magnitudes of deformation, and it is difficult to judge which is more realistic than others. The author supposes that there is no exact solution of deformation because of lots of uncertainties in liquefaction problem of soil and that the calculation should give us an “index” of seismic performance under the name of “residual deformation.” From this viewpoint, good tools for calculation require fewer amounts of input data and computation but should not be too simplified. By using the”index”, structures and ground will be classified into class-A, B, C etc.

Because of the uncertainties, it is desired to establish earthquake damage insurance with a special consideration of uncertain soil problems. The currently available insurances are not very convenient in the author’s view because they do not fully cover all kinds of geotechnical damages.

8. CONCLUSIONS

The author attempted to address in this short paper the situations and problems in seismic liquefaction of sandy subsoil. It is important that the current situation is not satisfactory yet in spite of the past efforts since 1960s. The fundamental reason for this is that our life style is always changing and, after every change, creates new problems in our community. Therefore, it is important that engineers are always watching the changing life style and finds future problems in advance. The major points that were made in this paper are summarized as what follows:

1. Liquefaction mitigation is not sufficient for relatively inexpensive structures such as private houses, river levees and embedded lifelines.
2. Similarly, private residential land that is situated on earth fill is subject to significant seismic hazard.
3. In spite of ongoing efforts, there is not yet good technology to improve the bad subsoil under existing structures. This point is in clear contrast with the situation of new construction.
4. Classification of seismic performance or seismic safety on the basis of a simple index can improve the people’s recognition of the quality of properties.

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