Performance-based Evaluation of Saturated Loess Ground Liquefaction

Évaluation des risques de liquéfaction d'un Loess saturé

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ABSTRACT: This paper reviewed the characteristics of loess liquefaction. Based on triaxial test, criteria for loess liquefaction is proposed. Later, Liquefaction evaluation procedure for both preliminary and detailed evaluation of loess liquefaction is modified for evluation of loess liquefaction. These modifications are based on study of liquefaction potential of loess and field test data, which now is adopted by Specification for Seismic Design of Buildings of Gansu Province, China. This progess marks a new milestone for study and treatment of loess liquefaction.

RÉSUMÉ : Cet article analyse les caractéristiques de liquéfaction d'un loess. A partir de l'essai triaxial, les critères de liquéfaction du loess est proposé. Ensuite, la procédure d'évaluation de liquéfaction pour l'évaluation préliminaire et détaillée de la liquéfaction du loess est modifiée pour évaluer la liquéfaction du loess. Ces modifications sont fondées sur l'étude du potentiel liquéfaction du loess et des données d'essai in situ. Cette procédure est maintenant adoptée dans les recommandations pour la conception parasismique des bâtiments de la province du Gansu, en Chine. Cette avancée marque une nouvelle étape pour l'étude et le traitement de la liquéfaction du loess.

KEYWORDS: loess, liquefaction, performance-based design, seismic code.

1 INTRODUCTION

Loess is a problematic soil in terms of its property in civil engineering. Studies revealed that saturated loess ground has high potential of liquefaction (Ishihara 1990, Wang 2000 & 2003, Hwang and Wang 2000) under effect of earthquake ground. During the Great Haiyuan Earthquake of 1920 in China, a sandy layer of loess liquefied and triggered flow of nearly horizontal loess ground with maximum displacement of nearly 1.5km (Bai & Zhang, 1990). During the 5.5 magnitude earthquake occurred in Tajikistan in 1989, liquefied loess layer turned into mud flow and buried one village.

Through series studies carried out by Wang L.M. et al. the liquefaction of loess is better understood and recognized by more and more professionals in China. The cases in China and Tajikistan show that it surely exists and could be disastrous. Liao S.X also reported the loess liquefaction caused by vibration during ground treatment of loess ground (Liao 2007).

In order to properly treat liquefaction potential of loess ground, it is important to establish proper procedures for evaluation of loess liquefaction both in laboratory and in the field.

2 THE CHARACTERISTICS OF LOESS LIQUEFACTION

Liquefaction of loess is a flow type of liquefaction. That is, under the effect of cyclic loading, the pore water pressure in loess rises, effective stress is down and large amount of residual strain develops, finally, loess loses its strength and became mud flow. The amount of residual strain could easily reach 10% during liquefaction test of loess.

Loess has the low permeability; pore water movement is quite uneven at different parts of the sample, most of the pore water running through the channels composed with the round holes and channels connecting or around them. For sand liquefaction, it is the result of densification of sand structure which forced some portion of water move out from the skeleton and even rise up. But for loess, because of its low permeability, water cannot move as freely as it is in sand. As a result, the pore water pressure build up applies shear stress to loess structure and causes it to collapse. The collapse and consequentially, the development of larger amount of residual strain are because of loess structure is porous with void ratio usually more than 1.

3 CRITERIA OF LOESS LIQUEFACTION BASED ON TRIAXIAL TEST

Due to the characteristics of loess liquefaction, there is need to establish test criteria to assess liquefaction potential. Laboratory test using triaxial, it is found that because of the pore microstructure, weak cementation among particles and the hydraulic sensitivity of the loess, the air in the enclosed void is difficulty to discharge. Usually, the degree of saturation ranges from 0.8 to 0.95.

3.1 Loess liquefaction test under isotropic and anisotropic consolidation

Generally, under the isotropic consolidation, the excess pore pressure of the saturated undisturbed and remolded loess can reaches the effective consolidation pressure. When the axial strain is less than 2%, the structure of the loess is relatively stable and the excess pore pressure increases continually; when the axial strain reaches 3%, the excess pore pressure increases obviously and the deviatoric stress decreases obviously; when the axial strain is more than 3%, the axial strain increases largely, the increase of the excess pore pressure is slow and can be negative value, and the soil is destroyed.

Figure 1 is development curve of the excess pore pressure, deviatoric stress and axial strain of undisturbed loess with loading cycles under the anisotropic consolidation. The effective consolidation pressure is 130kPa and the consolidation ratio is 1.2.

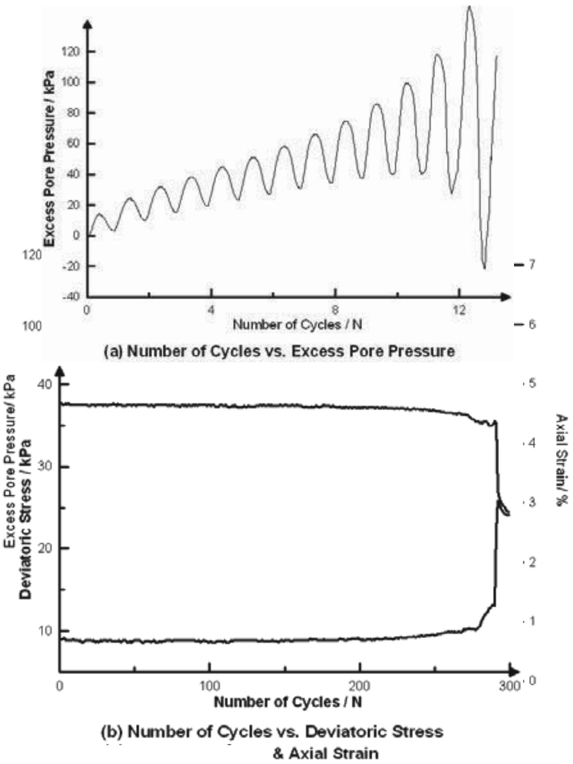

Figure 1. Development of excess pore pressure, deviatoric stress, axial strain of saturated undisturbed loess under the anisotropic consolidation.

In Fig.1, 3% axial strain occurs before the biggest value of excess pore pressure. Before 3% axial strain, the axial strain and excess pore pressure increase slowly; after 3% axial strain, the excess pore pressure still increases slowly and the axial strain increases largely.

Under anisotropic consolidation, the excess pore pressure cannot reach the consolidation pressure when the loess liquefied after anisotropic consolidation. For a cyclic loading, the changes of the excess pore pressure can increase or decrease. Only when one cycle finishes, the excess pore pressure can have a pure increase. When the excess pore pressure accumulates to a certain level, it can reach the effective consolidation pressure, i.e., instant liquefaction. Under isotropic consolidation, the instant liquefaction occurs when the deviatoric stress reaches zero. While under anisotropic consolidation, the deviatoric stress can be divides into two parts: one is deviatoric stress applied during consolidation; another is axial stress applied during vibration. The vibration causes the volume of voids decrease. The water in the voids cannot discharge in time, which leads to the increase of the excess pore pressure, sharp decrease of the effective stress applied on the soil skeleton. The loss of the soil strength makes the application of the outer axial stress impossible. While another part stress, deviatoric stress applied during consolidation has been applied to the sample all the time. When the deviatoric stress reaches the deviatoric consolidation stress, the soil has been liquefied. It means that the excess pore pressure can never reach the effective consolidation pressure because of the presence of the deviatoric consolidation stress.

3.2 *Criteria for loess liquefaction based on triaxial test*

As test results shows that for saturated loess, when the axial strain increases to reach 3%, the development of residual strain increase sharply, which indicates a substantial change of loess structure, or to say that the loess structure collapses at this juncture. Because the collapse of the loess structure, pore water enters some of the previously enclosed pores and prevent the excess pore pressure from reach the effective consolidation pressure if the loess structure collapse created enough pores to be filled with pore water. Wang L. M. et al. pointed out that 3% is the value of the axial strain of the structural damage for loess (Wang, 2003).

Based on the triaxial test study on the behavior of the undisturbed and remolded loess, the criteria for the discrimination loess liquefaction using triaxial test data are given as follows:

i) Under the isotropic consolidation,

$$\varepsilon_d \geq 3\% \ \& \ \frac{u_d}{u_f} \geq 0.4 \qquad (1)$$

$$\frac{u_d}{u_f} = 1 \qquad (2)$$

Of the two criteria, the one which firstly reaches, would be adopted.

ii) Under the anisotropic consolidation,

$$\varepsilon_d \geq 3\% \ \& \ \frac{u_d}{u_f} \geq 0.2 \qquad (3)$$

As discussed above, 3% axial strain is the structural damage value of the loess. And the increase of the pore pressure ratio of loess during liquefaction is mostly determined by two factors: one is degree of saturation and the other is structure strength of loess microstructure. To reach the status of liquefaction, pore pressure ratio is generally lager than 0.4 for isotropic consolidation and 0.2 for anisotropic consolidation. The latter has a lower pore water pressure because the structure collapse is more significant for anisotropic consolidated samples. The higher strength of loess microstructure, the longer the continuous buildup of pore water pressure, usually, loess with more sand content will reach higher pore pressure ratio during liquefaction test.

When residual strain is used to evaluate liquefaction potential of loess, pore pressure ratio must be used at the same time. Only there is clearly indication of pore water buildup, loess shows a "sand-like" characteristics of liquefaction, if there is no significant buildup of pore water pressure, the development of larger amount of residual strain can only be regarded as "clay-like" cyclic soften and cannot be classified as liquefaction .

4 PRILIMINARY EVALUATION OF LIQUEFACTION POTENTIAL OF LOESS

4.1 Loess Liquefaction evaluation in Code for Seismic design of buildings in Lanzhou Urban area

To minimize the effect of loess liquefaction, evaluation of loess liquefaction is the first step for treatment of loess ground to reduce or eliminate liquefaction potential. Lanzhou is located in Loess Plateau and in recent decades, the urban area of Lanzhou expands very quickly. Since the national "Code for Seismic Design of buildings (GB50011-2001)" does not reflect adequately all problems concerning seismic safety in Lanzhou. In 2006, the Provincial Department of Construction entrusted Provincial Committee on Architecture Sciences and Lanzhou Institute of Seismology to draft new code for seismic design of buildings for Lanzhou Urban Area (Lanzhou Code). Wang L.M et al. applied the research results into practices through drafted Lanzhou Code, which is the first local engineering specification for the discrimination and treatment of loess liquefaction.

In Lanzhou Code, the concept of performance-based design was incorporated in a cautious way. That is, although performance based recommendations are made for ground treatment for buildings of different importance under different geotechnical seismic hazard setting, no such recommendation were made for structure design.

The significance of the Lanzhou code is liquefaction of loess is formally introduced as one of the hazard needs to be considered for seismic design. This provides practical experience for better evaluation of loess liquefaction and its treatment. Furthermore, it also laid foundation for incorporate loess liquefaction in wider region such as Gansu province.

4.2 Preliminary evaluation of loess liquefaction in Specification for seismic design of buildings of Gansu province

To update seismic design in Gansu province and also adopted some of the local conditions and practices, the Gansu Committee of Construction Experts started draft of new specification for seismic design in Gansu province. The authors were involved in draft provisions on loess liquefaction. This time, a lot of new findings and new methods were discussed, which results a much mature guidelines for evaluation of loess liquefaction. The Specification on Seismic Design of Gansu Province (DB62/T25-3055-2011) (to be referred as Gansu code) provide much better method for evaluation of loess liquefaction both in term of reliability and feasibility.

The preliminary evaluation of liquefaction of loess adopted in Gansu code is as follows:

1) Saturated new loess (geological age younger than the middle of Quaternary)
2) And Under design seismic intensity of 7, 8 and 9, the content of clay is less than or equals 12, 15 and 18 respectively.

If the saturated loess meets both of the two criteria, it should be further considered for liquefaction potential evaluation and treatment.

The first clause is the same as the national seismic code. Until now, all cases of liquefaction of loess are found in deposit with age from Q_4 to Q_3.

Loess has a wide range of clay content. Hwang and Wang conducted liquefaction test (Hwang and Wang, 2000) on loess from China and the United States and found that even with clay content of 19%, loess can liquefy under certain ground motion level. To take this fact into consideration, in the second clause, the clay limit for liquefiable loess raised 2% under all design seismic intensities compared with the national seismic design code.

5 DETAILED LOESS LIQUEFACTION EVALUATION BASED ON SPT

If the loess deposit is evaluated as liquefiable using the preliminary evaluation methods, it should be evaluated with field test data to give more accurate information of soil liquefaction compared with preliminary evaluation.

5.1 SPT of loess sites

Fig.2 shows the SPT value of loess ground with different degree of saturation. The SPT value of loess ground ranges from 1.8 to 14. Usually, for loess if degree of saturation is at 0.7 or above, it is relatively "saturated" and liquefaction is possible if other conditions also satisfy. Based on this assumption, the SPT of loess ground is classified into two groups, one with degree of saturation (S_r) less than 0.7, the other group has Sr≥ 0.7. Largely, the saturated loess ground has less SPT values compared with loess with lower S_r. The calculated average SPT for loess ground with low degree of saturation is 9.4, while that for loess ground with high degree of saturation is 6.3.

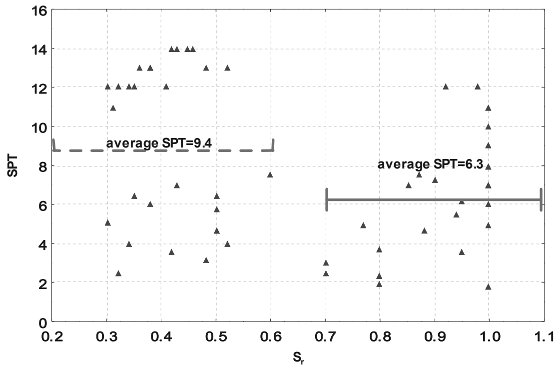

Figure 2. SPT value of loess ground

Compared with other types of soils such as sand and gravel, the SPT value of loess ground is the lowest (Fig. 3). The most relevant comparison of SPT value is between saturated loess and saturated sand ground. This causes it problematic for detailed evaluation of loess liquefaction to simply copy that in national seismic design code.

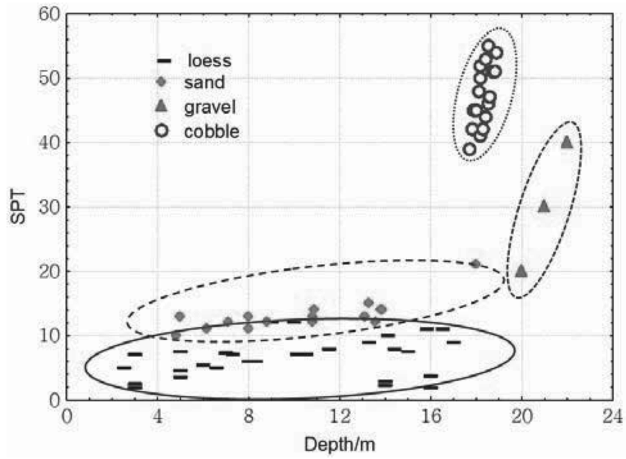

Figure 3. SPT value of loess, and, gravel and cobble

5.2 Loess liquefaction evaluation using approach from National seismic design code

In Chinese national seismic code, formula (4) is used to evaluate liquefaction of sand and silt soils (loess is exclude.).

$$N_{cr} = N_0\beta[\ln(0.6d_s + 1.5) - 0.1d_w]\sqrt{3/\rho_c} \quad (4)$$

In the formula, N_{cr} is critical value of SPT for liquefaction evaluation, if SPT value from a site is larger than N_{cr}, then the site would not liquefy and has no liquefaction potential under the circumstance. Otherwise, if the SPT value of a site is less than N_{cr}, the site is liquefiable, it liquefaction potential should be calculated.

N_o is reference SPT value for liquefaction evaluation, it is an empirical value assign based on large amount of field data. In national seismic design code, the N_o for different ground motion level of design is given as Table 1.

Table 1. Reference SPT value for liquefaction evaluation (From Chinese Seismic design code (GB50011-2010)).

PGA(g)	*0.10*	*0.15*	*0.20*	*0.30*	*0.40*
N_0	7	10	12	16	19

The β is a parameter depends on site condition which is classified into three groups using characteristic period. For site with longer period, which also means soft soil, β is larger.

The d_s is depth of soil layer for liquefaction evaluation in meters.

The d_w is depth of ground water table.

The ρ_c is clay content in percentage.

Using formula (4), N_{cr} for all the loess ground was calculated. Under most cases, N_{cr} is larger than SPT value of the loess site. As a result, 94% of the cases will be evaluated as liquefiable. This creates significant exaggeration of loess liquefaction. Hence, the loess ground has liquefaction potential should be relatively loose and SPT value should be lower than average, the evaluation based o approached recommend in Chinese seismic design code is contradictive and cannot be apply for loess ground without modification.

5.3 Modified approach for detailed evaluation of Loess liquefaction

To reflect the fact that SPT value of saturated loess is generally less than that of sand, a simple modification is to reduce N_0 for loess site. After consultation with engineers, the recommended reference SPT for liquefaction of loess ground adopted by Specification for Seismic design of Buildings of Gansu Province is given as Table 2.

Table 2. Reference SPT value for liquefaction evaluation of loess ground (Adopted by Specification of Seismic Design of Buildings of Gansu Province, 2012).

PGA(g)	*0.10*	*0.15*	*0.20*	*0.30*	*0.40*
N_0	7	8	9	11	13

Except for PGA of 0.10g, N0 for loess liquefaction evaluation is reduced by 2 to 6 to avoid exaggeration of loess liquefaction potential.

Incorporate the modification of N0, loess liquefaction evaluation results shows that the number of loess ground evaluated as liquefiable decreased, the percentage of loess site evaluated as liquefiable and mean N_{cr} is given as Table 3.

Table 3. Percentage of liquefiable loess site and mean Ncr using the modified approach for liquefaction evaluation of loess ground (Adopted by Specification of Seismic Design of Buildings of Gansu Province, 2012).

PGA(g)	*0.10*	*0.15*	*0.20*	*0.30*	*0.40*
Percentage of liquefiable site	19	25.8	48	71	84
Mean of N_{cr}	4.5	5.2	5.8	7.1	9.1

With the modification , the N_{cr} calculated is more reasonable. The percentage of loess ground regarded as liquefiable is only 19% under ground motion of 0.10g, and 84% under ground motion of 0.4g.

5.4 Calculating of Liquefaction Index

Liquefaction index is an indicator of possibility of loess liquefaction under different ground motion effect. The liquefaction index is determined by formula (5)

$$I_{lE} = \sum_{i=1}^{n} [1 - \frac{N_i}{N_{cri}}] d_i W_i \qquad (5)$$

Where I_{lE} is liquefaction index, N_i is SPT values of layer i, N_{cri} is critical SPT value for liquefaction evaluation, d_i is thickness of soil layer I, Wi is weight factor of thickness.

If $0 < I_{lE} \leq 6$, the site has slight liquefaction potential;
If $6 < I_{lE} \leq 18$, the site has moderate liquefaction potential;
If $I_{lE} > 18$, the site has high liquefaction potential.

6 CONCLUSIONS

From this study, the following conclusions can be drawn:
1) Loess liquefaction has its unique characteristics, which is larged determined by porous and weak cementation of loess microstruce.
2) To discriminate liquefaction of loess liquefaction based on triaxial test, the purpose is to make sure that loess show "sand-like" behavior. Since the microstruce of loess collpase and pore water could fill the enclosed pores, the pore water pressure increase during loess liquefaction often below than confining pressure.
3) Consider the effection of isotropic and anisotropic consolidation, certiera for discrimianting of loee liquefaction is given by combined a residual strain and a minimum pore pressure ratio.
4) For preliminary evaluation of loess liquefaction, the age and clay content should be used. For loess, the range of clay content is higher, clay content limit for loess liquefaction is raised by 2%.
5) The approach for detailed liquefaction evluation recommended in Chinese seismic design code is still useful for loess liquefaction evaluation. But since the SPT value of saturated loess is less than that of sand, N_0 is reduced to reflect the fact and avoid exaggeration of loess liquefaction.

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