Technical framework of performance-based design of liquefaction resistance

Jinyuan Yuan[1], Lanmin Wang[2], Xiaoming Yuan[1*]

[1] Institute of Engineering Mechanics, China Earthquake Administration; Key Laboratory of Earthquake Engineering and Engineering Vibration, China Earthquake Administration, Harbin 150080, China
[2] Lanzhou Institute of Seismology, China Earthquake Administration, Lanzhou 730000, China
* Corresponding author, email: yxmiem@163.com

Abstract. Seismic liquefaction hazard is always a very challenging problem in earthquake geotechnical engineering and it is necessary to develop the performance-based technology of liquefaction hazard governance. In the paper, by investigating the characteristics of seismic liquefaction hazard and combined with the existing performance-based earthquake engineering (PBEE) thought, the connotation and key points of the performance-based liquefaction hazard governance are proposed, and a technical framework of performance-based design of liquefaction resistance (PBDLR) is constructed according to the technical system construction rules**.** The results indicate that the liquefaction hazard has its own characteristics in the target, scale, mechanism, mode, chain effect, treatment technology and uncertainty of the influencing factors, and its technical system of hazard governance needs special consideration. The presented PBDLR, which integrates advantages of both the advanced risk management theory and the existing performance-based earthquake engineering technology system, and the elements and structure consider the sociality of the target, the integrity of the function, the hierarchy of the composition, the relevance of elements and the completeness of technology, and may provide guidance and reference for the technology development of liquefaction hazard governance in earthquake geotechnical engineering.

Keywords: Liquefaction Hazard, Liquefaction Resistance, Performance-Based Design, PBDLR.

1 Introduction

Soil liquefaction under earthquakes is both a complex and interesting natural phenomenon, and meanwhile it can cause significant damage to human life and property. Soil liquefaction under earthquakes can cause the reduction or loss of foundation bearing capacity, which in turn leads to massive damage to various engineering structures and infrastructures. Notable examples include the 1964 Niigata earthquake (Ishihara and Koga 1981), the 1976 Tangshan earthquake (Liu 2002), the 1999 Chi-Chi earthquake (Yuan *et al*. 2003).

Since this century, disasters caused by soil liquefaction have continued to occur and become more serious than before, and earthquake losses due to soil liquefaction have accounted for an increasing proportion of earthquake disaster losses, such as the 2003 Xinjiang Bachu earthquake, the 2008 Wenchuan earthquake, the 2010 Maule earthquake in Chile, the 2010 Darfield earthquake in New Zealand, the 2011 New Zealand Christchurch earthquake, 2011 Tohuko earthquake in Japan, 2016 Kaikoura earthquake in New Zealand, 2016 Meno earthquake in Taiwan, China, 2018 Sulawesi earthquake in Indonesia, 2018 Songwon earthquake in China and 2019 Hokkaido earthquake in Japan, etc. Large-scale liquefaction of gravelly soils has occurred in the 2008 Wenchuan earthquake in China (Chen *et al*. 2009, Hou *et al*. 2011). The 2018 Songwon earthquake in China saw a liquefaction phenomenon of more than 200 sites stretching several kilometers, but the lowest magnitude (M_w=5.2) ever recorded. The research of soil liquefaction has attracted wide attention again.

2 Characteristics of earthquake liquefaction hazard

In particular, it should be noticed that the 2011 Christchurch earthquake in New Zealand (Cubrinovski *et al*. 2011) had a rare liquefaction damage, which became the main cause of the earthquake-induced significant losses. As shown in Figure 1, the liquefaction caused severe damage to 16,000 residential houses and a large number of bridges, dykes, underground lifelines and other infrastructure, and eventually led to the permanent abandonment of some urban areas. Another recent severe liquefaction hazard event of concern occurred in the 2018 earthquake in Sulawesi, Indonesia (Kiyota *et al*. 2020). Petobo and Balaroa these two areas occurred severe soil liquefaction, where essentially all housing structures and infrastructure in the liquefaction zone were completely destroyed and liquefaction caused massive surface runoff, directly resulting in the death and disappearance of thousands of people.

Fig. 1. The liquefaction damage in 1976 Tangshan earthquake

In the past, earthquake disasters were mainly caused by the collapse of houses due to site shaking, now with the progress of human science and technology, the collapse of buildings under site shaking is becoming less and less, but the proportion of earthquake damage caused by soil liquefaction site damage is becoming noticeable increase. In modern urban construction, underground space is continuously exploited, and most of the lifeline facilities are buried underground. Modern human life and production are increasingly dependent on underground facilities, soil liquefaction which mainly destroys underground facilities, will pose a greater threat to human safety.

Fig. 2. The liquefaction damage in 2011 New Zealand earthquake

Fig. 3. The liquefaction damage in 2018 Indonesian earthquake

The phenomenon of site liquefaction damage from recent major earthquakes shows that, unlike in the past, site liquefaction can cause greater economic losses and also lead to a large number of casualties, making it an extremely dangerous event that may endanger human lives. It is especially important to develop liquefaction governance technology with the concept of performance-based design.

Compared with other types of seismic hazards, site liquefaction hazards have several distinctive features as follows:

Liquefaction disaster targets are comprehensive and extensive.

Liquefiable soils often exist in areas with abundant water supply, fertile land, flat surface, easy access to farming, etc., where human activities are frequent and economically developed. Seismic investigation shows that liquefaction not only causes damage to buildings, but also to infrastructure such as highways, railroads, bridges, harbors, berms, farmland and water conservancy, artificial islands, etc. Soil liquefaction is especially harmful to lifeline systems, and can cause extensive damage to both various individual engineering structures and entire cities.

The scale of soil liquefaction under strong earthquakes is huge.

The soil liquefaction found so far is located in the range of several tens of meters below the surface, and due to the stratified nature of geological deposition, the liquefaction under strong earthquakes will show a patchy area distribution, and large scale of liquefaction is usually occurred under strong earthquakes. In 1976 Tangshan earthquake, the liquefied zones involved an area of 24,000 km^2; the ground fracture caused by liquefaction in a village in the Wenchuan earthquake in 2008 stretched for hundreds of meters. Moreover, not all liquefaction zones have macroscopic phenomena visible on the surface such as sand and water spouts and ground fractures, the actual distribution of liquefaction zones is much larger than we can imagine.

The mechanism of liquefaction causing disaster is special.

The site is both a building support layer and a seismic wave propagation medium. Unlike the single mechanism that causes damage to engineering structures on non-liquefied sites by excessive seismic inertia forces, the site liquefaction does not directly cause engineering damage, but first causes ground failure and changes in ground shaking, and then transmits such damage and changes to engineering structures, which leads to the final damage of engineering structures. Therefore, the analysis of seismic damage by liquefaction is much more complicated than that of engineering damage on non-liquefied sites.

Liquefaction leads to significant chain effects.

The site liquefaction will not only lead to the destruction of buildings, especially to the destruction of infrastructure, especially the buried lifeline system, which will lead to serious secondary disasters and cause chain reactions. After the 1906 San Francisco earthquake, the liquefaction caused the water pipes to break, which greatly hindered the delivery of water to extinguish the fires; the earthquake On March 11th, 2011 in Japan, caused many water and gas pipelines to break due to large-scale liquefaction, resulting in the breakage of water and gas pipes in the mainly reclaimed land in Urayasu City, which had a huge impact on the life of citizens; The 2016 Southern Taiwan earthquake in China, shook out the liquefaction crisis in Taiwan and caused panic in housing prices. Therefore, liquefaction many times has a chain effect and has a great impact on society.

The liquefiable site treatment technology is complicated and costly.

Since liquefaction is the result of sudden change of physical and mechanical properties of soil under earthquake, the technology of liquefiable foundation reinforcement is special and complicated, and the cost of liquefiable foundation reinforcement is much higher than that of seismic reinforcement of buildings. This makes a great contradiction between the investment of liquefaction hazard governance and the affordability of the society. It is a difficult but necessary subject to answer how to consider both safety and economic factors, set the target in the best balance, and achieve the maximum value of liquefaction hazard governance.

The factors affecting liquefaction hazard have significant uncertainties.

First of all, unlike the artificial materials and structures used in buildings, the carrier of liquefaction hazard is the site, which is not a product of human selection and design, but a natural geotechnical body with complex properties. Liquefaction occurs in the subsoil layer, and the uncertainty of the factors affecting the carrier itself is significant. Meanwhile, as mentioned above, the transmission process of site liquefaction to engineering structure damage and the treatment of liquefiable soils are complex and diverse, and the influencing factors also have great uncertainty. It is necessary to study the governance of liquefaction damage with significant uncertainty factors by using risk theory as a guide, but the research is also very difficult at the same time.

As it can be seen that, site liquefaction hazards have their own unique characteristics in terms of the target, scale of occurrence, mechanism, mode of occurrence, chain effect, treatment technology and uncertainty of influencing factors. Therefore, on the one hand, it is necessary to develop a technical system for governing the risk of site liquefaction hazards suitable for the development of modern society based on performance design, and on the other hand, when establishing its technical system, separate research and design are needed for the characteristics of liquefaction hazards.

3 Existing technical process of soil liquefaction resistance

The existing technical framework of the liquefaction hazard governance in China was formed in the 1970s and 1980s, and the most typical representative is the Code for Seismic Design of Buildings, whose technical process are shown in Fig. 4. The technical system in Fig. 4 has been used until now and has played a significant role in the work of earthquake prevention and mitigation in China's engineering construction, but due to the limitations of the previous level of understanding, this system has some problems in dealing with today's complex engineering construction and needs to be improved.

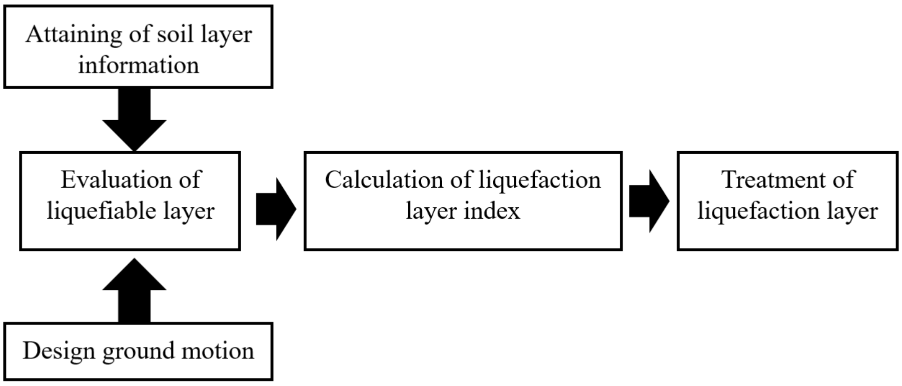

Fig. 4. The existing technical process of soil liquefaction resistance design

4 Performance-based earthquake engineering and its global framework

In the work on performance-based seismic design led by the Pacific Earthquake Engineering Research Center (PEER), they have set the lofty goal of developing and disseminating urban earthquake risk-reduction technologies, and the performance-based earthquake engineering (PBEE) is defined as "An approach to improve decision-making about seismic risk by making the choice of performance goals and the tradeoffs to facility owners and society at large".

Several conceptual frameworks for PBEE have been developed in recent professional efforts (SEAOC Vision 2000, FEMA 273, ATC-40). They differ in details but not in concepts. Fig. 5 illustrates a global framework which identifies processes, concepts, and major issues that need to be addressed in this context (Krawinkler, 1999).

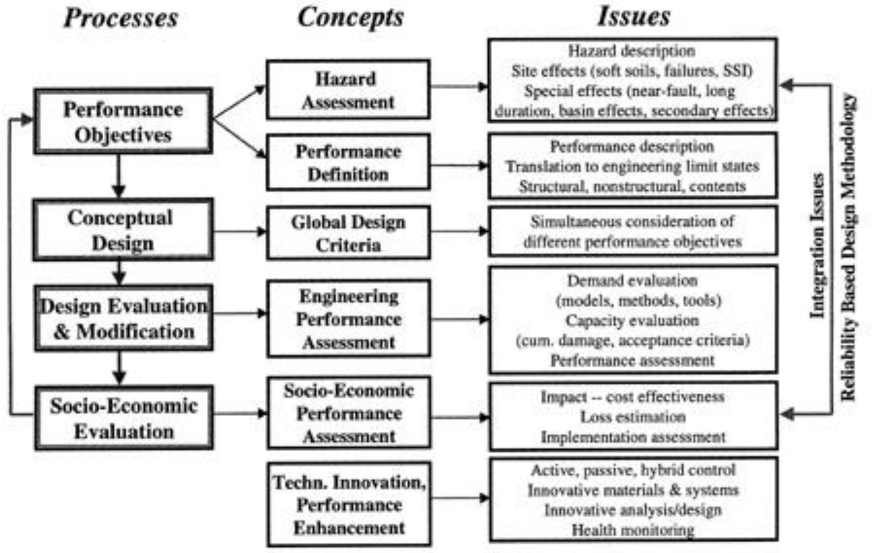

Fig. 5. Technical framework of performance-based earthquake engineering

PDEE in Fig. 5 encompass seismological, geotechnical, structural, architectural and MEP (nonstructural), and socioeconomic considerations. Each issue is associated with an extensive research agenda that covers much more than PEER can address (Krawinkler, 1999). What distinguishes this research agenda from a general shopping list is the focus on a single objective, which is the common one of providing knowledge, methods, tools, and data for development and implementation of PBEE. The challenge is to select subsets of this comprehensive research agenda that will result in substantial and measurable progress on critical aspects that bring PBEE much closer to realization (Krawinkler, 1999).

Although both serve to mitigate earthquake disasters, the PBEE technology system in Fig. 5 is significantly improved compared with the existing technical process of soil liquefaction resistance design in Fig. 3 for liquefaction treatment, which is mainly reflected in:

(1) Prioritizing performance objectives and conceptual design, which is lacking in the existing technical process of liquefaction hazard governance. Compared with the

thought of performance-based seismic design, the objective of liquefaction governance system needs to be clarified.

(2) PBEE design system will be social economy as a separate element, emphasizing the cost-benefit analysis, which makes the seismic design more close to the nature of seismic work, but also reflects the seismic design can meet the requirements of personalized seismic design in a more flexible way, is a very useful idea. At present, cost-benefit analysis of liquefiable soil treatment is lacking in the soil liquefaction treatment technology system, which is particularly important for the expensive liquefiable soil treatment.

PBEE design system in Fig. 5 provides us with new ideas for reference, but from its content, it is more directly aimed at the building engineering, which is not entirely suitable for the performance-based design problem of soil liquefaction resistance. For the soil liquefaction, a separate design system of soil liquefaction resistance based on the performance concept should be established according to the characteristics of liquefaction hazard.

5 Technical framework of performance-based design of liquefaction resistance

5.1 Definition and key points of PBDLR

In this paper, the technical system of the performance-based design of soil liquefaction resistance (PBDLR) refers to a unified technical system organically linked by various technologies to eliminate or mitigate liquefaction earthquake risk under objective laws and social conditions.

According to the characteristics of site liquefaction hazard mentioned above and the risk management theory, the risk governance goal of liquefaction hazard is defined in this paper as: to establish the optimal balance between liquefaction hazard governance goal, liquefaction governance investment and social acceptable capacity, and to maximize the governance value through economic and effective countermeasures.

Taking PDEE thought as reference, in this paper, the PBDLR is defined as: an approach to improve decision-making about risk of seismic liquefaction hazard governance by selecting and balancing the performance objectives for the facility owner and the society.

In this paper, the risk governance of liquefaction hazard should be controlled by two basic factors, namely, governance objectives and performance analysis, expressed by the following:

$$\text{Liquefaction hazard governance} = F\,(\text{governance objective, performance analysis}) \quad (1)$$

Where, the governance objective is composed of seismic ground motion fortification standard, liquefaction risk threshold, liquefaction hazard acceptability and liquefaction governance investment acceptability; The performance analysis consists of the identification, correlation, evaluation and response of liquefaction hazard.

The connotation of liquefaction hazard governance includes three main points:

(1) The liquefaction hazard due to site liquefaction risk is the main line. As shown in Formula 1, the governance of liquefaction hazard is composed of two basic elements: governance objectives and performance analysis, and liquefaction risk and its hazard play an important role in both of them. The acceptability of liquefaction hazard is one of the key factors in the governance objectives and also one of the targets of risk response in performance analysis.

(2) The principle of the establishment of governance objectives is to keep a balance between liquefaction hazard, liquefaction governance investment and social acceptability. The liquefaction damage is very serious and the governance investment is very low, so the loss risk is too large. However, the liquefaction damage caused by strong earthquakes is a rare event, so the liquefaction-resistant capacity of engineering system should be improved to a certain extent, and the excessive economic investment will exceed the social bearing capacity. It is a necessary condition to maximize the value of liquefaction hazard governance to find the optimal balance between the governance investment and the risk of liquefaction damage and the social acceptability as the principle of the establishment of the governance goal.

(3) The correlation analysis between site liquefaction risk and earthquake damage of engineering system is the key. The ultimate goal of liquefaction research is to serve the earthquake damage prevention and mitigation work of engineering system. Site liquefaction without engineering structure and infrastructure has no risk of earthquake damage, and liquefaction hazard must be related to the destruction of engineering structure and infrastructure caused by liquefaction. Sites under earthquake play two roles: seismic wave media and engineering system bearing layer, and the damage and destruction of engineering structure caused by site liquefaction are basically indirect. Therefore, only consider site liquefaction risk itself is not enough, building of the relationship between site liquefaction risk and earthquake damage risk of engineering system is also a necessary condition to maximize the value of liquefaction hazard governance.

Among the three main points of liquefaction hazard governance proposed in this paper, the program is the governance objective, and the main line is site liquefaction risk and its hazard, and the correlation between site liquefaction risk and liquefaction hazard is the key. The three are interdependent and interact with each other. Only comprehensive consideration can maximize the value of liquefaction hazard governance.

5.2 Technical framework of PBDLR

Basic requirements for technical system construction.

Technical system is a unified technical system organically linked by various technologies required to achieve specific functions under objective laws and social conditions, and should meet the following requirements:

(1) The sociality of goals. The technological system has dual attributes of nature and society and is composed in accordance with certain social purposes. It is not only the external requirements of the technological system but also the basic criteria for measuring the function of the technological system [20]. It should not only follow the

natural operation law and the actual social bearing capacity, but also meet the long-term requirements of social sustainable development.

(2) Functional integrity. What the technical system pursues is not the single function of a certain technology, but the overall function formed by the combination of different technologies, and the whole is greater than the sum of its parts.

(3) The hierarchy of composition. The elements of the technical system are combined together in a certain order, and the internal elements of the technical system are the relations of mutual influence and interaction.

(4) Linkage of elements. In the technology system, all kinds of technologies are mutually prerequisite. When one kind of technology changes, related technologies should have corresponding adjustment reaction to maintain the internal balance of the technology system.

(5) Technical completeness. All kinds of technical elements are complete in the technical system. In either case, the system should operate in closed loop mode.

Technical framework of PBDLR.

According to the above requirements for technical system construction and combined with the characteristics of liquefaction damage and advantages of PBEE, this paper constructed a technical framework of performance-based design of liquefaction resistance (PBDLR), as shown in Fig. 6.

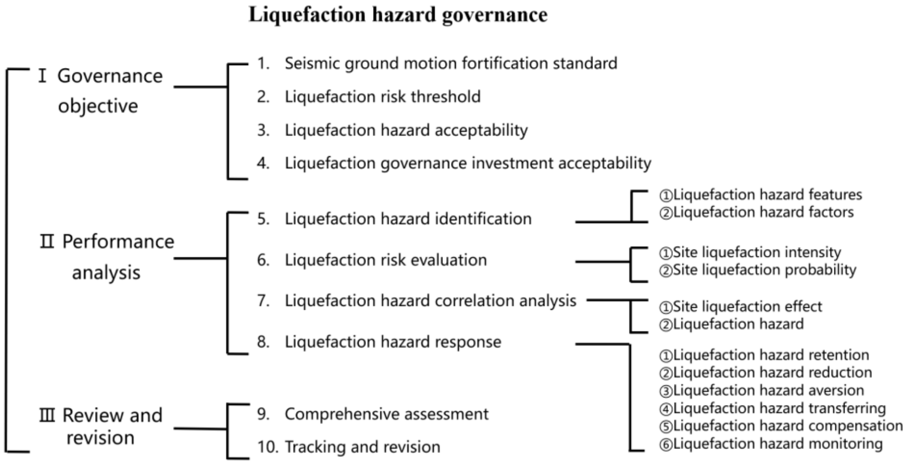

Fig. 6. Technical framework of performance-based design of liquefaction resistance (PBDLR)

Interpretation of elements of PBDLR.

In order to better understand the meanings and their relationships of the elements of PBDLR, the interpretations of the elements in Fig. 6 are given as follows:

I governance objective: during the action of the designed seismic ground motion, the general governance objectives of engineering system under site liquefaction are achieved, including:

1. Seismic ground motion fortification standard: the intensity and probability level of seismic ground motion for which the engineering system is located.

2. Liquefaction risk threshold：the lowest value of site liquefaction risk under possible liquefaction hazard to engineering system. If the site liquefaction risk is lower than this value the site liquefaction will not be considered.

3. Liquefaction hazard acceptability: the acceptable level and scope of earthquake damage under site liquefaction include the risk of liquefaction hazard to engineering system and the consequences of liquefaction hazard chain effect.

4. Liquefaction governance investment acceptability: the acceptable level and scope of investment in liquefaction treatment, including the economic cost of liquefiable soil treatment and the economic cost of dealing with the consequences of liquefaction hazard chain effect.

II Performance analysis: the site liquefaction hazard and its performance after disposal are analyzed, including the identification, correlation, evaluation and response of liquefaction hazard, including:

5. Liquefaction hazard identification: identify the risk factors of site liquefaction hazard, including:

①Liquefaction hazard features: integrate site liquefaction and engineering system earthquake damage events and determine their features;

②Liquefaction hazard factors: determine the factors affecting liquefaction of site and earthquake damage of engineering system.

6. Liquefaction risk evaluation: determine the liquefaction risk of the site itself, including:

①Site liquefaction intensity: determine the scale and severity of liquefaction at the site;

②Site liquefaction probability: determine the probability of liquefaction at the site.

7. Liquefaction hazard correlation analysis: determine the liquefaction site effect associated with seismic damage of engineering system, and assess the seismic damage risk of engineering system caused by liquefaction, including:

①Site liquefaction effect: The ground failure and the changes in ground motion characteristics due to liquefaction, including intensity and probability level, are considered;

②Liquefaction hazard: the risk assessment results of liquefaction hazard to engineering systems are given, including the intensity and probability level of economic loss, casualties, chain effect, social impact, etc.

8. Liquefaction hazard response: based on the results of the liquefaction hazard analysis, different countermeasures are taken to maximize the value of liquefaction hazard governance, including:

①Liquefaction hazard retention: the risk of liquefaction hazard to the engineering system is negligible if the risk of the liquefaction hazard obtained from the analysis is within the lower limit of the acceptable range.

②Liquefaction hazard reduction: when the risk of liquefaction hazard obtained from the analysis exceeds the lower limit of the acceptable range, measures such as soil treatment are taken to eliminate or reduce the risk of liquefaction hazard, followed by a performance reanalysis to confirm whether the objectives are met.

③Liquefaction hazard aversion: after the implementation of liquefaction hazard reduction measures, the analysis of the risk of liquefaction hazard still exceeds the upper limit of the acceptable range, the project can be abandoned to achieve the purpose of risk avoidance.

④Liquefaction hazard transferring: transferring the risk of liquefaction hazard to society through, for example, earthquake liquefaction insurance.

⑤Liquefaction hazard compensation: for liquefaction hazard bearers, a certain amount of financial compensation is given before the occurrence of seismic liquefaction disaster to reduce the pressure of liquefaction hazard bearers.

⑥Liquefaction hazard monitoring: when the established technology is difficult to achieve the desired effect or is difficult to grasp the effect, the factors with unpredictable consequences can be monitored, and according to the situation the graded early warning is put forward.

III Review and revision: by reviewing entity performance, how well the technical system components are functioning over time is considered and in light of substantial changes, what revisions are needed, including:

9. Comprehensive assessment: the changes that may substantially affect governance objectives are identified and assessed, and the entity performance is reviewed.

10. Tracking and revision: when the established technology is difficult to achieve the expected effect or the overall operation of the technology system is problematic, the governance objectives can be adjusted or the technology system can be revised according to the actual situation.

6 Conclusions

This paper expounds the connotation and key points of the performance-based liquefaction hazard governance, and combined the characteristics of seismic liquefaction hazard with the existing PBEE, the technical framework of performance-based design of liquefaction resistance (PBDLR) is constructed. The PBDLR is specially designed for liquefaction hazard governance, and it also meets the general requirements of technical system construction, such as target sociality, functional integrity, hierarchy of composition, linkage of elements and the completeness of technology. The full implementation of PBDLR is still a long way off, but the presentation of PBDLR will provide guidance for future work of liquefaction hazard governance.

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