Advancement of liquefaction assessment in Chinese building codes

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Abstract. China has suffered extensive liquefaction hazards in destructive earthquakes. The post-earthquake reconnaissance effort in the country largely advances the methodology of liquefaction assessment distinct from other countries. This paper reviews the evolution of the specifications regarding liquefaction assessment in the seismic design building code of mainland China, which first appeared in 1974, came into shape in 1989, and received major amendments in 2001 and 2010 as a result of accumulated knowledge on liquefaction phenomenon. The current version of the code requires a detailed assessment of liquefaction based on in situ test results if liquefaction concern cannot be eliminated by a preliminary assessment based on descriptive information with respect to site characterization. In addition, a liquefaction index is evaluated to recognize liquefaction severity, and to choose the most appropriate engineering measures for liquefaction mitigation at a site being considered.

Key words: liquefaction assessment; seismic design code; anti-seismic design

1. Introduction

Liquefaction often occurs in saturated granular soils due to earthquake shaking, and causes significant damages on buildings and other urban infrastructure systems as a result of dramatic reduction in strength of liquefied soils. As one of the most important subjects in the field of geotechnical earthquake engineering, the phenomenon of liquefaction has attracted intensive studies in the world after two major earthquakes in 1964 [1]. Liquefaction assessment has become part of seismic design of any important project located in seismically affected areas prone to liquefaction. Like other seismically active regions, China has also suffered from several devastating earthquakes with over one hundred thousand casualties in the past century [2] including 1976 Tangshan earthquake, in which extensive examples of liquefaction have been observed. With accumulated knowledge on liquefaction, the specifications related to liquefaction assessment appeared in the national seismic building code in mainland China in 1974 and received three major amendments according to lessons learnt from

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historical strong earthquakes. Although the blow count of a standard penetration test (SPT) is also employed in Chinese building codes to feature liquefaction resistance of a site, the detailed procedure is less acquainted elsewhere in the world and distinct from the simplified procedure originally proposed by Seed and his colleagues [1, 3, 4]. Chen [5] provided a good review in the local language on the revolution of the Chinese seismic design code before 2001. Yuan and Sun [6] proposed further improvement based on an overview of the state of practice of liquefaction assessment specified in the Chinese building code. However, the readership of their works was confined locally due to language, and a comprehensive review on the upgrade in the past 15 years remains insufficient. This constitutes the motivation of this paper.

2. Timeline of major earthquakes and amendments in Chinese building codes

Earthquake-induced liquefaction has occurred in almost every strong earthquake in China. A comprehensive overview of typical liquefaction phenomena and their characteristics during recent major earthquakes in China can be found in [2]. Some new phenomena, such as liquefaction of gravelly soil and deep-level sandy soils, and re-liquefaction, have been also observed in these recent earthquakes, drawing increasing attention in further study [2]. Among other strong earthquakes, 1970 Tonghai earthquake, 1975 Haicheng earthquake, and 1976 Tangshan earthquake provided particularly important data resulting in improvements in the liquefaction assessment procedure adapted in Chinese building codes [6].

Figure 1 illustrates the timeline of a number of major earthquakes in mainland China and the milestones leading to evolution of Chinese seismic building codes particularly regarding liquefaction assessment. The efforts for launching a national seismic code began in early 1920s by conducting intensive site investigations after 1918 Nanao earthquake in Guangdong province with the magnitude of 7.3 and 1920 Haiyuan earthquake in Ningxia Province with the magnitude of 8.6. These efforts resulted in the first seismic intensity map in China, but further studies were unfortunately terminated due in large part to the wars. Because of an increasing demand of seismic disaster mitigation after the civil war in China, a revisit of previous work gave birth to the first draft of Chinese seismic design code Building Regulations in Seismic Area published in 1959, in which the seismic design is based on the response spectrum theory in compliance with the Building Regulations in Seismic Area CH-8-57 published by the former Soviet Union. The draft version of Seismic Code of Building was accomplished and available in 1964. This draft introduced the concept of site classification, which paved the way for the first specification regarding liquefaction concern in Seismic Code for Industrial and Civil Buildings (TJ11-74) available in 1974 [7]. This code implements liquefaction assessment by comparing the field measurement of SPT blow count and the critical blow count, below which liquefaction likely occurs. As a milestone, the code TJ11-74 introduced a quantitative approach to evaluate liquefaction potential of a site, and accordingly provided detailed guidelines on selecting appropriate engineering measures for liquefaction mitigation. Since then, liquefaction assessment becomes a routine practice of seismic design of buildings in China. The code TJ11-74 was revised four years later in order to implement lessons learnt from the disastrous earthquake at Tangshan, and an updated code Seismic Code for Industrial and Civil Buildings (TJ11-78) was available to public in 1978 [8]. However, the terms regarding liquefaction assessment remain largely unchanged in the updated version. By looking back at the lessons learnt from earthquakes taking place during 1970 to 1989, a further update was made and Code for Seismic Design of Buildings (GBJ11-89) entered into force in 1989 [9]. The major revisions regarding liquefaction assessment in GBJ11-89 is the first usage of the liquefaction index, which indicates liquefaction severity and guides the anti-liquefaction design. Another amendment was made in 2001 [10] to extend the depth limit of liquefaction assessment from 15 m to 20 m, considering liquefaction observed in deep-level sandy soils in the historical earthquakes. This revision was implemented into Code of Seismic Design of Buildings (GB50011-2001), and was continuously used in the latest version of national code in mainland China, Code of Seismic Design of Buildings (GB50011-2010) [11], which incorporated a number of new findings from strong motions taking place in 2000s including the catastrophic shake in 2008 at Wenchuan. In summary, the country
was frequently attacked by strong earthquakes, which prompted advancement in the seismic building codes particularly regarding liquefaction assessment.

3. Methodology of liquefaction assessment adapted in Chinese seismic codes and its revolution

3.1 The Basic Principle

Figure 2 schematically illustrates the flow chart of liquefaction assessment adapted in the current version of Chinese seismic design code of buildings [11], which remains largely unchanged from the earlier version TJ11-89 [8]. As shown in the figure, the general procedure includes site characterization, preliminary assessment (qualitative), detailed assessment (quantitative) and liquefaction severity recognition.

In the phase of site characterization, a comprehensive set of information about the site is collected, including the building classification, hydraulic conditions of the site, seismic characteristics of the site, and the site classification. A preliminary assessment is then conducted based on the information in a qualitative manner by simply looking up the matrix of site characterization. A further quantitative assessment in details is necessitated if the site is recognized as liquefiable in the step of preliminary assessment. If the detailed assessment indicates the site is prone to liquefaction, liquefaction severity is identified using the liquefaction index and guides the anti-liquefaction design. The general framework of liquefaction assessment was preserved in the past nearly 30 years, while the detailed procedure in each step has been evolved with growing knowledge on liquefaction obtained from post-earthquake reconnaissance. The remaining of this section is to review the major revisions of each step.

| No. | Year | Event |
|-----|------|-------|
| 1   | 1920s | The first seismic intensity map |
| 2   | 1959  | Building Regulations in Seismic Area (draft): the first version of building regulation at seismic areas in mainland China |
| 3   | 1964  | Seismic Code of Building (draft): implementing the concept of site ranking, which paved the way for liquefaction assessment |
| 4   | 1974  | Seismic Code for Industrial and Civil Buildings (TJ11-74): the first national seismic code with consideration of liquefaction |
| 5   | 1978  | Seismic Code for Industrial and Civil Buildings (TJ11-78): revisions after 1976 Tangshan earthquake. |
| 6   | 1989  | Code for Seismic Design of Buildings (GBJ11-89): usage of liquefaction index |
| 7   | 2001  | Code of Seismic Design of Buildings (GB50011-2001): extending the depth limit from 15 m to 20 m in liquefaction assessment |
| 8   | 2010  | Code of Seismic Design of Buildings (GB50011-2010) |

Figure 1. Major amendments of Chinese seismic building codes regarding liquefaction assessment inspired by destructive earthquakes in mainland China.
3.2 Amendments

3.2.1 Site characterization

The information collected in the phase of site characterization provides necessary data or parameters for liquefaction assessment. Building classification indicates different levels of importance of buildings according to their types and functions, and hydraulic conditions are mainly about the ground water table and its seasonal variation. The methods used to feature these two groups of information have not been significantly altered, while several major amendments have been made for seismicity characterization and site characterization attributed to a rapid advancement of geotechnical field testing techniques and seismic theory.

The national seismicity zonation is the prior information for site characterization. Table 1 summarizes the evolved approaches for seismicity zonation in China. The earliest seismic map of China was published in 1920s, and however it only covered eastern China. A complete seismic map of the entire country was not available until 1956 after the civil war. This map use Chinese seismic intensity scale to classify seismic impacts into 12 degrees of intensity in Roman numerals from I for insensible to XII for landscape reshaping, in a similar manner of the 1992 version of the European macroseismic scale (EMS-92). This approach had been continuously used in the subsequent two upgraded versions until the 2001 version, in which a subjective evaluation was developed based on the peak ground acceleration and the characteristic period of the response spectra. Additionally, a probabilistic approach was implemented. This framework continues in the latest 2010 version, which is still under development. Note that the upgrade of the seismic evaluation has affected the procedure of liquefaction assessment adapted in the Chinese building codes.

| Version       | Seismic parameter(s)                                                      |
|---------------|---------------------------------------------------------------------------|
| 1956 Version  | Seismic intensity                                                         |
| 1977 Version  | Seismic intensity                                                         |
| 1990 Version  | Current standard issue by using seismic risk analysis of comprehensive     |
|               | probability method                                                        |
| 2001 Version  | The peak ground acceleration and the period of response spectra            |
| 2011 Version  | The peak ground acceleration and the period of response spectra            |
Table 2 lists the evolution of site characterization in different versions of the Chinese seismic building code. Initially, a very rough categorization was used in the 1964 draft of Seismic Code of Building by considering types of soils underlying the site. The descriptive approach remained in TJ11-74 (see Table 3) and the site categories were reduced from four to three: rock, soil and soft soil. With the development of in situ testing tools, a more precise approach based on the shear wave velocity was proposed in GB50011-2001 for characterizing a site in the quantitative manner (see Table 4). This approach remains in the latest version GB50011-2010, while the class I is divided into two sub-classes (i.e., I₀ and I₁) to further distinguish a site with equivalent shear wave velocity over 800 m/s (see Table 5).

### Table 2. Evolved methods for site classification

| Code version     | Method                                                                 |
|------------------|------------------------------------------------------------------------|
| 1964 Draft       | Descriptive terms (qualitative)                                        |
| TJ11-74          | Descriptive terms (qualitative with more accurate statement)           |
| GBJ11-89         | Descriptive terms (qualitative) and consideration of rigidity of soils and overburden thickness (quantitative) |
| GB50011-2001     | Consideration of equivalent shear wave velocities (quantitative)       |
| GB50011-2010     | Consideration of equivalent shear wave velocities in a wide range (quantitative) |

### Table 3. Qualitative site classification in TJ11-74

| Site category | Description                                                                 |
|---------------|-----------------------------------------------------------------------------|
| I             | Rocks consisting of strongly cemented rocks.                                 |
|               | General soils consisting of gravels, sands, clays soil, collapsible loess and other geomaterials excluded in I and III. |
| II            | Soft soils consisting of saturated loose sands, high plastic light loam, muck and mucky soil, soft soils with high compressibility, and fills. |
| III           |                                                                                     |

### Table 4. Quantitative site classification in GB50011-2001

| Equivalent shear wave velocity $V_{se}$ (m/s) | Averaged thickness of overlaying soils (m) |
|----------------------------------------------|------------------------------------------|
| $V_{se} > 500$                               | 0                                        |
| $500 \geq V_{se} > 250$                      | $< 5$                                    |
|                                              | $\geq 5$                                  |
| $250 \geq V_{se} > 140$                      | $< 3$                                    |
|                                              | $3 \sim 50$                               |
|                                              | $> 50$                                    |
| $V_{se} \leq 140$                            | $< 3$                                    |
|                                              | $3 \sim 15$                               |
|                                              | $15 \sim 80$                              |
|                                              | $> 80$                                    |

### Table 5. Quantitative site classification in GB50011-2010

| Equivalent shear wave velocity $V_{se}$ (m/s) | Averaged thickness of overlaying soils (m) |
|----------------------------------------------|------------------------------------------|
| $V_{se} > 800$                               | 0                                        |
| $800 \geq V_{se} > 250$                      | 0                                        |
| $500 \geq V_{se} > 250$                      | $< 5$                                    |
|                                              | $\geq 5$                                  |
| $250 \geq V_{se} > 150$                      | $< 3$                                    |
|                                              | $3 \sim 50$                               |
|                                              | $> 50$                                    |
| $V_{se} \leq 150$                            | $< 3$                                    |
|                                              | $3 \sim 15$                               |
|                                              | $15 \sim 80$                              |
|                                              | $> 80$                                    |
3.2.2 The preliminary assessment

In general, liquefaction assessment is not required at a site with the seismic intensity of 6. To be effective, TJ11-89 started to recommend a preliminary assessment of liquefaction potential of a site before a detailed evaluation. The preliminary assessment is qualitatively conducted in a rapid manner simply based on the descriptive information collected in the phase of site characterization. According to TJ11-89, liquefaction concern can be eliminated in any of the following circumstances:

1) Soil deposits at the site are the Late Pleistocene of Quaternary ($Q_3$) deposits or older;

2) The fine content of the soils (with the particle size less than 0.005 mm) at the site is more than 10%, 13% or 16% if a site is designed at the seismic intensity of 7, 8, or 9 at the China scale, respectively;

3) The unliquefiable regime is inferred based on Figure 3 for a shallow foundation embedded at a depth less than 2 m.

These terms remains largely unchanged in GB50011-2010 except two minor amendments: (1) The first term above was amended as “Soil deposits at the site are the Late Pleistocene of Quaternary ($Q_3$) deposits or older if the seismic intensity is 7 or 8”; (2) It explicitly states that the preliminary assessment was not suitable for loess.

![Figure 3](image)

**Figure 3.** Liquefaction preliminary assessment chart ($d_w$ and $d_v$ are the depth of the underground water table and thickness of the overburden unliquefiable layer, respectively. Note that this chart is also applicable to foundations with embedded depth of 2~5 m by replacing $d_w$ and $d_v$ with corrected values)

3.2.3 The detailed assessment

A detailed quantitative assessment of liquefaction potential is required if liquefaction concern cannot be eliminated in the preliminary assessment. In general, liquefaction is inferred by the following inequality:

$$N_{63.5} \leq N_{cr}, \text{ liquefiable}$$  \hspace{1cm} (1)

in which the basic principle is to compare the SPT blow count measured at the site without length correction ($N_{63.5}$) and the critical SPT blow count ($N_{cr}$), below which the site being considered likely liquefies. This differs from the simplified procedure proposed by Seed and Idriss [1], which compares the cyclic stress ratio representing the earthquake demand and the cyclic resistance ratio inferred from in situ tests such as SPT, cone penetration tests and shear wave velocity test [4]. The SPT method is the only quantitative liquefaction assessment method mentioned in GB50011-2010. Note that SPT is not applicable to some particular soils such as gravelly soils [12,13,14,15], and thus GB50011-2010 cannot deal with liquefaction assessment for such soils. Nevertheless, some other methods are included in some local building codes and speciality codes. For example, the shear wave velocity
method was used in local building code of Tianjing City (TBJI-88) [16], and the method based on cone penetration test (CPT) was also suggested in Code for Investigation of Geotechnical Engineering (GB50021-2001)[17].

Although Eq. (1) has not been changed in the subsequent upgrades since it first appeared in TJ11-74, the procedure to determine \( N_{cr} \) has been updated several times as summarized in Table 6. Considering the formula for computing \( N_{cr} \) in TJ11-74 being less reliable for clayey soils, TJ11-89 took the effect of the fine content into account and provided a unified formula for sandy and clayey soils. Due to increasing demand of deep foundations, the impact depth of liquefaction was extended from 15 m to 20 m. The formula of \( N_{cr} \) was accordingly modified in GB50011-2001 to manipulate the liquefaction assessment in deep soils. In the current version GB50011-2010, a unified formula was developed for an entire depth profile and a corrected factor \( \beta \) was introduced to account for the effect of seismic levels. In general, \( \beta \) is equal to 0.80, 0.95 and 1.05 at the first, second and third types of earthquake, respectively. The type of design earthquake is defined according to Table 7.

Regardless of changes in the formula for computing \( N_{cr} \), the reference blow count (\( N_0 \)) is always a necessary parameter related to seismic input, and its suggested values have been changed in accordance with the evolution of seismic zonation in China. In the earliest version TJ11-74, \( N_0 \) is assigned based on seismic intensity at the China scale. The updated version GBJ11-89 suggests distinguishing different earthquake types (i.e., near-field earthquake and far-field earthquake). Since 2001, the peak ground acceleration has been used as one of the parameters in seismic zonation in China, and accordingly \( N_0 \) is assigned based on the peak ground acceleration instead of seismic intensity. Table 8 provides suggested values of \( N_0 \) in the latest code GB50011-2010 for the peak ground acceleration no more than 0.4g, above which GB50011-2010 provides no detailed guidance unfortunately.

### Table 6. Formula for calculating \( N_{cr} \) in different versions of national seismic code in China

| Code version | Formula for the critical SPT blow count | Improvement |
|--------------|----------------------------------------|-------------|
| TJ11-74      | \( N_{cr} = N_0[1 + 0.125(d_s - 3) - 0.05(d_w - 2)] \) | Corrected SPT blow count according to depth and ground water table |
| GBJ11-89     | \( N_{cr} = N_0[0.9 + 0.1(d_s - d_w)]\sqrt{3/\rho_c} \) | Effect of fine content |
| GB50011-2001 | \( N_{cr} = \begin{cases} N_0[0.9 + 0.1(d_s - d_w)]\sqrt{3/\rho_c}, & d_s \leq 15 \\ N_0(2.4 - 0.1d_s)\sqrt{3/\rho_c}, & 15 < d_s \leq 20 \end{cases} \) | Impact depth extended from 15 m to 20 m |
| GB50011-2010 | \( N_{cr} = N_0\beta[\ln(0.6d_s+1.5)-0.1d_w]\sqrt{3/\rho_c} \) | A correction factor \( \beta \) |

*Note: \( d_s \) – SPT depth (m); \( d_w \) – underground water level (m); \( N_0 \) – reference SPT blow count; \( \rho_c \) – fine content in percentage (\( \rho_c = 3 \) if fine content is less than 3%); \( \beta \) – correction factor depending on the seismic level.

### Table 7. Characteristic periods of earthquake in GB50011-2010

| Type of design earthquake | I_0 | I_1 | Site type | II | III | IV |
|---------------------------|-----|-----|----------|----|-----|----|
| First type                | 0.20| 0.25|          | 0.35| 0.45| 0.65|
| Second type               | 0.25| 0.30|          | 0.40| 0.55| 0.70|
| Third type                | 0.30| 0.35|          | 0.45| 0.65| 0.90|

### Table 8. The reference blow count of SPT in GB50011-2010

| The basic design earthquake acceleration (g) | 0.10 | 0.15 | 0.20 | 0.30 | 0.40 |
|---------------------------------------------|------|------|------|------|------|
| The reference value of SPT, \( N_0 \)       | 7    | 10   | 12   | 16   | 19   |
3.2.4 Liquefaction severity

Assessment at an individual depth is inadequate to define the severity of liquefaction of an entire profile of a site. Accordingly, the liquefaction index \( I_{LE} \) appeared in GBJ11-89 to indicate the severity of liquefaction at a site. This index can be computed as follows:

\[
I_{LE} = \sum (1 - N_i/N_{cr}) d_i \omega_i
\]  

where the subscript \( i \) denotes the number of the layer, \( d \) is the thickness in meter, and \( \omega \) is the weight factor decreasing with the increase of the depth of the layer as illustrated in Figure 4. This definition is similar to the liquefaction potential index proposed by Iwasaki et al. [18,19] by considering the blow count ratio as a safety factor against liquefaction.

The usage of \( I_{LE} \) provides a way to distinguish different levels of liquefaction severity. Table 9 provides the categories of liquefaction severity based on the liquefaction index in different versions of the code. Note that the border values for each category have been slightly justified to account for the change of impact depth of liquefaction. Another benefit of \( I_{LE} \) is to group routine design options into different levels of liquefaction severity, providing guidance on appropriate engineering measure to mitigate liquefaction hazards for different building types defined in Table 10. For the significant buildings falling into Category I, particular in-depth anti-liquefaction design should be conducted. Table 11 provides general guidelines on engineering measures of liquefaction mitigation for other buildings.

![Figure 4. The definition of weight factor \( \omega \) in different versions of Chinese codes (not for scale)](image)

| Code            | Light | Moderate | Serious |
|-----------------|-------|----------|---------|
| GBJ11-89        | \( 0 < I_{LE} \leq 5 \) | \( 5 < I_{LE} \leq 15 \) | \( I_{LE} > 15 \) |
| GB50011-2010    | \( 0 < I_{LE} \leq 6 \) | \( 6 < I_{LE} \leq 18 \) | \( I_{LE} > 18 \) |

| Building type | Description                                                                 |
|---------------|-----------------------------------------------------------------------------|
| Category I    | Special buildings, buildings with high seismic vulnerability and etc.         |
| Category II   | Lifeline system in the national key cities and buildings with relatively high level seismic vulnerability. |
| Category III  | Others except category I, II and IV.                                        |
| Category IV   | Buildings with low population density and low seismic vulnerability.         |


Table 11. General guidelines of anti-liquefaction design in GB50011-2010

| Building type | Liquefaction severity |
|---------------|-----------------------|
|               | Light  | Moderate | Serious    |
| Category II   | EPLS or FSM | EALS or EPLS + FSM | EALS      |
| Category III  | FSM or no measures | at least FSM | EALS or EPLS + FSM |
| Category IV   | no measures | no measures | FSM or SM |

Note: EALS—eliminate all liquefaction-induced settlement; EPLS—eliminate partial liquefaction-induced settlement; FSM — foundation and structural measures; SM — supplemental measures.

4. Summary
This paper reviews major advancement of the specifications on liquefaction assessment in the seismic design building code in mainland China. The country suffered extensive liquefaction hazards during a large number of destructive earthquakes in the past century. The post-earthquake reconnaissance efforts gave birth to a methodology of liquefaction assessment in 1974, which later became mature in 1989 and continuously received amendments after every strong earthquake as a result of increasing knowledge on liquefaction phenomenon. In the current version of the code, a detailed assessment of liquefaction potential is required based on SPT blow count without depth correction, if liquefaction concern cannot be eliminated by a preliminary assessment based on descriptive information collected in the phase of site characterization. A liquefaction index is evaluated to recognize liquefaction severity considering an entire profile of the site being considered, and also to filter the most appropriate engineering measures for liquefaction mitigation.

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