Method of liquefaction prediction of gravelly soils

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Abstract

Following the 2008 Wenchuan, China earthquake, investigators from the Institute of Engineering Mechanics, China Earthquake Administration identified 118 sites with surface liquefaction effects. The existing methods for evaluating the liquefaction of sandy soils can not be used in the gravelly soils. In terms of the in-situ tests for the liquefaction sites, the liquefaction prediction method of gravelly soils based on CDPT, i.e., the Chinese dynamic penetration tests, is presented and the corresponding calculational model and formula are attained in the paper. In the discrimination, five parameters including the standard value of N_{120}, the gravel content of gravelly soils, the depth of gravelly soils, the water levels and the seismic intensity are concerned. Considering the wide range of liquefied soil depths and its water levels, the standard value of N_{120} is deduced by the normalization method and the influence coefficients of the gravelly soils depths and the water levels are obtained by the optimal method. Moreover, using post-earthquake field investigation data from the meizoseismal area in the Wenchuan earthquake and historical documents on gravelly soils liquefaction in the world, the necessary conditions for triggering gravelly soils liquefaction and relevant characteristic parameters are presented in the paper.

Keywords: gravelly soils, liquefaction prediction, in-situ test, Chinese dynamic penetration

1. Introduction

Soil liquefaction under earthquake loading is one of the most important topics in soil dynamics and engineering practice. Thereafter, proper prediction and evaluation of liquefaction behaviors become imperative. Moreover, liquefaction field investigation and in-situ testing techniques are the effective ways for developing relevant methods. In 60s and 70s in the 20th century liquefaction phenomena were discerned in the tremendous earthquakes which shock China mainland. Through detailed investigation and systematically research soil liquefaction evaluation methods especially for China are proposed and used in seismic design codes.

On May 12th 2008, a devastating earthquake M_s8.0 struck Sichuan Province. By systematical and detailed field investigation, it is found that the liquefaction macro-phenomena is quite different from previous observation and emerges new features worthy of profound study [1, 2]. One of the prominent features is gravel liquefaction which has been confirmed by specific investigation. Meanwhile, analysis indicated that gravel liquefaction is predominant in this event. Geologically, gravel is widely distributed in Sichuan Province, e.g., more than 8400 km2 in Chengdu basin only [3]. Furthermore, gravelly soils are commonly used as bedding material in earth dams in China. Therefore, liquefaction prediction and evaluation for gravelly soils are important for engineering site selection and seismic fortification.

Comparing with sandy liquefaction, the documents and experience on gravel liquefaction is quite rare and the relevant evaluating methods are immature. The current liquefaction prediction and evaluation methods which are established based on sandy soil liquefaction data and documents are not applicable on gravel liquefaction prediction and evaluation, because the widely-used techniques including standard penetration tests (SPT) and cone penetration tests (CPT) cannot be conducted on gravel sites. Besides, shear wave velocity testing can be employed both on sandy sites and gravel sites. However, sand and gravel belong to different soil categories. Consequently different physical soil properties result in different relative densities even though shear wave velocities are equal. For example, sandy soil generally cannot liquefy when its shear wave velocity exceeds a certain value (e.g., 220m/s), since sandy soil tends to be quite dense under the certain value but gravel for the certain value still remains loose and possibly liquefies. According to our preliminary research [4], the successful liquefaction judging rates on gravel sites are only about 30% by present liquefaction prediction models which are based on shear wave velocities[5]. Such judging results obviously are dangerous. Therefore, principally the discrepancy of sandy soils is not suitable for and gravel and, the evaluation methods for gravel liquefaction potential need new tools and procedures.

The Japanese scholars proposed gravel evaluation methods based on large dynamic triaxial tests [6]. Nevertheless, the present large dynamic triaxial testing techniques are complicated and the apparatuses are expensive. Besides, scholars and engineers in USA use Becker penetration tests (BPT) for gravel liquefaction evaluation [7]. The BPT-based procedures rely on field testing data and it has not been recommended and employed in China. Furthermore, in BPT method, penetration blows are converted into SPT penetration blows and then the possibility of site liquefaction is assessed by SPT procedures. The SPT procedures are developed on sandy soils, but properties of gravel or cobble are quite different from sand. Hence the straightforward converting method from BPT to SPT is not reliable and requires further investigation.

In this paper gravel liquefaction behaviors in Wenchuan earthquake have been presented and then a fundamental procedure and a formula for evaluating gravel liquefaction by means of in-situ investigation and field testing data are proposed.

2. Gravel Liquefaction Investigation

Field investigation shows the liquefaction affected region in Wenchuan earthquake is about 500km long and 200km wide and a rectangular region 160km long and 60km wide contains most of the liquefied sites. The liquefied sites were distributed in Chengdu, Mianyang, Deyang, Meishan, Leshan, Suining, Ya'an and Guangyuan but are mainly located in Chengdu, Deyang and Mianyang areas. Moreover, liquefaction phenomena have been observed in different intensity regions but mainly in intensity 0.3 regions.

To investigate soil conditions in liquefied and nearby non-liquefied areas, more than 40 boreholes were drilled with continuous core sampling. Retrieved samples were logged to develop soil profiles as plotted on Fig.1. The boreholes were drilled with rotary equipment and core samples were cut and extracted with 90 to 100 mm diameter core barrels equipped with diamond bits. The bits commonly cut through cobbles and other large particles encountered and parts of the extracted core were disturbed by the rotary action. Intact sections of core without cut cobbles were selected for laboratory grain size testing. Typical extracted core samples are shown in Fig.2. Therefore, gravel deposits liquefaction can be confirmed.

An upper layer of clayey fill, 1m to 4m thick, caps the soil profile of each borehole log plotted on Fig.1. The fill is underlain by thick sequences of gravelly sediment, the upper part of which is generally loose. Few non-gravelly sand layers were penetrated beneath the Chengdu plain. In the Mianyang area, however, gravelly coarse sand was commonly penetrated between depths of 1.2m and 3.5m as illustrated by soil profile for Borehole E and F (Fig.1). Thick deposits of dense gravel lie beneath the coarse sand.

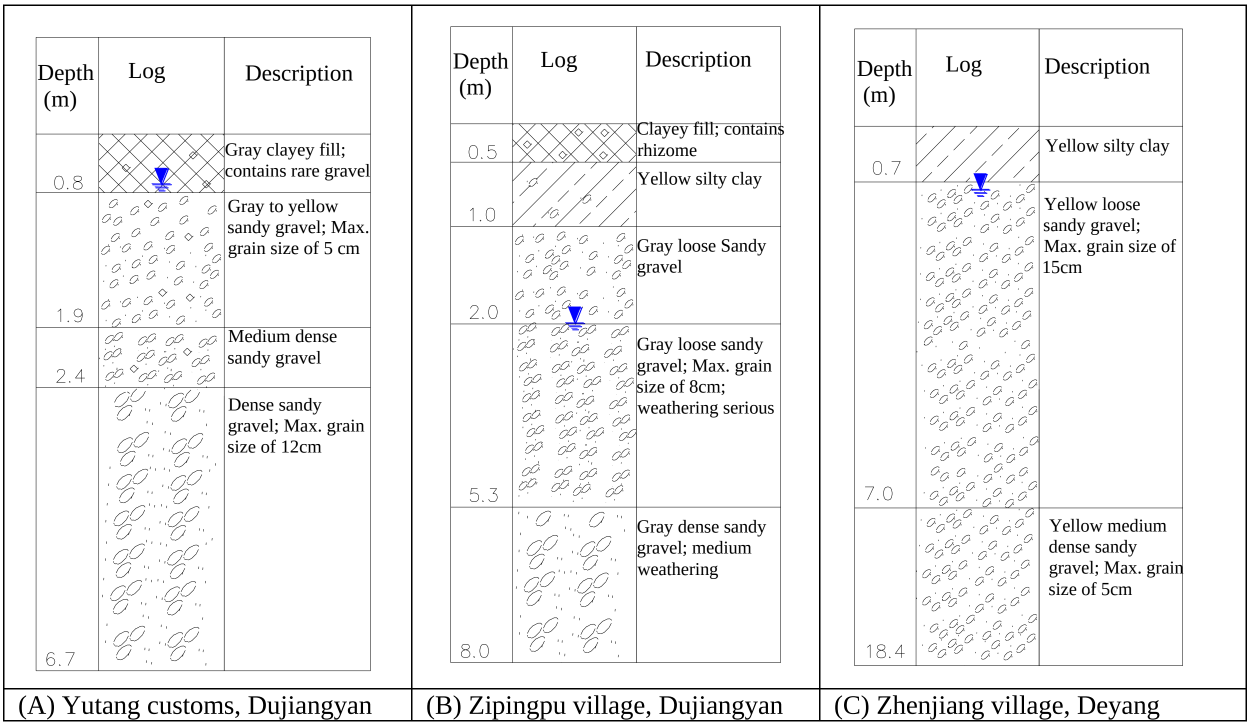


Figure 1. Typical borehole logs from drilled liquefaction sites.

Figure 2. Typical extracted core samples

2.1 Index Selection

The indices for evaluating gravely layer liquefaction have to be tested from in-situ investigation and testing in principle; meanwhile, the testing techniques must be well developed and widely used. In China, the current fundamental liquefaction evaluation index is SPT blows. But SPT and CPT testing cannot be conducted in gravely layers. In Sichuan province where gravel is widely distributed, the dynamic penetration tests (DPT) which are commonly used in China to measure penetration resistance of gravels during foundation investigations[8,9]are employed for engineering investigation with an index N_{120}, i.e., the number of blows required to achieve 10cm penetration of the sampler. Herein, N_{120} is selected as an index for evaluating gravel liquefaction. DPT is an ordinary technique for gravel investigation and N_{120} is a continuous variable which can represent many properties of course-grained soils.

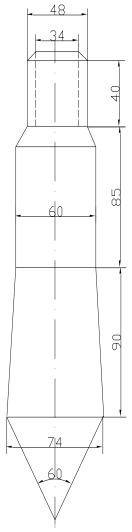
Furthermore, investigation results show that seismic intensities, water tables and depths of liquefiable gravel layers are also important effects on gravel liquefaction. Therefore, earthquake intensity and soil conditions have to be embodied in the new model for liquefaction evaluation of gravelly soils.

2.2 Dynamic Penetration Tests

During this investigation, the Chinese DPT was used for the first time to measure penetration resistance of gravels that liquefied. DPT profiles were compiled from 36 soundings at localities where liquefaction effects were or were not observed. These gravels are too coarse to allow effective use of either SPT or CPT, the most commonly used penetration tests used for liquefaction investigations worldwide. The DPT equipment consists of a 120 kg hammer, with a free fall height of 100 cm, dropped onto an anvil attached to 60 mm diameter drill rods which are in turn attached to a solid cone tip with diameter of 74 mm and a cone angle of 60 degrees. The drill rods have smaller diameter than the cone tip to reduce friction between the rods and soil. DPT blow counts are defined as the number of hammer drops required to advance the cone tip 10 cm. A diagram of the penetrometer tip and DPT apparatus is reproduced in Fig. 3. DPT logs from three of the four selected sites on the Chengdu Plain are plotted on Fig. 4. The lowest DPT resistance below the water table was the primary measure used to determine which soil layers liquefied. At these four sites, DPT resistances less than 5 blows/10 cm were generally indicative of liquefaction. These lower resistances were measured at shallow depths (<10 m) at sites that were strongly shaken by the earthquake (Intensity VII to IX) with estimated a_{max} between 0.25g and 0.45g. Results and analyses of DPT tests are the subject of a second paper on liquefaction during the Wenchuan earthquake.

The DPT is a very rugged instrument, capable of penetrating dense gravel layers and breaking or displacing cobbles as it is driven. In loose gravelll;s ($N_{120} \leq 4$), interference of large particles to penetration generally causes narrow penetration spikes, such as those plotted on the penetration logs in Fig 4. After a large particle was fractured or pushed aside, the penetration resistance returned to the matrix value for the deposit. Penetration depths up to 14 m were easily attained at most sites; however large cobbles and boulders proved to be impenetrable.

DPT Cone



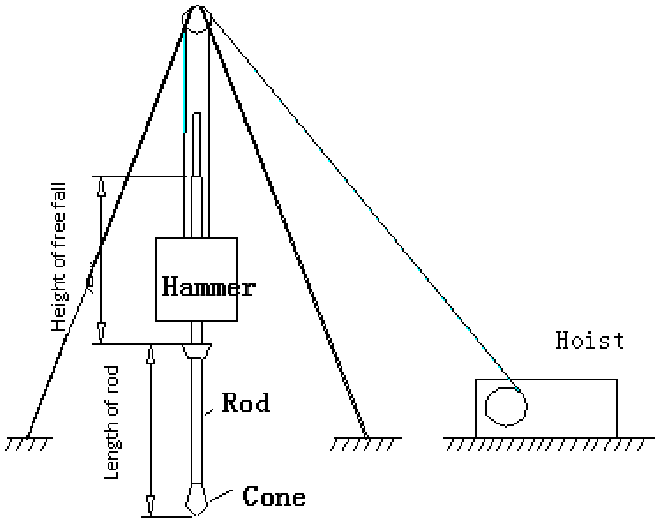
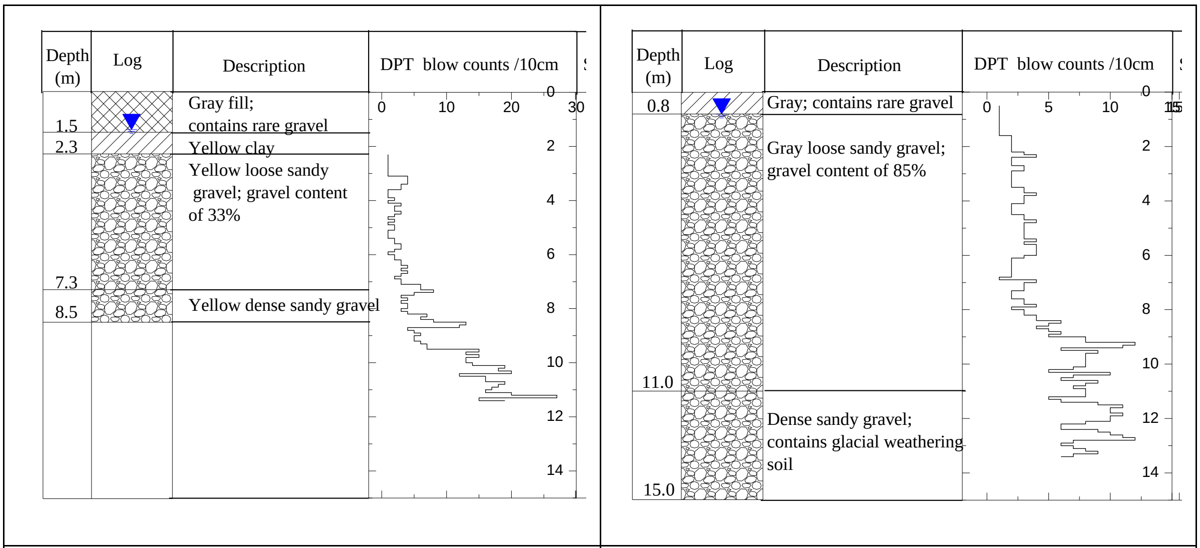


Figure 3. Component sketch of dynamic penetration test (DPT) apparatus.



Site 1 Pilu elementary school	Site 2 Songbai village

Figure 4. Soil log and DPT blows for selected liquefaction sites 1 through 4.

2.3 Testing Data

In this paper, 35 typical liquefied sites, on which liquefaction generated obvious ground failure or caused serious structural damage, are selected for in-situ investigation and testing. The sites are dotted in Fig. 5, including 14 liquefied sites and 21 non-liquefied sites. The selected sites are located in different intensity regions, including 8 sites in intensity VII(above 0.2g), 17 sites in intensity 0.3 and 10 sites in intensity IX(above 0.4g). Table 1 lists the site data, including seismic intensities, water tables, gravel sediment depths and N_{120}.

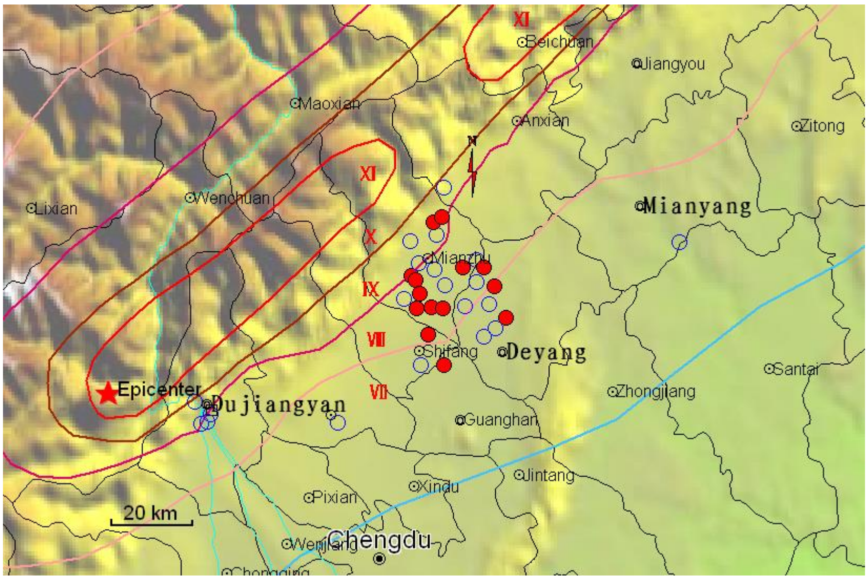


Figure 5. The distribution of Dynamic Penetration Test (DPT) sites.

Table 1. liquefied sites data of gravelly soils

Intensity(g)	No. of in situ test	Liquefaction
0.2	3	Y
	5	N
0.3	9	Y
	8	N
0.4	2	Y
	8	N

The gravel liquefaction evaluation method contains two stages, i.e., pre-judgment and re-judgment. Pre-judgment eliminates the imposable liquefaction. After that, the actual possibility of liquefaction for gravel is conducted by the Re-judging calculation formula.

3. PRE-JUDGING CONDITIONS

3.1 Soil structure in Chengdu plain

In the Chengdu Plain, sedimentary gravelly layers, ranging from meters to hundred meters in depth, underlie generally flat terrain[10,11]. Based on a review of mapped geological units [12], local soil profiles can be modeled simply as an impermeable capping layer (*e.g.*, clayey) and overlying thick gravel deposits. Such configuration is optimal for gravel liquefaction.

Figure 6 is plots of data taken from a typical gravel liquefaction site on the Chengdu Plain: the Tian'e Village near Pengzhou City. Figure 6(a) shows core samples extracted from that locality with markers showing depths and thicknesses of the capping layer and liquefiable gravels, and underlying non-liquefiable layer dense gravels. This configuration illustrates the two-layer profile (capping layer over liquefiable gravels) used to model gravel liquefaction sites. Figure 6 (b) is a soil log with plots of DPT resistance (N_{120}) and shear-wave, V_s, and versus depth. Low values of these two parameters were used to define liquefiable layers and to distinguish layers that liquefied from those that did not. Figure 7 is a sketch of the two-layer model representing local hydraulic conditions beneath the Chengdu Plain. The two-layer model is characterized by two parameters, H_n and d_{nw}, representing hydraulic conditions. H_n denotes the thickness of the impermeable capping layer in m, and d_{nw} is the thickness of an unsaturated zone between the capping layer and the water table, if an unsaturated layer exists. If the water table lies within the impermeable layer, d_{nw} = 0. As suggested by Andrus et al. [13, 14], loose gravelly soils can be as susceptible to liquefaction as sands when they are capped by an impermeable layer. Supplementing to the *CYY* method [15], in this paper, H_n and d_{nw}, are analyzed to determine hydraulic conditions for which liquefaction did and did not occur and to define criteria predicting occurrence of liquefaction in loose gravels as a function of thickness of capping layer and thickness of an unsaturated zone.

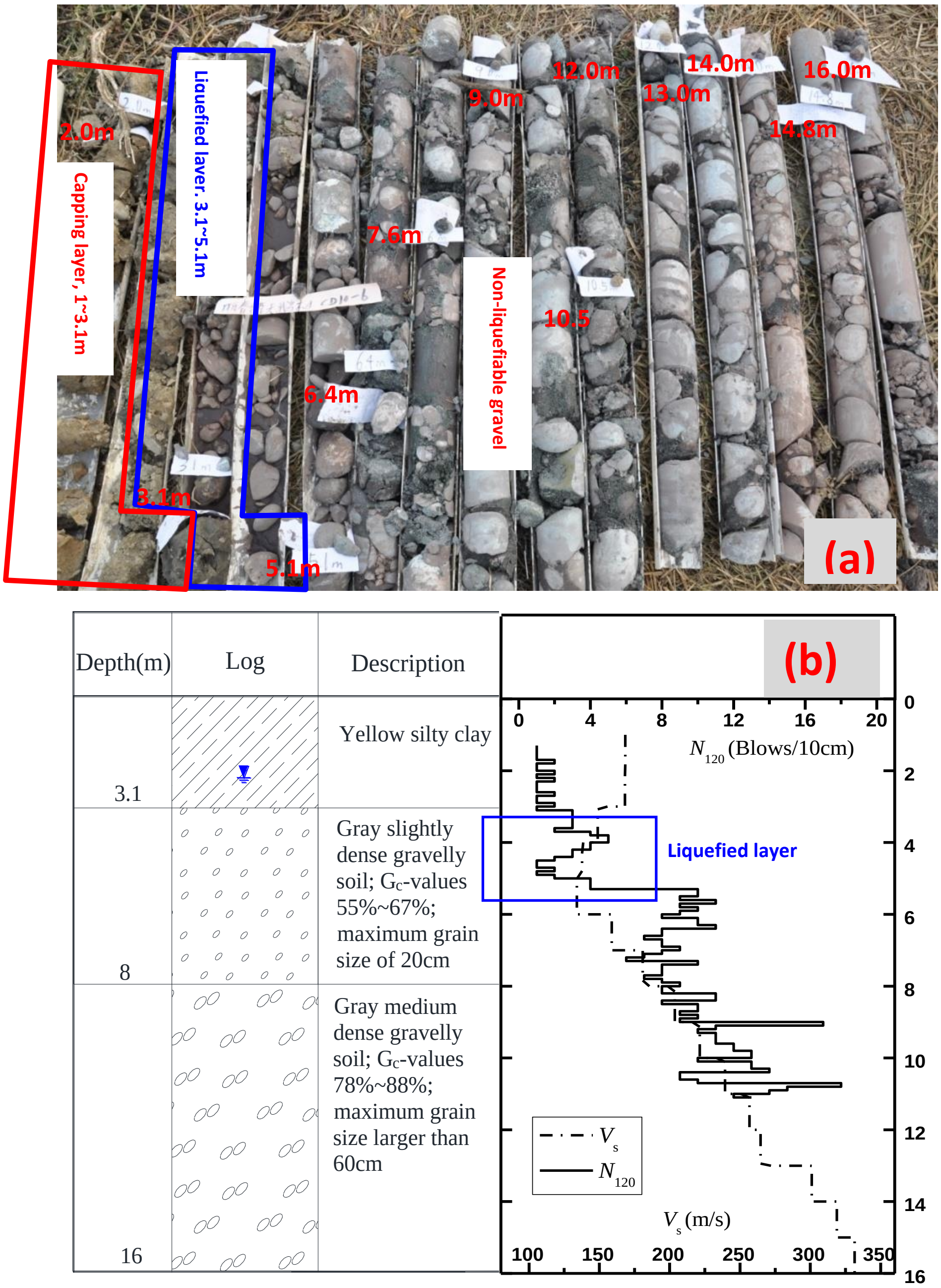


Figure 6. Liquefaction case study at Tian'e village. (a) The extracted core samples from the borehole. (b) Soil log description and the N_{120} and V_s test data. A loose gravelly layer between 3.1m and 5.1m was identified as having liquefied based on the test data.

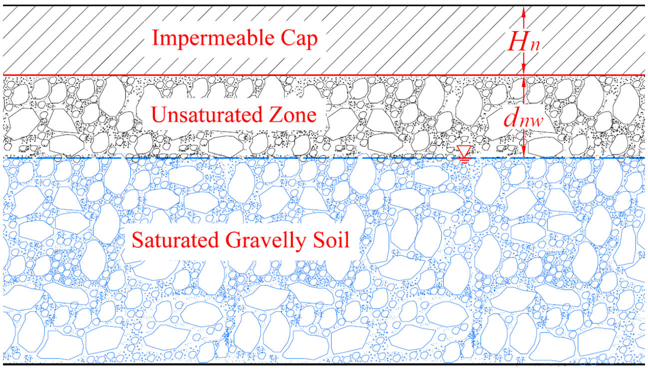


Figure 7. Soil structure model sketched on soil profiles in the Chengdu Plain with two characteristic parameters, H_n and d_{nw}, that are found to be diagnostic for predicting occurrence of the gravelly soil liquefaction.

3.2 Impermeable cap

The H_n values at the liquefied and non-liquefied sites investigated are statistically displayed in Figure 8 [16]. No H_n at liquefied sites was smaller than 0.7m. In contrast to 4 non-liquefaction sites were found with an upper layer of loose gravel but without an impermeable cap. One can see that conservatively, H_n values range from 0.5m to 5.5m at liquefied sites but with a spike at 1.0- to-2.0m; at non-liquefied sites, the data are fairly uniformly distributed from 0 m to 4m. From a review of historical gravel liquefaction cases, we found, that a non-liquefiable cap of artificial fill, clay or stiff crust of thickness 0.5m to 1.5m always existed above the gravelly layers. Therefore, it can be said that the presence of an impermeable cap to seal the excess pore water pressure and inhibit rapid dissipation is a necessary requirement for gravel liquefaction.

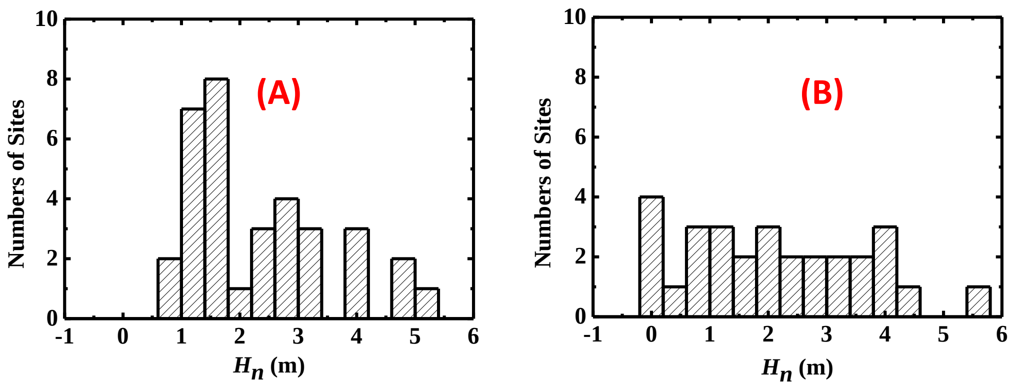


Figure 8. Distribution of H_n values at, (A) liquefied sites; (B) non-liquefied sites.

3.3 Unsaturated layer beneath impermeable cap

In addition to the thickness of the impermeable cap, the thickness of unsaturated space between the impermeable cap and the water table, is denoted by the parameter $d_{nw.}$ Figure 9 displays the distribution of d_{nw} for liquefied and non-liquefied sites determined from our field studies following the Wenchuan earthquake. To simplify, d_{nw} is set to zero if the water table lies within the impermeable cap. For liquefaction sites, about 65% of d_{nw} values were equal to zero. For non-liquefied sites 70% of d_{nw} values exceeded 1.0m with a maximum value of 5.4m. The large d_{nw} values means drainage space for dissipating excess pore water pressure was sufficient that the excess pore pressure could drain rapidly into that space without disrupting the ground surface. On the other hand, if there was not sufficient space to contain the expelled water from lower layers, the impermeable cap typically ruptured creating ground fissures allowing venting of water at the ground surface. Ground fissures and eruption of sand boils is the evidence used in this study and many previous studies to classify sites as having liquefied.

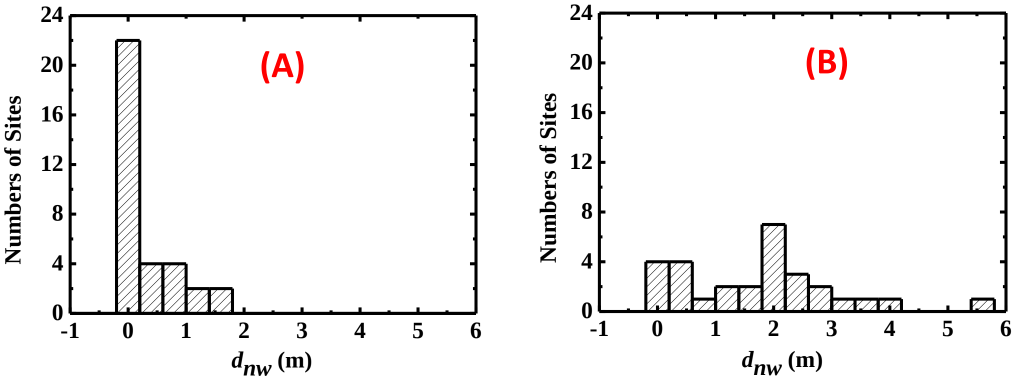


Figure 9. Distribution of d_{nw} values at, (A) liquefied sites; (B) non-liquefied sites.

3.4 Requirements for liquefaction of gravelly soils

From the developed database of H_n and d_{nw} values obtained from the explored gravelly sites, it is proposed that two hydraulic conditions correlate with the occurrence of gravelly soil liquefaction, i.e., (1) the presence of an impermeable capping layer at least 0.5 m lying above the liquefiable gravelly layer; and (2) the thickness of an unsaturated layer beneath the impermeable cap, d_{nw}, should not larger than 2.0 m. Otherwise, even loose gravelly soil is unlikely to liquefy.

4. RE-JUDGING FORMULA

4.1 The formula for liquefaction of gravelly soils

After satisfying the pre-judging conditions for liquefaction of gravelly soils a liquefaction evaluation model for gravelly soils can be developed using N_{120} as a fundamental index as following,

$$N_{cr-120} = N_{0-120}[1+\alpha_w(d_w-2)+\alpha_s(d_s-3)]\alpha_p \quad (1)$$

Where $N_{\mathrm{cr-120}}$ is a critical DPT blow; $N_{0\text{-}120}$ is a referring DPT blow; d_{s} is a sandy layer depth; d_{w} is a water table; α_{w} is a water table influencing coefficient; α_{s} is a gravely layer depth coefficient; α_{p} is the coefficient of the gravel content. Then to determine the coefficients in Eq. (1) is discussed below.

4.2 Coefficient Determination of $\boldsymbol{N_{0\text{-}120}}$

The gravel liquefaction data in Wenchuan earthquake presents that gravel layer depth and water tables vary remarkably. Hence, it is difficult to straightforwardly establish the relationship between DPT blows and intensities. Adopting the current correcting formula for shear wave velocity [17], the measured DPT blows can by corrected to values with 3m gravel depth and 2m water table. The formula is,

$$N_{120}^{'} = N_{120}(47/\sigma_v^{'})^{0.5} \quad (2)$$

Where, N'_{120} is corrected DPT blows; N_{120} is a measured DPT blow. Fig. 10 delineates the dividing line between liquefied and non-liquefied. The reference values can be read from the plot, shown in Table 2.

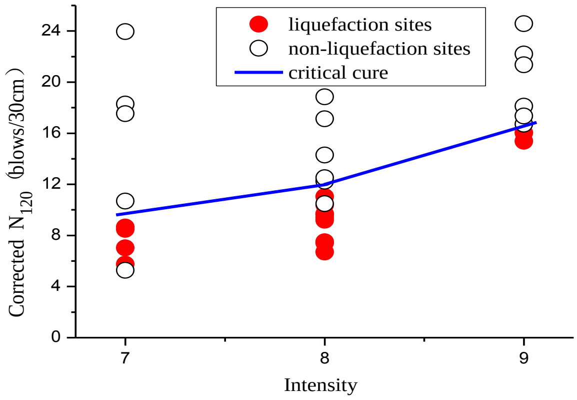


Figure10. Critical cure of N_{120} for discriminating liquefaction sites from non-liquefaction sites.

Table 2. Reference $N_{0\text{-}120}$ values

PGA	0.2g	0.3g	0.4g
$N_{0\text{-}120}$	9	12	16

4.3 Coefficients of gravel depth and water tables, αs and αw

According to the field testing results, liquefied gravely layer depths and water tables vary within considerable range. Furthermore, the data are significantly small, so directly deducing α_s and α_w will be of unavoidable uncertainty. Thereafter, an optimization method is explored to minimize the uncertainty.

The influencing coefficients of water tables can be read from Fig. 15, in which the successful judging rate for liquefied and non-liquefied sites all exceed 90%, presents the best values of α_w and α_s. To simplify, the values for α_w and α_s are 0.05 and -0.05, respectively.

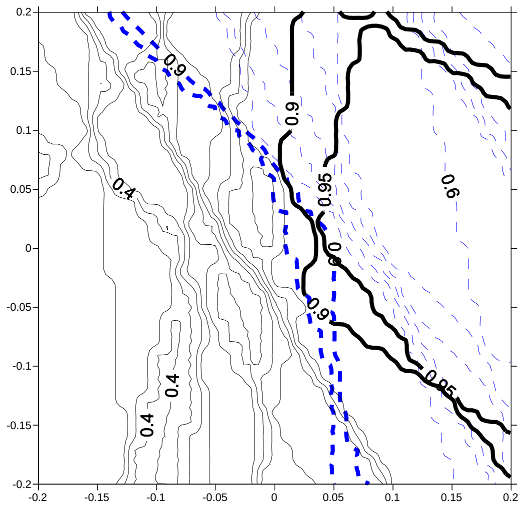


Figure 15. Optimized values for α_w and α_s

4.4 Gravel content P5

A gravel content P_5 is defined as the percentage of grain with particle sizes larger than 5mm. In the papper, large dynamic triaxial tests have been used for evaluating the influence of gravel contents on gravel liquefaction potential. The testing results illustrate the effect of P_5 on the liquefaction strength of gravelly soils can be expressed as

$$\alpha_p = 1 + \frac{0.003 \cdot (\frac{P_5}{50})}{-0.03 + 0.24^{(\frac{P_5}{50})}} \tag{4}$$

4.5 Re-judging Formula

Inasmuch above, the critical DPT-based re-judging formula for liquefaction of gravelly soils can be written as,

$$N_{cr-120} = N_{0-120}[1 - 0.05(d_w - 2) + 0.05(d_s - 3)][1 + \frac{0.003 \cdot (\frac{P_5}{50})}{-0.03 + 0.24^{(\frac{P_5}{50})}}] \tag{5}$$

Where $N_{0\text{-}120}$ can be expressed in Table 3.

Table 3. Reference $N_{0\text{-}120}$ values

PGA	0.1g	0.2g	0.3g	0.4g	0.5g
$N_{0\text{-}120}$	7	9	12	16	21

Using Eq. (5) or (6), the measured N_{120} blows is greater than $N_{cr\text{-}120}$ then the gravelly soils layer is deemed as liquefied, otherwise non-liquefied. Meanwhile, using Eq. (5) to reversely judge the testing sites, the successful judging rate are 93% for liquefied sites and 90% for non-liquefied sites. The reliability of the procedure and formula is verified and confirmed. It should be noticed the Eq. (5) is generally suitable with in 10m depth of gravelly soils layer and for P_5 >10%.

5. Conclusions

Through liquefaction investigation and in-situ testing a DPT-based liquefaction evaluation method for gravelly soils is proposed. The pre-judging conditions and re-judging formula are established. The imperative conclusions are:

(1) SPT-based liquefaction evaluation methods developed on sandy soil liquefaction data and are not applicable on gravel layers or coarse grain soil. Moreover, SPT cannot be conducted on gravel or cobble layers. In this paper, a new index DPT N_{120} is selected for gravel layer liquefaction evaluation.

(2) The liquefaction evaluation for Gravelly soils includes two stages, *i.e.*, pre-judgment and re-judgment. Pre-judgment includes the presence of an impermeable capping layer at least 0.5m lying above the liquefiable gravelly layer; and the thickness of an unsaturated layer beneath the impermeable cap should not larger than 2.0 m.

(3) The gravel liquefaction evaluation formula is consist of five parameters, i.e., DPT reference values, gravel layer depths, water tables, seismic intensity and gravel contents. An optimization method is used to deduce influencing coefficients of gravel layer depths and water tables and a normalization method is employed to gain DPT reference values.

6. Acknowledgments

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