
Article

New Formula for the Identification of Liquefaction Based on the Investigation of the Songyuan Site

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Abstract: Based on the 5.7-magnitude earthquake that stroke Songyuan (China) and 172 groups of liquefaction data collected in mainland China, the hyperbolic liquefaction discriminant formula originally proposed by Sun Rui was revised, and a new formula for the liquefaction of sand was put forward. Groups of data derived from the Bachu earthquake in Xinjiang and an earthquake that occurred in New Zealand (47 and 195 groups, respectively) were used to carry out a back-judgment test, then, the results were compared with those of the existing standard method. Overall, the results showed that the new formula for hyperbolic liquefaction discrimination compensates for the conservative liquefaction discrimination of the older formula; moreover, it has a good applicability to different intensities, groundwater levels, and the deep sand layer of the Songyuan site, reflected by a more balanced success rate. Therefore, combining the existing liquefaction discrimination methods and the research results of discrimination, it is necessary to establish a suitable regional identification method through the continuous accumulation of liquefaction data and expanding database.

Keywords: Songyuan earthquake; Songyuan site; sand liquefaction; hyperbolic model; discriminant formula

1. Introduction

It has been shown that sand soil liquefaction is a kind of destructive and certain regional seismic disaster through the earthquake damage investigation at home and abroad. Large-scale sand liquefaction will destroy infrastructure such as roads, bridges, industrial facilities, civil buildings, and water conservancy projects, resulting in loss of foundation bearing capacity, uneven settlement, slope slip, and several catastrophic damages. Therefore, scholars at home and abroad have studied the liquefaction mechanisms, as well as the influencing factors and possible discriminant methods. Their findings have allowed an effective reduction of the disasters caused by sand liquefaction [1-8, 31-32].

In actual engineering investigations, sand liquefaction discriminations are carried out at the engineering sites, and the effective foundation treatment of the site (done according to the discriminant results) can effectively reduce the liquefaction disaster of sandy soil, so the reliability of the sand liquefaction discrimination method applied is vital. Hence, with the accumulation of seismic data, the accuracy with which liquefaction sites can be identified will gradually improve. [28] It is important to improve the sand liquefaction discrimination method based on sand liquefaction data collected at earthquake sites On May 28, 2018 AM01:50:52, in Songyuan City (Jilin Province, Ningjiang District, Maodu Station Town), a 5.7-magnitude earthquake occurred. Post-earthquake investigations [9] have shown that, in this location, farmland covered by sand, housing settlements and gable walls cracked, etc. was caused by sand liquefaction. The day after the earthquake, a field team of more than ten people from the Institute of Disaster Prevention entered the earthquake area. The phenomenon of sand liquefaction was investigated in detail (e.g.,

through field surveys, drilling, shear-wave velocity tests, and static penetration). In this way, it was possible to estimate the seismic damage, the site characteristics in the epicenter area, and the liquefaction of sand I during the seismic event. In this paper, based on the sand liquefaction data collected for the Songyuan 5.7-magnitude earthquake and on 172 groups of basic liquefaction data collected through the standard penetration method, the hyperbolic liquefaction discriminant formula was established. The variables of formula are groundwater level, buried depth, and the standard penetration hammer number.

By investigating the large-scale sand liquefaction caused by the Xingtai, Tonghai, Haicheng, and Tangshan earthquakes in the 1960s and 1970s through post-earthquake field surveys, it has been possible to accumulate a large amount of liquefaction data. A method for sand liquefaction discrimination in China, based on such data, was first published in the "Code for Seismic Design of Industrial and Civil Buildings" (TJ11-78) [10]. This method was continuously improved and gradually evolved in the "Building Seismic Design Code" (GB50011-2010) discrimination method. In the "Code for Seismic Design of Buildings" (GB50011-2010) a method for involving the use of a standard penetration hammer number (based on the "Code for Seismic Design of Industrial and Civil Buildings", TJ11-78) is proposed. The method proposed in the "Code for Seismic Design of Industrial and Civil Buildings" (TJ11-78), instead, only considers the effect of seismic intensity on liquefaction. In the "Code for Seismic Design of Buildings" [11], the liquefaction discrimination presented in GBJ11-89 is considered suitable for the discrimination of liquefaction within the upper 15 m of sand. Since the foundation burial depth established by this code is only three depths of more than 10m for statistical analysis (The data were selected from the damage investigation results of the Tangshan earthquake and Haicheng earthquake in China), the discriminant formula is only suitable for sand layers at a maximum depth of 10m. The "Code for Seismic Design of Buildings" [12] (GB50011-2001) proposes the use of a pre-standard discriminant formula to investigate soil liquefaction within 15m depth, when soil liquefaction is identified between 15–20 m depth, a depth of 15m would be considered and directly applied to the discriminant formula, which is not related with the buried depth of the liquefied soil layer, however the critical value of liquefaction cannot be determined from a straight linear function. In the "Code for Seismic Design of Buildings [13]" (GB50011-2010), the critical value of liquefaction discrimination is determined from a continuous nonlinear function. The shape of the critical standard penetration curve of the standard method is mainly controlled by the shallow data points. Notably, the variation rate of the liquefaction critical value (critical hammering value) is faster even when the soil layer depth greater than 10m, resulting in a critical hammering value of 37 at 20 m. The current recognition liquefied samples with more than 30 blows were not found, so the judgment method is conservative.

A method for the determination of liquefaction in saturated sandy soil was proposed by Seed, etc [20]. By the horizontal shear-stress under actual seismic action divided by the anti-liquefaction shear stress of sandy soil, they were able to evaluate in detail sandy soil liquefaction. The method proposed in the "Code for Seismic Design of Industrial and Civil Buildings promulgated by China" [10] (TJ11-78) provided similar results. Experts convened by Idriss and Yound (1998) to study the data of the past 10 years[2], the Seed simplification method is introduced in more detail[19]. Based on the simplification method of Seed, a simplified discriminant method and a new concept of liquefaction safety factor (1.0 being the reference value for liquefaction discrimination) were proposed in the "Japanese Road and Bridge Seismic Design Code" [22]; here, moreover, a simplified liquefaction analysis experience chart was established based on the standard penetration stroke number, which is published by "European Seismic Design Code 8"[22]. However, when applying the above method, the critical standard penetration value was found to abnormally decrease with the increase of depth; the critical standard penetration curve of soil in the XIII intensity region maybe retracted and Seed's discriminant method tends to be conservative.

2. Hyperbolic discriminant formula for liquefaction discrimination

2.1. Data sources

Based on the analysis of the deficiency of the existing discriminant formula, 172 sets of raw data of the discriminant formula of the “Code for Seismic Design of Buildings” (GB50011-2010) [23] and 26 sets of drilling data are formed at the Songyuan seismic site [9]. Based on the groundwater and soil depth data, as well as on the standard penetration hammer number, the liquefaction criterion formula is established. The distribution of the liquefaction data in different seismic regions is shown in Tables 1 and 2. **Results**

This section may be divided by subheadings. It should provide a concise and precise description of the experimental results, their interpretation, as well as the experimental conclusions that can be drawn.

Table 1. Data source and distribution of the liquefaction in mainland China

Earthquake name	Year of occurrence	Earthquake magnitude	Seismic intensity	Number of points
Hejian earthquake	1967	6.3	6	2 (2)
Xingtai earthquake	1966	6.7	7–8	10 (3)
Bohai Sea earthquake	1969	7.4	7	4 (4)
Yangjiang earthquake	1969	6.4	7	4 (3)
Heyuan earthquake	1962	6.4	8	1 (0)
Xingtai earthquake	1966	7.2	9	8 (7)
Tonghai earthquake	1970	7.8	8–10	39 (18)
Haicheng earthquake	1975	7.3	7–8	12 (7)
Tangshan earthquake	1976	7.8	7–9	92 (55)
Songyuan earthquake	2018	5.7	7	26 (6)

Note: Values in parentheses indicate the number of liquefaction points

Table 2. Liquefaction data distribution in different intensity zones

Intensity	Number of points		
	Liquefied	Non-liquefied	Total
VI	2	0	2
VII	34	46	80
VIII	28	27	55
IX	40	20	60
X	1	0	1
Total	105	93	198

2.2. Establishment of a discriminating formula for the double curve

When the independent variable was small, the dependent variable increased rapidly with the increase of the former. However, when the independent variable increased to a certain extent, gradually tending to infinity, the increase rate of the dependent variable diminished with the increase of the former variable. Based on the advantages that the hyperbolic model conforms to the change of the liquefaction critical value with the depth of the soil layer, the hyperbolic shear wave velocity discriminant model and the discriminant formula are established for the liquefied soil layers of different depths by Sun Rui [26],

and the hyperbolic model was used to study the pore pressure growth. The variation law of the coefficients in the dynamic constitutive relationship of the liquefied soil layer was developed by Sun Rui et al. [27]. In this paper, based on the formation of standard penetration discriminant method of liquefaction basic data [23], the hyperbolic model discriminant formula for liquefaction discrimination was established, and the hyperbolic model discriminant formula was used to verify the data of different seismic sites.

The basic formula (Equation (1)) for liquefaction discrimination at the Songyuan site was constructed by using 198 sets of liquefaction data (172 sets of liquefaction basic data obtained through the standard penetration method and 26 sets of Songyuan seismic drilling data):

$$N_{cr} = N'_0 d_\omega \frac{d_s}{d_s + k_1} \quad (1)$$

where N_{cr} — the critical value of the standard penetration hammer number, d_s — the buried depth(m), d_ω — the groundwater level(m), and k_1 — a parameter to be determined, N'_0 — a standard penetration hammer reference value.

According to equation (1), when d_s takes 0, N_{cr} is 0. The surface soil layer has been considered to be not liquefied. Since this assumption is inconsistent with actual engineering situations, the correction coefficient about the reference value of the standard penetration hammer number (k_2) needs to be included in Equation (1). If the critical value of the standard penetration hammer number decreases gradually when the local groundwater level increases, the influence coefficient about the buried depth of the groundwater level (k_3) should be included relatively to the reference value of the standard penetration hammer number in Equation (1). Therefore (1) is further:

$$N_{cr} = N'_0 (1 + k_3 d_\omega) \left[k_2 + \frac{d_s}{d_s + k_1} \right] \quad (2)$$

where k_2 — the soil depth. when is 0, the influence coefficient about the critical initial value of the standard penetration hammer number, k_3 — the influence coefficient of the groundwater's depth.

2.3. Parameter selection

The ranges of the three undetermined coefficients in the formula should meet the following requirements. (1) As regards the depth of groundwater level (d_ω), if the critical value of the standard penetration hammer number increases with the increase of the soil layer depth, then k_1 is greater 0. (2) When the groundwater level (d_ω) and soil depth (d_s) are 0, the value range of the correction coefficient k_2 of the standard penetration hammer number reference initial value is 0-1. (3) When the soil depth is constant, the critical value of the standard penetration hammer number decreases with the increase of the groundwater level. It is negatively correlated with the groundwater level, then k_3 is less than 0.

After selecting the survey and test points at the seismic sites, statistical analysis was been done about the buried depth of the groundwater and the depth of the liquefaction investigation layer; furthermore, the standard penetration hammer number was determined at different depths to obtain the critical values of the liquefaction and non-liquefaction points. The reference value of the standard penetration hammer number N'_0 obtained from the regression analysis is shown in Fig. 1. For accelerations of 0.15g, 0.2g and 0.4g the reference values were between 13–20, 20–26, and 34–40, respectively.

In the new discriminant formula, N'_0 represents the range of reference values about the three undetermined coefficients, while the standard penetration hammer numbers have to be determined. In this study, 198 groups of measured data samples were regressed to obtain the optimal solution. The hyperbolic discriminant formula of site liquefaction in

the Songyuan planning area (hereinafter referred to as “hyperbolic discriminant formula”) was hence obtained (Equation (3)):

$$N_{cr} = N_0' (1 - 0.04d_w) \left[0.29 + \frac{d_s}{d_s + 11.5} \right] \quad (3)$$

where the value of N_0' , it was calculated according to Table 3. When using the above equation for liquefaction discrimination, only if the measured standard penetration hammer number of the sand layer is lower than the critical value of the standard penetration hammer number, it is judged as liquefaction, otherwise it is not liquefied.

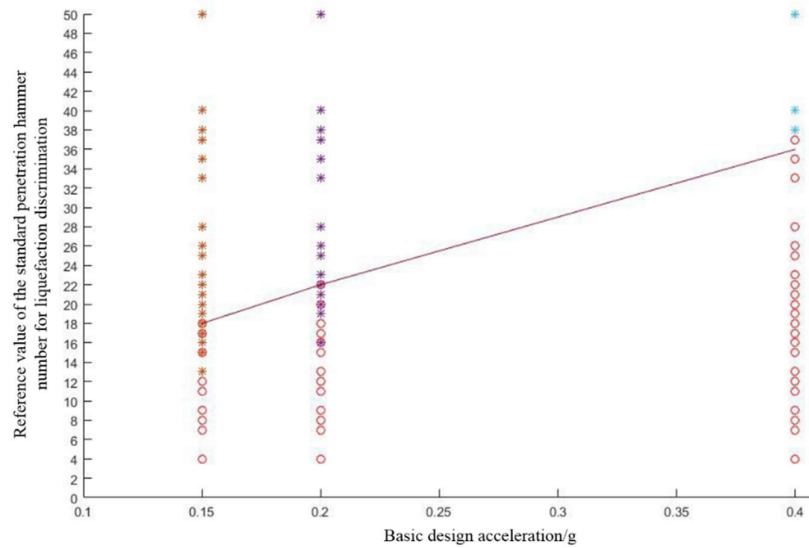


Fig.1 The estimation of reference value about standard penetration hammer number

Table 3. N' -value for different accelerations

Design basic acceleration (g)	0.10	0.15	0.20	0.30	0.40
Reference value of the standard penetration hammer number for liquefaction discrimination	15	20	23	29	35

3. Reliability analysis of the three hyperbolic discriminant formulas

3.1. Recovery analysis of Songyuan seismic data

The hyperbolic liquefaction discriminant formula (Equation (3)) and the “Code for Seismic Design of Buildings (GB50011-2010 in China)” was applied to determine the liquefaction data for the Songyuan area (China), which were then compared and analyzed (Table 4).

Table 4. Comparison between the success rates of the hyperbolic formula and the code method for the liquefaction data of Songyuan

Method	Total samples	Liquefaction samples (all)	Non-liquefaction samples (all)
Normative method	88.5%	100%	85%
Hyperbolic discriminant formula	96.2%	100%	95%

In Table 4, it can be shown as follows: both the hyperbolic discriminant formula and standard method performed very well (success rate for liquefaction point data = 100%). However, for non-liquefaction point data, the success rate of the hyperbolic discriminant formula is 95% and that of the standard method is only 85%, and the success rate of the hyperbolic discriminant formula was more balanced. Overall, these results indicate that the hyperbolic discriminant formula proposed in this paper has a good applicability to the liquefaction data of the Songyuan site compared with the existing standard method.

3.2. Recovery analysis for Chinese mainland seismic data

The hyperbolic liquefaction discrimination formula (Equation (3)) and the “Code for Seismic Design of Buildings” (GB50011-2010) were applied to determine the liquefaction data of Chinese mainland areas [23]. Some information about the liquefaction discrimination and a comparison between the discriminant results are shown in Tables 5 and 6. The results indicate that, among 172 groups of liquefaction data, the success rates of the two different liquefaction discriminant formulas are similar. However, the success rate of the non-liquefaction discrimination through the hyperbolic discriminant formula is 74%, while that obtained through the standard method is only 51%. Under different intensity regions, the accuracy of the model for the liquefaction data is significantly higher than that of the standard method. Compared with the existing standard method, the proposed hyperbolic discriminant formula has a good applicability to the seismic liquefaction data of Chinese mainland sites.

Table 5. Comparison between the success rates of the hyperbolic formula and of the standard method in relation to the liquefaction data of the Chinese mainland

Method	Total samples	Liquefaction samples (all)	Non-liquefaction samples (all)
the standard method	72%	91%	51%
hyperbolic discriminant formula	86%	95%	74%

Table 6. Comparison between the success rate of the hyperbolic formula and of the standard method for liquefaction data collected in China under different intensities.

Intensity region	Site situation	2010 normative Law	Hyperbolic discriminant formula
VII	Liquefied	100%	100%
	No liquefaction	52%	80.4%
	Overall	72.5%	85%
VIII	Liquefied	89%	96.4%
	No liquefaction	81%	85.2%
	Overall	85%	89%
IX	Liquefied	87.5%	90%
	No liquefaction	65%	70%
	Overall	80%	83%

3.3. Test results of the new method for seismic liquefaction data during Bachu Earthquake

In this paper, Forty-seven sets of Bachu earthquake data [28-29] was collected and sorted out, which include 21 and 26 sets of liquefaction and non-liquefaction data, respectively.

As a whole, the success rate of the liquefaction discrimination done through the hyperbolic discriminant formula is lower than done through the normative method in (results shown in Table 7). For the different degree intensity region, the success rate of liquefaction discrimination of hyperbolic discriminant formula is lower than that of normative method, however, that the success rate of the non-liquefaction discrimination done through the hyperbolic discriminant formula is higher than that obtained through the normative law, and the success rate of the overall discriminant is lower. Comparison of two discriminative methods from VII, VIII and IX degrees, these results show that the normative law is more suitable for determining the liquefaction during the Bachu earthquake, and the success rates of the liquefaction discrimination are higher.

Table 7. Success rates of the two methods applied to the Bachu earthquake

Intensity region	Liquefaction	Normative law	Hyperbolic discriminant formula
VII	Liquefied	57%	14%
	No liquefaction	100%	100%
	Overall	75%	50%
VIII	Liquefied	62.5%	50%
	No liquefaction	86.7%	100%
	Overall	65%	82.6%
IX	Liquefied	100%	66.7%
	No liquefaction	50%	83%
	Overall	75%	75%

3.4. Test results of the new method for New Zealand seismic data

In this paper, 195 groups of seismic data (including 147 and 48 sets of liquefaction and non-liquefaction data, respectively) from New Zealand were collected [30].

The hyperbolic discriminant formula was applied to these data, and its results were compared to those of the standard method (results shown in Table 8). For the VIII intensity region, the success rates of the hyperbolic discriminant formula and of the standard method are very different. As a matter of fact, the above results of the both discriminant methods are consistent with those of sandy soil liquefaction in the VIII intensity region of the New Zealand earthquake. Meanwhile, the hyperbolic discriminant formula seemed more suitable for judging sand liquefaction in the IX intensity region of the New Zealand earthquake. Furthermore, the building seismic design code could not judge satisfactorily the liquefaction in the X degree intensity region; however, when establishing the hyperbolic discriminant formula, the basic database contained the liquefaction point of X degree. Comparison of VIII, IX and X degrees the hyperbolic discriminant formula was found to be more suitable for judging the sand liquefaction intensity region of the New Zealand earthquake.

Table 8. Success rates of the two methods for the New Zealand earthquake

Intensity region	Liquefaction	Normative law	Hyperbolic discriminant formula
VIII	Liquefied	84.2%	81.6%
	No liquefaction	100%	100%
	Overall	85%	82.5%
IX	Liquefied	99.5%	96.2%
	No liquefaction	43.7%	93.0%
	Overall	85.4%	95.4%
X-ray	Liquefied		100%
	No liquefaction		
	Overall		100%

4. Discussion and conclusion

Based on the study of the Songyuan site and relevant seismic data, the sand liquefaction discrimination method was studied. The discriminant formula for sand liquefaction was established using the hyperbolic model in soil dynamics, and some results have been achieved. The main conclusions of this paper are as follows:

The reliability of the hyperbolic discriminant formula proposed in this paper was tested and compared with the discriminant results of the standard method. The results show that the discriminant success rate of the hyperbolic discriminant formula is higher than that of the standard method, and its results could better reflect the actual liquefaction at the study site. When applied to different intensity regions, the success rate of the hyperbolic liquefaction discriminant formula is always higher than that of the standard method, showing that the hyperbolic discriminant formula has a higher accuracy.

Due to the uncertainty of sand liquefaction and the complexity of geological conditions at engineering sites, the current discrimination method is based on survey data of liquefaction damage collected in specific areas or where major earthquakes occurred. As

a matter of fact, effective seismic damage data are relatively few and there are some regional limitations. Therefore, it is necessary to establish a regional discriminant method

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