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Shear Wave Velocity-Based Approach for Predicting Liquefaction of the Gravelly Soils

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Abstract

Although the in-situ shear wave velocity tests have been used commonly as engineering testing techniques and shear wave velocity V_s has gradually become a basic index for soil liquefaction evaluation, the in-situ V_s-based liquefaction assessment methods for gravelly soils are not available so far. The gravelly soils here refers to the coarse-grained soils with the gravel contents from 0% to 100% including the gravelly sand, the gravelly soil, silty gravelly soil, sandy gravel soil and gravel soil. The significant phenomena of liquefaction for the gravelly soils in the M_s 8.0 Wenchuan Earthquake in 2008 are found and the in-situ V_s structures for 45 sites in the event are obtained. In terms of the investigation data, the V_s-based approach for liquefaction prediction of the gravelly soils is presented. The liquefaction prediction of the gravelly soils can be divided into the two steps: the preliminary evaluation and further evaluation. In the preliminary step the geological ages and the buried condition of gravelly soils layers are considered. The parameters including seismic intensity, groundwater table, depth of the gravelly soils and the in-situ shear wave velocity of gravelly soils are concerned in the further step. In the formulation of the method, the influential coefficients of the gravelly soils depths and groundwater levels are deduced by normalization method and optimization method respectively. As the relative densities between the gravelly soils and the sandy soils even for the same V_s value are different the methods of liquefaction evaluation for sandy soils are not suitable for the gravelly soils. If the existing liquefaction assessment procedures for sandy soils are employed, the liquefaction resistance of the gravelly soils will be significantly overestimated.

Keywords: the gravelly soils；liquefaction prediction；shear wave velocity；M_s 8.0 Wenchuan Earthquake

1. Introduction

Soil liquefaction has been a hot issue in the soil dynamics and earthquake engineering[1-5]. As a comprehensive parameter of soil behavior involving void ratio, effective stress and chronologic age[6], the shear wave velocity of a soil layer has been commonly used in the civil engineering. At the same time, as strongly correlated with the liquefaction resistance of soils, the shear wave velocity has gradually developed into a basic index of the liquefaction evaluation[7, 8]. Besides, since the SPT and CPT techniques generally cannot be used in the gravelly soils site and the dynamic triaxial tests for estimating the liquefaction potential of the gravelly soils are rather complicated[9], the shear velocity may become a more powerful tool for evaluation of the gravelly soils liquefaction. However, the existing liquefaction evaluation methods by the shear wave velocity are mainly used for the sandy soils.

On May 12th 2008, a devastating M_s8.0 Wenchuan earthquake struck the Sichuan Province of China mainland. An investigation shows that the gravelly soils liquefaction is one of the typical features of the Wenchuan earthquake[10]. Through the in-situ investigation on liquefaction damages in the Wenchuan earthquake, the testing data in 45 sites for the gravelly soils is obtained. Based on the data, the applicability of the existing shear wave velocity methods for liquefaction prediction of the gravelly soils are verified and then the new liquefaction prediction approach based on shear wave velocity for gravelly soils is presented.

2. The field test and basic data

2.1 Field investigation

Field investigation shows the liquefaction region in the Wenchuan earthquake mainly located in Chengdu plain. Moreover, liquefaction phenomena have been observed in different intensity regions.

The distribution of 45 typical sites of gravelly soils for shear velocity test is shown in Fig.1, including 28 liquefied sites and 17 non-liquefied sites. 11 sites are in intensity VII regions, 25 sites in intensity VIII regions and 9 sites in intensity IV regions, respectively.

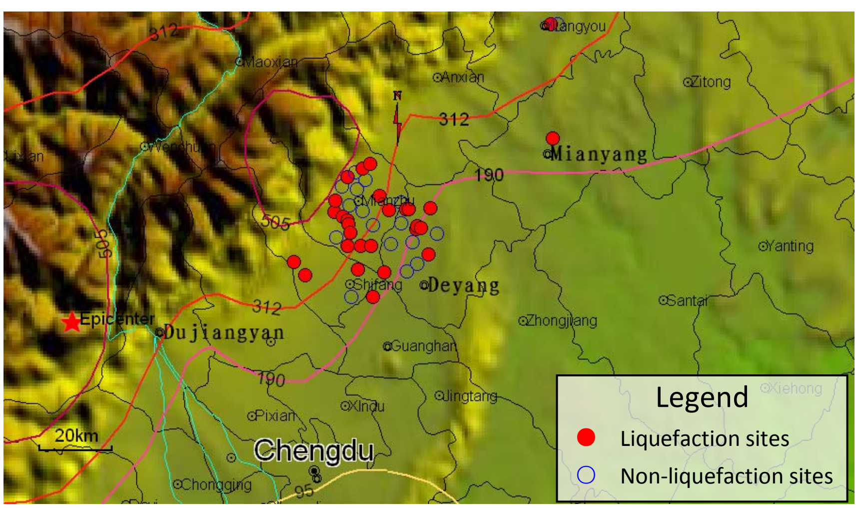
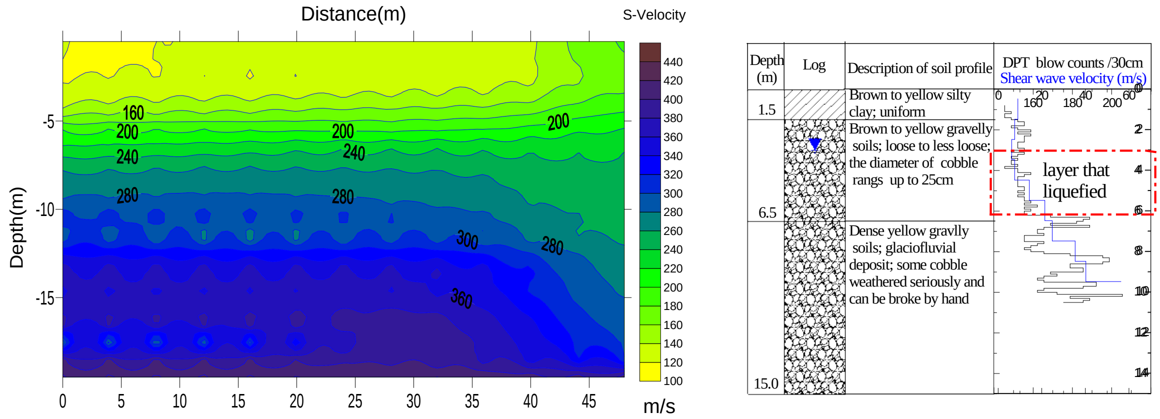
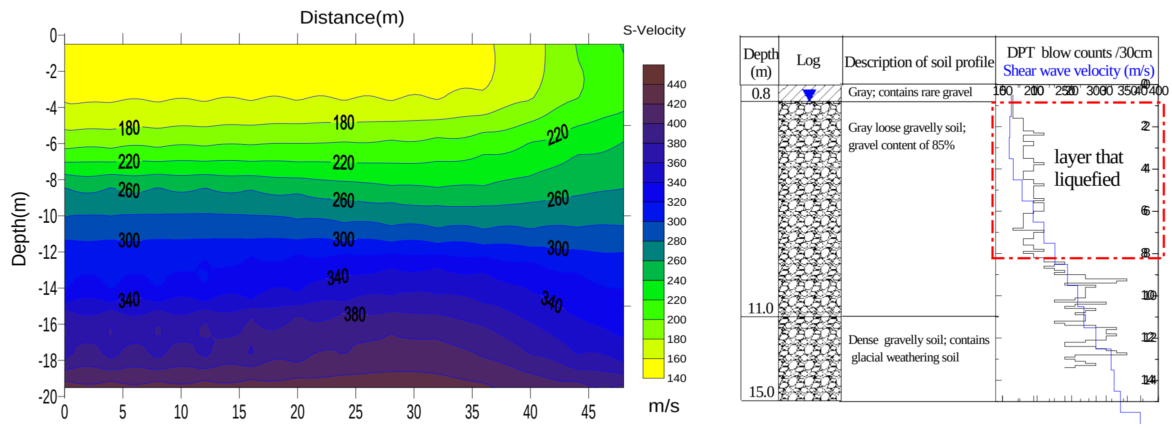


Fig.1 The location of investigation sites

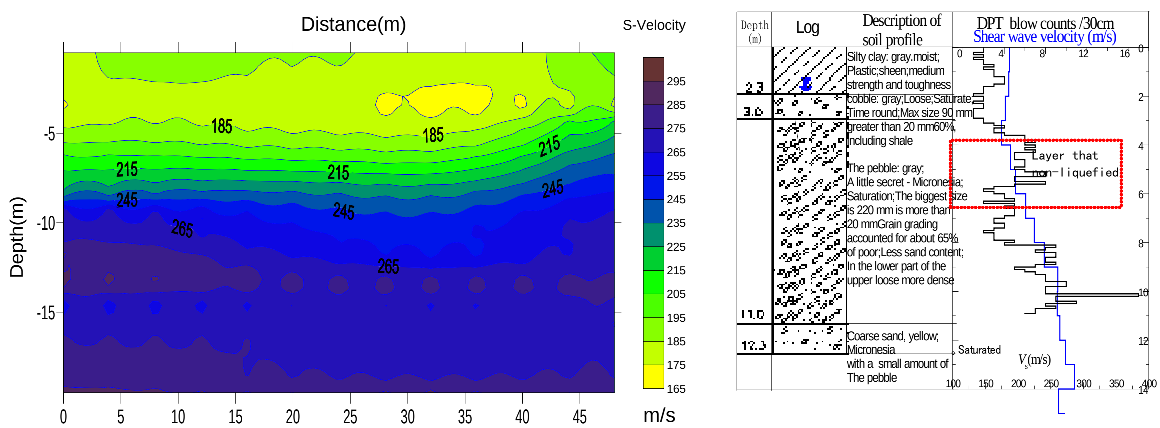
The surface wave tests are conducted by the OYO company instrument for all sites. Surface wave meter have 24 channels, 4.5 Hz geophone, totally 25 heavy hammer percussion respectively in adjacent geophone midpoint. The software automatically generates two-dimensional shear wave velocity structure and the mean values of each layer are calculated as shown in Fig. 2. At the same time, The Chinese Dynamic Penetration tests (CDPT) also be conducted in all sites.



(a) Banqiao school（Site 9，liquefaction）



(b) Songbai（Site 10，liquefaction）



(c) Wufang（Site 40，non-liquefaction）

Fig.2 Typical profiles of the in-situ test sites

The depth and thickness of the liquefied and non-liquefied layer is jointly determined by the shear wave velocity structure and the CDPT structure. The results for the three typical sites are shown in Fig. 2.

2.2 Basic data

The investigated data of the 45 sites is listed in Table 1.

Table 1 Summary of investigated data

No.	Location	Intensity	d_s (m)	d_w(m)	$V_s(m/s)$	Liquefaction
1	Pilu elementary school	VII	2.3-8.0	1.4	161	Y
2	Guoyuan	VII	1.5-2.2	1.5	165	Y
3	Jinqiao	VII	4.0-6.1	2.2	164	Y
4	baijiang	VII	2.2-6.0	2.2	142	Y
5	shengli	VII	2.2-5.0	1.9	187	Y
6	changzheng	VII	1.0-3.0	1.0	160	Y
7	yongquan	VII	2.0-6.0	1.3	152	Y
8	Xinshi school	VIII	2.5-3.5	1.0	133	Y
9	Banqiao school	VIII	3.0-6.1	3.0	159	Y
10	Songbai	VIII	0.8-8.3	0.8	185	Y
11	Xinglong	VIII	4.0-9.5	2.4	195	Y
12	Shihu	VIII	2.9-5.8	2.9	161	Y
13	Qifu elementary school	VIII	3.5-7.0	3.5	180	Y
14	Guihua	VIII	0.6-3.7	0.6	153	Y
15	Zhenjiang	VIII	1.8-2.9	0.9	187	Y
16	Sangyuan	VIII	2.8-4.2	2.8	199	Y
17	yongfeng	VIII	4.0-8.0	2.8	238	Y
18	An'ping	VIII	1.8-2.8	1.8	141	Y
19	baiyang	VIII	1.5-6.1	1.5	150	Y
20	linyan	VIII	6.0-8.0	6.1	250	Y
21	qingliang	VIII	1.0-5.0	1.0	203	Y
22	siyuan	VIII	2.0-4.0	1.5	164	Y
23	jiangyou railway station	VIII	2.4-7.0	2.4	215	Y
24	Xiangliu	IX	3.4-6.2	3.4	233	Y
25	An'ren	IX	4.0-6.0	4.0	267	Y
26	wudu	IX	5.0-7.7	1.6	150	Y
27	baihutou	IX	1.2-3.2	1.2	178	Y
28	shuangquan	IX	2.5-5.0	2.5	200	Y
29	Wulang	VII	5.0-13.0	5.0	269	N
30	Quezhu	VII	6.0-15.0	6.0	287	N
31	Yangjia railway station	VII	6.1-8.7	6.1	218	N
32	shegnhua	VII	2.5-7.5	2.0	208	N
33	Nangui	VIII	9.8-14.0	4.7	304	N
34	Pharmacy factory	VIII	3.4-7.4	3.4	282	N
35	Pinghe	VIII	9.6-12	3.7	305	N
36	Bayi	VIII	6.2-7.2	6.2	248	N
37	Yongning	VIII	8.1-12.2	1.4	337	N
38	Dacheng	VIII	5.7-7.8	4.5	257	N

39	Min'an	VIII	7.3-9.0	3.7	259	N
40	Wufang	VIII	3.6-5.6	2.0	187	N
41	yujiaguan	VIII	5.0-8.0	3.0	233	N
42	Chuanmu	IX	8.5-9.9	8.0	272	N
43	Tonglin	IX	9.4-11.0	2.0	234	N
44	linfa	IX	4.3-8.3	4.3	365	N
45	changlin	IX	4.0-6.0	4.0	323	N

3. Verification of existing methods

3.1 Two existing methods

The first method (simplified as method 1) to be verified is derived by Andrus and Stokoe[8]. The cyclic stress ratio (CSR) and cyclic resistance ratio (CRR) of soils are calculated and CSR can be written as:

$$CSR = 0.65(a_{\max} / g)(\sigma_v / \sigma_v^{'})r_d \tag{1}$$

where $a_{\max}$ is the peak horizontal acceleration at the ground surface, g is acceleration of gravity, σ_v is the overburden stresses, σ_v' is the effective overburden stresses, r_d is the stress reduction coefficient. CRR can be expressed by:

$$CRR = 0.022(V_{s1}/100)^2 + 2.8[1/(V_{s1c} - V_{s1}) - 1/V_{s1c}] \tag{2}$$

where V_{s1} is the corrected shear wave velocity and V_{s1c} is the upper limit of the shear wave velocity of liquefaction.

The second method (simplified as method 2) to be verified is derived by Shi *et al*[7]. The expression is:

$$V_{scri} = \overline{V_s}(d_s - 0.0133 d_s^2)^{0.5}[1.0 - 0.185(d_w / d_s)] \tag{3}$$

where, d_s is depth of soil, d_w is depth of groundwater, $\overline{V_s}$ is the reference value of shear wave velocity and the values are 42 m/s, 60 m/s and 84m/s in intensity VII, VIII and IX, respectively.

3.2 Verification of two existing methods

Bring the above two formulae into the test results in Table 1 and the judging results for the two methods can be attained. It should be noticed that the PGA is 0.1g, 0.2g and 0.4g in intensity VII, VIII and IX, respectively. The judging success rate by the method 1 is 43% and 100% for liquefaction and non-liquefaction sites, separately. The judging success rate by the method 2 is 25% and 90% for liquefaction and non-liquefaction sites, separately.

It is obviously shown that both methods have the same trend: low judging success rate for liquefied sites and high judging success rate for non-liquefied sites. If the two methods are employed to predict the liquefaction of gravelly soils, the result is rather dangerous and is beyond the acceptable range.

The reason of the low success of the existing liquefaction evaluation methods for gravelly soils is that the methods are formed by the sand liquefaction data. The critical shear wave velocity for sandy soils liquefaction is about 210m/s. As shown in Table 1, however, the shear wave velocities in the five liquefied sites far exceed the critical value and the maximum shear wave velocity in the liquefied soil layer is 267m/s. The field testing results show those liquefied gravelly deposits are in loose or slightly dense state and while, the sandy soils for such high velocities will be very dense. Therefore, the existing liquefaction evaluation method is no longer suitable for deposits of gravelly soils.

4. New model

It can be seen from the above analysis that a new model is required for the gravelly soils liquefaction evaluation based on shear wave velocity. In the paper, the gravelly soils liquefaction evaluation method is divided into the two steps, i.e., pre-judgment and re-judgment.

4.1 Pre-judging analysis

(1)Geological age. If the deposits are before the pre-Quaternary (Quaternary included), the gravelly soils will be determined as non-liquefaction.

(2)Gravelly sediment depths and water tables. Fig.3 shows the relationship between the depths and water tables of gravelly soils layers in liquefied sites and non-liquefied sites. Liquefaction will not be taken into account if thickness of the non-liquefied overburden covers and water tables are larger than the values presented in Fig.3.

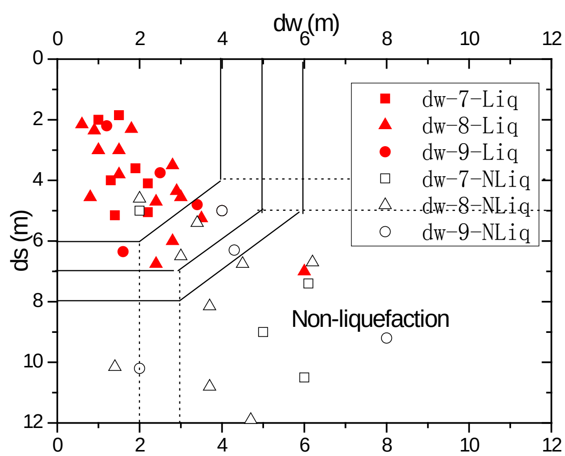


Fig.3 Relations of the water tables and the depths of the liquefied and non-liquefied gravelly soils layers

4.2 Re-judging model

Using the shear wave velocity as basic parameter, the prediction formula for liquefaction of gravelly soils layers can be written as:

$$V_{s-cr} = V_{s-0}[1+\alpha_w(d_w-2)+\alpha_s(d_s-3)] \tag{4}$$

where $V_{s\text{-cr}}$ is the critical shear wave velocity; $V_{s\text{-}0}$ is the reference value of shear wave velocity; d_s is the gravelly soils layer depth; d_w is the water table of the site; α_w is the influence coefficient of water tables; α_s is the influence coefficient of depth of the gravelly soils.

4.3 Reference value of shear wave velocity

According to the correcting formula for shear wave velocity[14], the measured shear wave velocity can by corrected to values in 3m depth and 2m water table as following:

$$V_s^{'} = V_s(47/\sigma_v^{'})^{0.25} \tag{5}$$

Where V_s' is the corrected shear wave velocity, V_s is measured shear wave velocity, σ_v' is the effective overburden cover stresses. Fig.5 delineates the dividing line between liquefied and non-liquefied and the reference values $V_{s\text{-}0}$ can be attained as shown in Table 2.

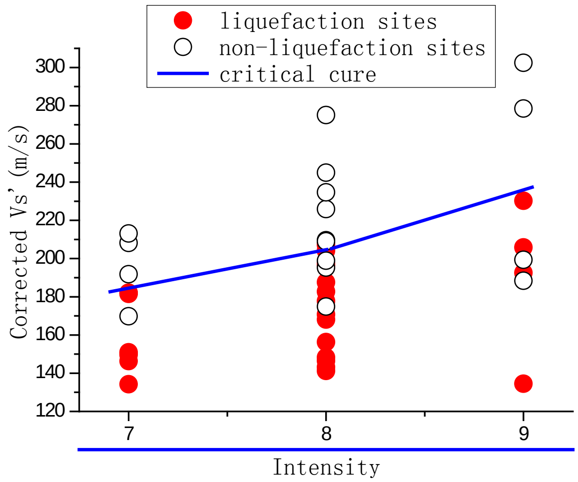


Fig.5 Relationship between the corrected shear wave velocity and the seismic intensity

Table 2 Reference value of shear wave velocity

intensity	VII (0.1g)	VIII (0.2g)	IX (0.4g)
$V_{s\text{-}0}$	180	200	230

4.4 Influence coefficients

Fig.6 presents the charts of shear wave velocity ratios with depths of gravelly soils layers. The shear wave velocity ratios are defined as the measured shear wave velocity divide by the reference value of shear wave velocity. The slops of the lines dividing liquefied sites from non-liquefied sites in Fig.6 represent the influence coefficients of gravelly layer depth. Similarly, Fig.7 presents the charts of shear wave velocity ratio with respect to water tables. The influence coefficients of water tables can be attained from Fig.7.

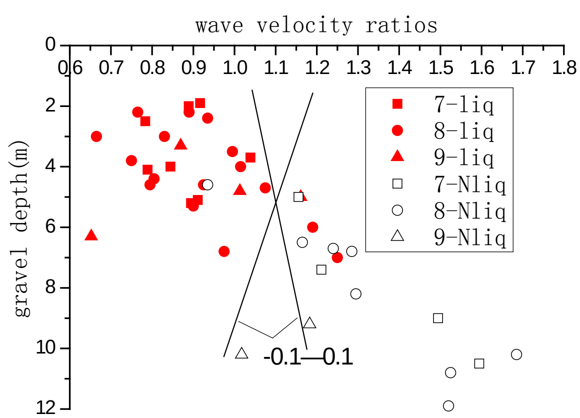


Fig.6 The gravelly soils depth Influence coefficient on the critical shear wave velocity

As shown in Fig.6 and Fig.7, the obtained coefficients vary within a certain range. The optimization method is used to obtain the values. First, the successful judging rates are calculated for all liquefied sites and non-liquefied sites under various the coefficients of depths and water tables, as plotted in Fig.8 and Fig.9. Then, Combining the results in Fig.8 and Fig.9, the best values for liquefied and non-liquefied sites in the overlapping area (shadow in Fig.10) are attained.

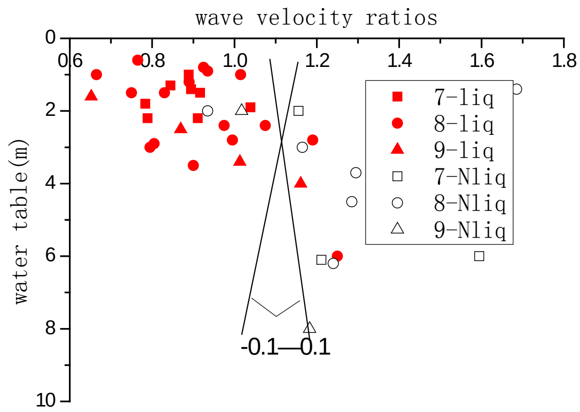


Fig.7 The water table Influence coefficient on the critical shear wave velocity

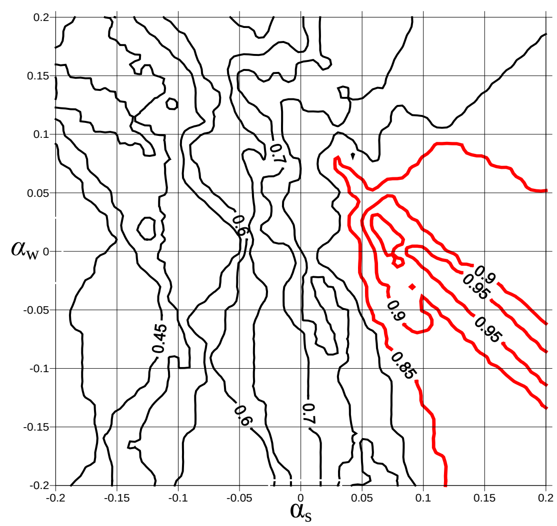


Fig.8 Effect of α_s and α_w on the discrimination success ratio for the liquefied sites

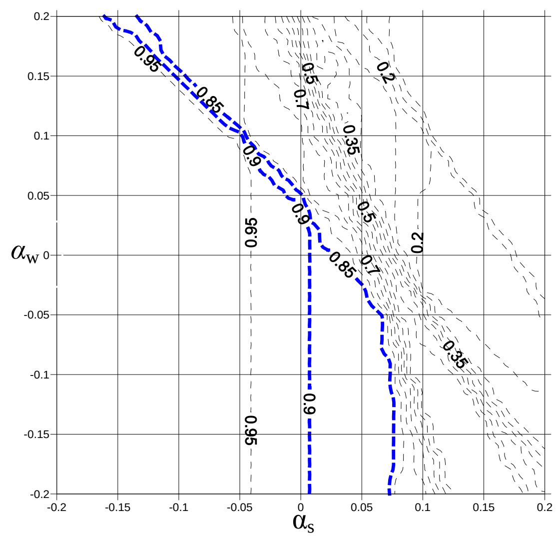


Fig.9 Effect of α_s and α_w on the discrimination success ratio for the non-liquefied sites

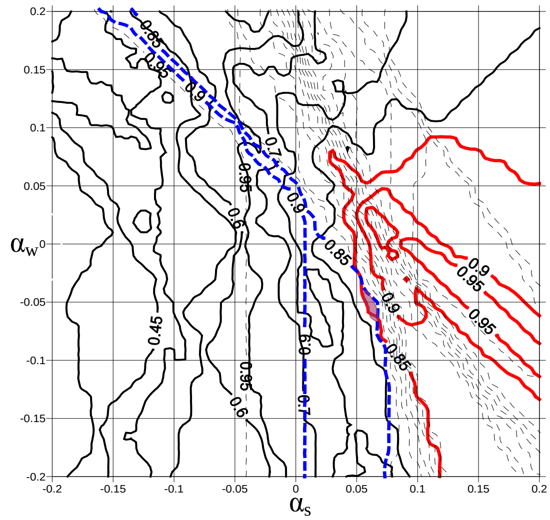


Fig.10 The optimum values of α_s and α_w

Form Fig.10 we can find the successful judging rate for liquefied and non-liquefied sites both exceed 85%, coefficients of depths and water tables are located in a small area (the shadow part of the figure) and the values for α_w and α_s are 0.06 and -0.06, respectively.

By substituting the data from Table 1 into Eq.(4), the successful rate for liquefied and non-liquefied sites is 89% and 88% respectively. The presented model is basically reasonable and credible.

5. Formula for evaluation of gravelly soils liquefaction

The re-judging formula based on shear wave velocity for gravelly soils liquefaction can be written as:

$$V_{s-cr} = V_{s-0}[1+\alpha_w(d_w-2)+\alpha_s(d_s-3)] \tag{6}$$

The coefficients α_s and α_w are 0.06 and -0.06, respectively. For different surface ground motion of PGA the reference value of shear wave velocity, $V_{s\text{-}0}$, can be attained by interpolation of Table 2. Finally, Eq. (6) can be simplified as:

$$V_{s-cr} = (500\alpha_{\max}^2 - 50\alpha_{\max} + 170)[1-0.06(d_w-2)+0.06(d_s-3)] \tag{7}$$

or

$$V_{s-cr} = (500\alpha_{\max}^2 - 50\alpha_{\max} + 170)[0.94+0.06(d_s-d_w)] \tag{8}$$

where $V_{s\text{-cr}}$ (m/s^2) is critical shear wave velocity; $a_{\max}$ (g) is the horizontal peak ground acceleration of the site; d_s (m) is gravelly soils depth; d_w (m) is water table. If the measured V_s value is greater than $V_{s\text{-cr}}$, the gravelly soils is then identified as non-liquefied, otherwise liquefied.

6. Conclusion

1. When the two typical kinds of methods for the sandy soils liquefaction based on shear wave velocity are used to the liquefaction sites in the 2008 Wenchuan earthquake, the successful judging rate for liquefied sites of the gravelly soils is very low, only about 20%~40%. It indicates that the existing methods do not be applied to liquefaction evaluation of gravelly soils.

2. The reason of the low success of the existing liquefaction evaluation methods for gravelly soils is that the relative densities between the gravelly soils and the sandy soils are different even for the same V_s value. Therefore, the method for liquefaction prediction of gravelly soils cannot be replaced by that of sandy soils.

3. The presented approach of gravelly soils liquefaction evaluation based on shear wave velocity in the paper consists of pre-judging and re-judging and it is simple and is easy to use in engineering.

4. The presented approach for predicting liquefaction of the gravelly soils in the paper can only be used within 10m depth for the deposits of gravelly soils. Meanwhile, the buried condition of gravelly soils layers need more detailed investigation.

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