RISK AND MITIGATION OF LIQUEFACTION HAZARD

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SUMMARY

When liquefaction is considered to be a possibility at a site, a realistic evaluation of the risk associated with liquefaction should be made. Based on the level of risk and giving consideration to the probability of occurrence, the potential consequences to the structure, and the economic impact, rational decisions may be made to determine the appropriate level of mitigation. Available mitigation techniques against liquefaction generally deal either with improvement of the soil properties to resist liquefaction, or with strengthening the structure to withstand the forces and deformations that may result if liquefaction occurs.

INTRODUCTION

At the mere mention of the possibility of "liquefaction", owner-developers, architects, and structural engineers may be brought to their knees by the geotechnical profession. For some, liquefaction is the ultimate malediction that could be pronounced by the wizards of geotechnology. However, upon the laying aside of the initial visceral afflictions of terror, there is a need to ascertain whether there has been a realistic evaluation of the potential for liquefaction. In particular, a liquefaction analysis should evaluate probability, extent, and detrimental impact of liquefaction occurrence upon the subject structure, surrounding structures, and the people that live, work and play in this environment. Once these determinations are made, mitigation procedures can then be evaluated on a rational basis related to the risk associated with liquefaction.

FACTORS AFFECTING LIQUEFACTION

Liquefaction has been defined as the process by which any substance is transformed into liquid. When referring to cohesionless soils, this transformation is from the solid state to a liquefied state which occurs as a result of increased porewater pressure and corresponding reduced effective confining stress (Ref. 1). Earthquake ground motions can cause such liquefaction to occur in cohesionless soils.

The significant quantifiable factors that may affect liquefaction include the ground acceleration, duration of shaking, soil type, particle size and gradation, water level, relative density, and confining pressure. The liquefaction potential is the greatest where the ground water level is shallow and loose fine sands occur within a depth of about

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50 feet. The liquefaction potential decreases as the soils become either finer or coarser than a fine sand. The liquefaction potential increases as the ground acceleration and duration of shaking increase. Other factors, which are less quantifiable, include the geologic age of the soil deposit, previous strain history, and the degree of overconsolidation.

CONSEQUENCES OF LIQUEFACTION

When liquefaction is considered a possibility, the consequences of liquefaction must be determined. Such consequences may be predicted from past experience as liquefaction is not a new phenomenon. Liquefaction has been observed in numerous earthquakes throughout the entire world (Ref. 2); for example, liquefaction has been confirmed as occurring in at least 44 earthquakes in Japan since 1872 (Ref. 3). However, it wasn't until 1964 when two major earthquake events literally shook the engineering profession and brought liquefaction into the forefront of interest and concern because of the spectacular damage that occurred. The Niigata earthquake is famous for the liquefaction-caused destruction, settlement, and severe tilting or overturning of structures (Ref. 4). The Great Alaska earthquake caused massive liquefaction induced flow failures that carried away large sections of the towns of Seward, Whittier, and Valdez (Ref. 5).

In a review of liquefaction effects in recent history, Ambraseys and Sarma (Ref. 2) suggest that little damage to structures founded on poor soil occurs as a result of severe ground shaking. They observed that damage is almost entirely due to ground failures which have been manifested in foundation failures, ground settlements, and tilting.

Youd (Ref. 5) classifies the ground failures caused by liquefaction into three groups. The first is the category of lateral spreads, which is the movement of surficial soil layers in a lateral direction which occurs when there is loss of shear strength in a subsurface layer due to liquefaction. Observed damage due to lateral spreading is not usually catastrophic in a direct manner in terms of destructiveness, but it can be extremely disruptive in an indirect manner. This can be especially true of lifelines which must pass through such zones of lateral spreads. Lateral spreading during the 1906 San Francisco earthquake was responsible for virtually every break in the water supply pipelines which severely hampered fire-fighting efforts against the fires that resulted after the earthquake. Lateral spreads generally develop on very gentle slopes (less than about five percent). The second category of ground failure due to liquefaction is flow failures. These flows occur when large zones of soil become liquefied or blocks of unliquefied soils flow over a layer of liquefied soils, such as those that occurred during the 1964 Alaska earthquake. Flow slides can develop where the slopes are generally greater than five percent. The third category of ground failure caused by liquefaction is the loss of bearing capacity. When this occurs, large soil deformations can occur. Structures supported on these soils may settle, tilt (overturn), or even rise out of the ground. In extreme cases, where the thickness of the liquefied soils is large, tilting or overturning failures such as those experienced at Niigata may occur. Where the liquefied soils are thinner or where relatively thick non-liquefied soils overlie the liquefied soils, severe tilting or overturning of structures may not occur, but differential vertical settlement could occur.

Generally the failures reported and described in the earthquake engineering literature tend to be on the "sensational" side. There are many cases where there has been observed liquefaction of soils but the structures founded on these soils have suffered little or no damage.

In some cases the consequences due to liquefaction may be very severe or even catastrophic. In other cases the consequences may not be very severe or may be even negligible depending on the degree and extent of the liquefaction induced ground failure. An assessment of the expected type of ground failure and the realistic consequences should be determined.

RISK ASSOCIATED WITH LIQUEFACTION

Once a realistic assessment of the potential consequences due to liquefaction has been made, the risk associated with liquefaction can be evaluated. Earthquake risk is indeed very difficult to define, but some quantifiable measure of risk is needed in order to make decisions on how to deal with the occurrence and consequences of liquefaction.

A simple definition of earthquake risk has been given by Ambraseys (Ref. 6) as:

RISK = (Earthquake Hazard) (Vulnerability) (Value)

The risk is composed of: the Earthquake Hazard which may be defined as the probability of liquefaction occurrence having sufficient damage potential at the subject site during the lifetime of the structure; the Value of the elements exposed to the liquefaction hazard (such as lives, property, function, etc.); and the Vulnerability of these elements to loss because of liquefaction. Thus, the risk may be defined as the probable loss of life, property, function, or whatever measure or quantity is used. If the risk associated with liquefaction is deemed to be "significant", then consideration must be given to address the consequences and determine the various alternatives to mitigate the problem.

MITIGATION TECHNIQUES AGAINST LIQUEFACTION

The various methods that can be used to mitigate against the problem of liquefaction are summarized in the table on the following page. The list of methods shown in the table is not represented to be comprehensive; however, mitigation techniques against liquefaction may be classified in two groups--soil improvement and structural fortification.

Liquefaction Mitigation Techniques

I. Soil Improvement Methods

Dewatering
Relief Wells (to reduce porewater pressures)
Stone Columns (Vibro-replacement)
Excavation of Poor Soils and Replacement with Compacted Fill
Grout Injection
In Situ Densification (e.g., Vibroflotation, Terraprobe, Impact Densification, Dynamic Compaction, Compaction Piles, etc.)
Placement of Additional Fill (to increase overburden pressures and soil strength)

II. Structural Fortification

Strengthen Structural Connections
Add Grade Beams and Tie Beams
Extend Pile Support into Deeper Stable Soils

When considering the components that comprise the liquefaction risk, generally the soil improvement methods seek to eliminate, or, at least, reduce the Earthquake Hazard associated with liquefaction. The soil improvement methods are intended to reduce the susceptibility of the soils to liquefaction. Some methods deal with the groundwater which is a necessary ingredient in producing liquefaction. Liquefaction potential can be reduced by lowering the groundwater level, or by providing a means of relieving the excess porewater pressures that develop during an earthquake so that the effective confining stresses (and corresponding soil strengths) can be preserved. Other methods deal with improving or modifying the soil conditions. This can be done by either soil replacement, densification, or improving soil strength.

The structural fortification methods do not attempt to reduce the Earthquake Hazard; rather, they seek to reduce the Vulnerability of the structure to the consequences of liquefaction. This is done by designing the structure to withstand the added forces and deformations that would occur in the event of liquefaction. For example, piling could be used to carry the foundation loads into deeper non-liquefiable soils. In addition, the piling would also be required to withstand possible buckling because of lack of lateral support in liquefied soils and downdrag loads caused by settlement after liquefaction. Additional piles, perhaps some even battered, may be required to transfer the lateral forces in the structure into the ground. Floors at ground level may be required to be structurally supported if the consequences of floor settlement or cracking are not acceptable. Since connections between structural members seem to be more vulnerable than structural members, more attention and care would be needed in their design and construction against failure.

Many of these techniques have been used in mitigating against the effects and consequence of liquefaction around the world. Some applications of mitigation techniques that have been used are reported in the literature (see Ref. 7 to 11); the applications reported in the literature are exclusively soil improvement methods. However, structural fortification techniques have also been used. To the writer's knowledge, practically all of the mentioned mitigation techniques have been used in Southern California. Soil improvement methods have been used extensively in the hydraulic fill soils in the Long Beach Harbor and Terminal Island area. In situ densification by Vibroflotation, Terraprobe, and Dynamic Compaction have been utilized. However, there are numerous structures in the same areas that have been fortified structurally to withstand the possible effects of liquefaction. In most of these structures, piling was used to extend through the potentially liquefiable soils and into deeper stable soil; these piling were also designed to resist the lateral forces on the structures and also to resist buckling due to loss of lateral soil support within liquefied soils.

For the most part, few of the sites that have implemented mitigation techniques have actually experienced an earthquake that truly tests the adequacy and effectiveness of these techniques. However, Ishihara et al (Ref. 7) report that oil tanks supported on sand soils compacted by the in situ densification Vibroflotation technique suffered little damage and settlement in the 1978 Miyagiken-Oki earthquake, while nearby oil tanks supported on loose sand deposits that were not densified suffered considerable damage and significant settlement.

MITIGATION STRATEGY

Both soil improvement and structural fortification techniques seek to reduce the risk due to liquefaction by either reducing the Earthquake Hazard or the Vulnerability of the structure. Of course, both soil improvement and structural fortification methods can be used in combination for either added benefit or an optimization of liquefaction relief. However, since there will always be some cost involved, the Value of the structure will increase. An economic analysis may be required to determine whether the cost of mitigation results in a significant enough reduction in the risk.

As mentioned previously, soil improvement techniques generally deal directly with the Earthquake Hazard and seek to eliminate or, at least, reduce somewhat the level of the hazard. Thus, soil improvement is very positive in its approach with respect to reducing the risk. Also, it may be viewed that soil improvement, at its ultimate, would eliminate the liquefaction problem once and for all.

Structural fortification, on the other hand, concedes that liquefaction might occur and seeks to reduce risk by reducing the Vulnerability of the structure. This is a less positive approach to reduce risk. The structure could be subject to multiple events of liquefaction occurrence.

It would be reasonable to assume that some repair or replacement costs would be incurred after each event and these would have to be included as part of the increase in Value in the risk equation.

Ultimately, economics will govern what mitigation techniques are to be utilized, if any at all. The incremental cost of mitigation must be compared with the amount of reduction in the risk, and the natural human reluctance to expend additional monies for mitigation must be balanced with some level of risk that the owner is willing to accept. The role of insurance may also be an added consideration.

When referring to an acceptable level of risk, it should be kept in perspective that the philosophy that governs building codes generally is one of providing minimum standards to assure life safety. Building codes contain requirements that are intended to safeguard against major failures and loss of life; damage control is not generally a purpose of earthquake provisions in building codes. Exceptions to this are the notable provisions of Title 17 and Title 21 of the California Administrative Code regarding hospitals and schools. However, the life safety philosophy is the basis of the Recommended Lateral Force Requirements of the Structural Engineers Association of California (Ref. 17). Briefly, these requirements state that structures should be able to:

1. *Resist minor earthquakes without damage;*
2. Resist moderate earthquakes without structural damage, but with some nonstructural damage;
3. Resist major earthquakes, of the intensity of severity of the strongest experienced..., without collapse, but with some structural as well as nonstructural damage.

It may be interpreted that the moderate earthquakes are ones that may occur with a reasonable probability during the economic lifetime of the structure. The major earthquakes may be interpreted as those which may approach the severest earthquakes possible that may affect the site and may have relatively low probability of occurrence during the lifetime of the structure. If the life safety philosophy is adopted and the guidelines listed above are used, one means of evaluating the acceptable risk may be established.

Applying the guidelines listed above to liquefaction, it is suggested that if the probability of liquefaction occurrence is "significant" during the lifetime of the structure, the level of acceptable risk should not be very high, and mitigation should be given serious consideration. The amount and degree of mitigation should be determined by the cost and effectiveness of the various mitigation options available. If the probability is significant and the potential consequences are quite severe, it may be appropriate to consider the more positive soil improvement mitigation techniques. If the potential consequences are not believed to be too severe, structural fortification methods may be used rather than the usually more costly soil improvement techniques.

Conversely, if it is determined that the probability of liquefaction occurrence during the lifetime of the structure is low or "not significant", a decision could be made to perform a low level of mitigation which would at least protect life safety if the event did occur. It is possible that a decision could also be made to not mitigate against liquefaction if it was felt that the risk was acceptable.

No attempt will be made here to define what is a "significant" or a "not significant" level of probability. This definition should be made by the owner with proper consultation from his design consultants.

As liquefaction is not usually a local site problem, but rather one governed by much larger geologic and hydrologic factors that are perhaps more regional, mitigation options may sometimes be restricted. If liquefaction is expected to be very extensive in area and depth, encompassing more than the site under consideration, practical measures may be very limited or even not possible. In some cases, it may be impossible or impractical to mitigate the problem; for example, the liquefaction flow failure at Valdez involved almost 100 million cubic yards (75 million cubic meters). In such cases, another option would be one not previously mentioned--abandon the site and seek another one.

The available mitigation options may also be limited by the physical constraints of the site. Some techniques, particularly the soil improvement techniques, may not be practical because of their possible adverse effects on existing structures on the site or on adjacent properties.

CONCLUSIONS

Mitigation options are available when soil liquefaction is a possibility. The available options include soil improvement and structural fortification techniques. Soil improvement techniques seek to reduce the Earthquake Hazard of liquefaction, while structural fortification techniques attempt to reduce the Vulnerability of the structure to the consequences of liquefaction. The acceptable level of risk associated with liquefaction should be established on some rational basis; a life safety criteria has been suggested. The type of mitigation used should be a function of risk, taking into account the probability of occurrence during the expected useful lifetime of the structure, the consequences of liquefaction occurrence, and cost of mitigation.

One of the motives for this paper was to bring attention to the options available to mitigate against liquefaction. Much literature is published presenting new analytical methods and theories explaining the phenomena of liquefaction, while there are relatively few publications that deal with mitigation. It is hoped that this paper will encourage a dialogue and exchange of ideas and experiences in dealing with the consequences associated with liquefaction. It is also hoped that this paper will contribute to a more rational approach to make decisions about mitigation of liquefaction effects.

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