Collapsibility potential of Brazilian latosol using CPT results

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ABSTRACT
We present results from CPT (cone penetration test) performed on tropical unsaturated latosol of the Federal District, Brazil. This soil, characterized by a dark reddish coloration, low resistance, and high void ratio, is mainly composed of sandy-clay with some traces of silt. Due to its porous structure, it shows a notable potential to hydraulic collapse. The soil profiling chart proposed by Eslami and Fellenius (1997) was used to qualitatively assess the collapsibility of the latosol in analysis. In our field investigations, we have carried out CPT under natural and modified soil moisture conditions. For the latter, we let tapped-water flow into the soil through four holes for 89 hours under atmospheric pressure. According to the abovementioned classification system, the soil within 3.25 m and 6.35 m depth was classified as collapsible.

RÉSUMÉ
On présente des résultats du CPT (cone penetration test) menés sur un latosol tropical non-saturé du District Fédéral brésilien. Ce sol, caractérisé par une coloration noir rouge, faible résistance et porosité élevé, est principalement composé d'argile-sableuse avec quelques traces de limon. Il montre un potentiel notable pour l'effondrement hydraulique en raison de sa structure poreuse. On utilise la carte de classification de sol proposée par Eslami et Fellenius (1997) pour évaluer l'effondrement du latosol. Dans notre investigations, on a mené CPT sous des conditions de humidité naturel et modifié. Pour la dernière condition, on a jeté l'eau de robinet dans quatre trous par 89 heures sous l'action de gravité. En utilisant le system de classification susmentionné, nous pouvons identifié le sol dans le profondeur 3.25 et 6.35 m comme effondrable.

1 INTRODUCTION

The collapse is one of the most well-known and worldwide studied characteristic phenomena in unsaturated soils. Its occurrence is not only linked to alluvial, colluvial, aeolian, and residual or volcanic soils (Dudley, 1970) but also to manmade compacted soils. Collapse can be realized as a process opposite to that of swelling (Fredlund & Rahardjo, 1993), that is, when the degree of saturation of the soil increases due to, say, rainfall or water table level rise, a volumetric subsidence takes place without any variation of external loading conditions undertaken by the soil layers.

Earlier there existed some divergent opinions about the definition and genesis of collapse in soils. Nowadays, however, a consensus seems more evident. With respect to its phenomenological notion, Matyas and Radhakrishna (1968), Cox (1978), Escario and Saez (1986), to name a few, define collapsible soils as those susceptible to large irreversible bulk deformation decrease when undergoing saturation. These soils have a loose open microstructure with large voids and bulky shaped grains, often ranging from silt to fine sand (Mitchell and Soga, 2005). According to Lawton et al. (1992), four main factors are necessary for collapse to happen: (1) an unsaturated soil with open and meta-stable microstructure; (2) a load (total stress) large enough to provoke collapse (this load can either be external load or the soil self-weight); (3) presence of bonding agents between grains able to secure the soil a stable state under unsaturated conditions; and (4) shear failure of these inter-granular connections due to water or other interstitial liquid action.

Collapsible soils may represent a threat to engineering constructions due to its meta-stable character. In the Northeast of Brazil a few loosely compacted earth dams have failed during the first reservoir filling phase. These dams, usually coined Sonrisal dams as an analogy to the anti-acid effervescent tablet Sonrisal that is completely pulverized after being added to water, presented a very open soil structure typical of collapsible soils (Pereira, 1996). Therefore, it is important to identify and classify these soils a priori. Gibbs and Bara (1967), for example, suggested using a density criterion to identify soils susceptible to large subsidence as a result of wetting. According to them, if the density is sufficiently low so that the void space is larger than the space needed to hold the liquid limit water content, then collapse problems are likely. On the other hand, if the void space is less than that needed for the liquid limit water content, then collapse only occurs under external load increase. Earlier Jennings and Knight (1957) proposed a laboratory test that allowed them not only to identify the soil as collapsible but also to quantify the soil collapse potential. This test, called double oedometer test, consists of carrying out two oedometer tests on the same soil but with specimens under two distinct initial saturation condition: (a) natural (or in situ) condition and (b) saturated condition. The specimens' subsidence is recorded at the end of each test and then compared to one another. The collapse potential is thus defined as the ratio of the difference in height between natural and wet samples to specimen's initial height. In this paper, we present a rather simple methodology to identify a soil as collapsible. We do not quantify the soil collapse potential, though. Our method is based on cone penetration tests (CPT) loggings and the soil profiling chart proposed by Eslami and Fellenius (1997). As will be explained in more details in a subsequent section, this soil profiling chart was compiled from an extensive database built with both CPT and CPTU tests performed around the globe. As a means to estimate the effect of soil saturation, we perform CPT tests under both natural and modified close-to-saturation soil moisture conditions. For the latter, we let tapped-water flow into the soil through four holes for 3 days and 17 hours under atmospheric pressure. This idea is somewhat inspired on the double oedometer test by Jennings and Knight. The soil under investigation is the tropical unsaturated latosol found in the Federal District of Brazil. From a geotechnical perspective, this latosol (see more details in the later sections) constitutes a collapsible sandy-clay with traces of silt. Its void ratio (1.0 – 2.0) and coefficient of permeability (10^{-3} – 10^{-4} cm/s) are relatively high compared to that of typical clays, but not high compared to that of sandy-textured soils. Due to its porous structure, it also presents a notable potential to hydraulic collapse.

2 CLIMATIC CONDITIONS AND GEOMORPHOLOGY OF THE FEDERAL DISTRICT

According to Koppen's (1923) climate classification, the Federal District (DF) is categorized within the group Aw (tropical savanna) which is characterized by a pronounced dry season. Two seasons are well distinguished in the DF: (a) a dry-cold season spanning from May till September, described by low temperatures, low precipitation and high evaporation rate; and (b) a rainy-warm season during the remaining months (CODEPLAN, 1984). The mean annual precipitation is about 1500 mm, where, as reported by Coimbra (1987), only 12% of this total infiltrates into the vadose zone and reaches the zone of saturation. The mean annual evapotranspiration is 900 mm.

The geomorphology of the Federal District consists of low-grade metamorphic rocks, characterized by slates of varying colors, metasiltstone, and quartzite beds. More than 80% of its total area is covered by a weathered lateritic layer from the tertiary-quaternary age (Mendonca et al. 1994). This laterite (or latosol) is basically a dark reddish residual soil whose thickness varies from a few centimetres up to 40 metres. It contains concentrations of iron oxides and hydroxides and aluminum hydroxides. Clay mineral caulinite is also predominant. Its silica has been extensively leached. In some localized parts of the Federal District, the latosol overlays a saprolitic/residual soil originated from a weathered, folded and foliate slate, a typical parent rock of the region (Cunha and Camapum de Carvalho 1997). This saprolitic layer has strong anisotropic mechanical behaviour and high standard penetration resistance (N_{SPT} blow counts), as opposed to the upper lateritic layer which has much lower resistance ($N_{SPT} < 5$).

3 SITE DESCRIPTION

The in situ tests reported in this paper were all performed in October of 2003 during the underground work for the new Centro de Convencoes Ulysses Guimaraes (CCUG) in Brasilia, Federal District. The CCUG, now completely finished, is a multi-purpose center building designed not only to host national and international conferences, meetings, and art exhibitions, but also conceived for the entertainment of the public in general, as it holds theatres and cinemas. With a total area of 50,000 m^2, it can shelter more than nine thousand people. This center lays its deep foundations composed of flight auger piles on an unsaturated soil. The soil profile is very typical of the Plano Piloto, where layers of lateritic-residual soil under intense weathering process can be identified, as earlier described in Section 2. Figure 1 shows some aerial views of CCUG during construction phase in October, 2003 and its localization inside Brasilia.

Figure 1: Aerial photographs of the CCUG (These photos were obtained using Google Earth in 2003 and 2008)

Undisturbed soil samples were retrieved from a hand-cut inspection well at five different depths (3.3, 5.7, 7.7, 12.2, and 15.0 m). The sole objective was to identify some physical properties and geotechnical parameters and thus characterize the soil profile. In Table 1 we report our laboratory results. Some important information related to soil collapsibility can be drawn out from this table. First, note the high void ratios (1.77 and 1.96) for the samples taken at depths 5.7 and 7.7 m, respectively. In particular for depth 5.7 m note the relatively lower values of shear strength parameters friction angle and cohesion, and the higher compression index (C_c). These numbers are good indicators of a collapsible soil. The values of Atterberg limit plotted in Figure 2 also concur towards this partial conclusion, as liquid limit water contents in the range 60-70 % are obtained. We remind you that the values of porosity for that zone (3-7 m) are about 65 %, a value within the liquid limit range; therefore, according to Gibbs and Bara (1967) the void space might be large enough to hold the liquid limit water content. Hence, collapse problems are likely to happen. A final conclusion, though, will be postponed to Section 6, where we present the results of our methodology under investigation.

Table 1: Physical properties and some other geotechnical parameters of CCUG soil profile (Anjos, 2006)

H (m)	S (%)	γ_d (kN/m^3)	γ_s (kN/m^3)	γ_t (kN/m^3)	G_s
3.3	71.7	11.2	15.5	26.6	2.71
5.7	83.9	10.9	15.9	26.8	2.73
7.7	86.0	12.4	16.7	26.9	2.74
12.2	81.6	16.8	16.8	27.6	2.81
15.0	74.5	16.8	16.8	26.7	2.72

H (m)	e	ϕ' (deg)	c' (kPa)	C_c
3.3	1.38	24.7	37	0.47
5.7	1.46	26.2	18	0.50
7.7	1.17	36.8	24	0.38
12.2	1.20	34.0	38	0.39
15.0	1.15	34.6	25	0.37

Note: H = depth; S = saturation degree; γ_d = dry unit weight; γ_s = unit weight of solids; γ_t = total unit weight; G_s = specific gravity; e = void ratio; ϕ' = friction angle; c' = cohesion; C_c = compression index. The values of C_c were indirectly obtained from Park and Koumoto's (2004) expression: $Cc = n/(371.747 - 4.275n)$, where n is the porosity.

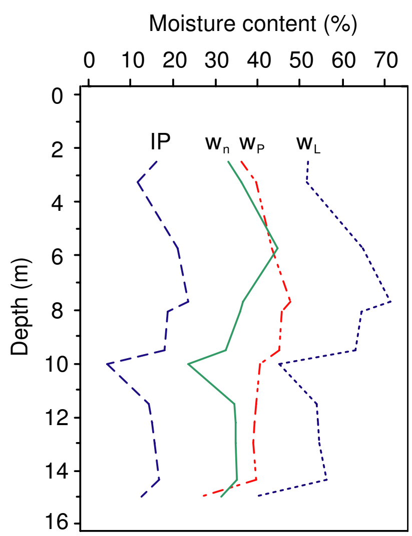

Figure 2: Atterberg limits for CCGU soil profile (Anjos, 2006)

4 IN SITU TESTS DESCRIPTION

Our experimental site investigation at CCGU comprises both standard penetration test (SPT) and cone penetration test (CPT). CPT data were directly used as input to Eslami and Fellenius (1997) soil profiling chart (see next section), while SPT data were only used to provide additional information. As such, in the following paragraphs we restrict our description to the cone penetration test.

The CPT is a simple in-situ test where a standard cylindrical cone is pushed into the ground at a fixed rate. The cone tip resistance (q_c) and sleeve friction (f_s) values are recorded continuously. The results from a cone penetration test can be utilized to evaluate stratification, soil type, soil density and in-situ stress conditions, as well as be correlated in order to estimate shear strength parameters for direct geotechnical design. The high quality and real time results of this test offers a great advantage because much finer strata delineation derived from readings taken as frequently as every 2 cm can be obtained. High productivity and minimal soil disturbance are other advantages of CPT (Brouwer, 2008).

Nowadays, we can encounter a large variety of models serving to different applications, for example, cone for measuring lateral stresses, cone with pressuremeters, cone for seismic measurements, acoustic cones, cone for measuring permeability, and even cones with built-in cameras (Melzer and Bergdahl, 2002). For our field tests we employed a standard electrical cone driven by a hydraulic ram. Some properties of this electrical cone are listed in Table 2.

Table 2: Features of CPT equipment used

Cone features	Values
Apex angle of cone (degree)	60
Dead-weight (kN)	200
Diameter (mm)	35.6
Projected area of cone (mm^2)	1000
Sleeve friction area (mm^2)	15000
Maximum force on penetrometer (kN)	100
Maximum sleeve friction (kPa)	1000

Four CPT tests were carried out at site under natural moisture condition. Data loggings of cone tip resistance and sleeve friction were recorded every 50 mm for a constant penetration rate of 20 mm/s. No measurement of pore-water pressure was taken as the equipment used had no such feature. The final depth reached at each test was limited by anchoring and penetration capacities of the equipment. Figure 3 resumes the data from these four tests plus describes the soil stratigraphy as obtained from SPT. The friction ratio in Figure 3c stands for $R_f = f_s/q_c$. From a visual-tactile examination of SPT loggings, an artificial landfill composed mainly of a stiff sandy-clay was identified in the first 3 m. After that upper layer, soft clay was found from roughly 3 to 10 m. Our attention is directed to this second layer because it has characteristics of collapsible soil as described earlier. CPT values of cone resistance and sleeve friction for that layer are quite low.

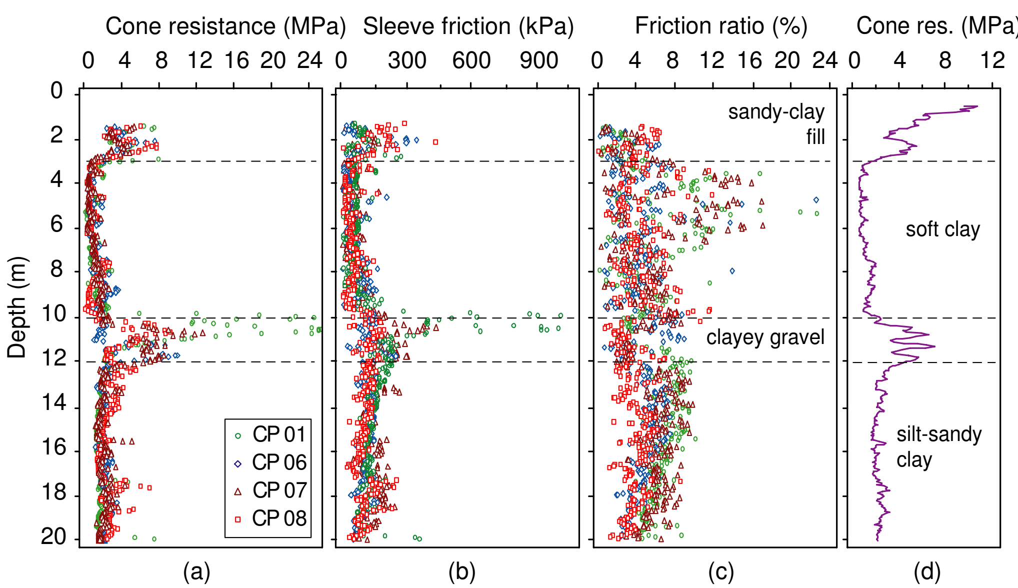

Figure 3: CPT field results at CCUG: (a) cone resistance; (b) sleeve friction; (c) friction ratio; and (d) geometric mean of cone resistance and soil stratigraphy (Anjos, 2006)

5 SOIL PROFILING CHART

Eslami and Fellenius (1997) designed a soil profiling chart based on a database of 102 case histories compiled from full-scale pile loading tests along with information about soil type and soundings of CPT performed nearby the pile location. Their database contains 36 sources from 40 sites in 13 countries, including Brazil and Canada, but mainly from the United States. A variety of soils is considered, namely, sediments of clay (soft clay, stiff clay, silty clay, sandy clay), silt (clayey silt, sandy silt), and sand (clayey sand, silty sand, gravelly sand). Cemented soils and stiff clays are not included. According to these authors, about 80% of the CPT cases included in the data are obtained by electrical cone and 20% by mechanical cone. About half the cases from silt and clay soils have pore-pressure measurements. Finally, most of the CPT measurements are at a vertical spacing of 300 mm or smaller.

Their database was sorted into five soil categories: (1) collapsible soil, (2) clay and/or silt, (3) clayey-silt and/or silty-clay, (4) silty-sand, and (5) sand to sandy-gravel. Latter on Fellenius (2002) further split category 4 into two: (4a) silty sand and (4b) sandy silt as shown in Figure 4. The qualifiers clayey, silty, and sandy correspond to fractions between 20-35 %. A profiling diagram similar to that designed by Begemann (1965) was chosen to group the categories. A clear difference between the two diagrams exists, though: an effective cone resistance, q_E, (= q_t - u_2) is used instead of the cone resistance q_c, where u_2 is the pore pressure measured behind the cone point and q_t is the corrected cone resistance for the pore pressure acting on the shoulder. The boundaries shown in the diagram enclose approximately 90% of all points of each category.

There exist many other soil profiling charts that attempt to capture the characteristic behaviour of soils and hence propose a sort of soil classification (or identification to be more precise). We have chosen Eslami and Fellenius' (1997) chart because it allows us to classify soils as collapsible. That is an especial advantage over other charts when tropical regions such as those found in the Brazilian Federal District are under study. In Brazil, charts were specifically designed to deal with tropical residual soils (Mota, 2003 and de Mio, 2005). These charts, however, lack a robust and solid database in order to become more applicable in practice.

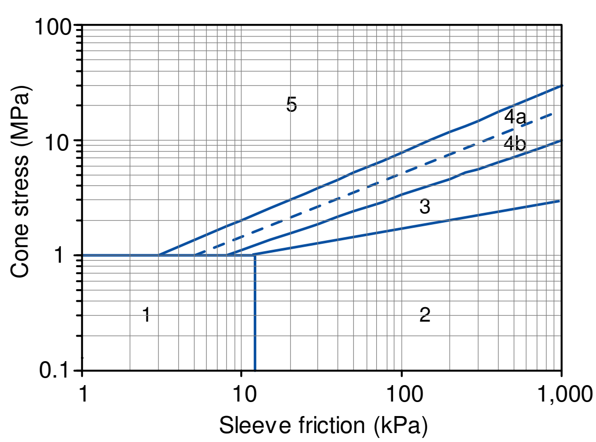

Figure 4: Soil profiling chart (Eslami and Fellenius, 1997 and Fellenius, 2002).

6 RESULTS AND ANALYSIS

In this last section we analyze and discuss the applicability of Eslami and Fellenius' (1997) soil profiling chart to identify collapsible soils at the Centro de Convencoes Ulysses Guimaraes. We also investigate the effect of soil saturation on CPT results. For that, we carried out an additional test, 25 cm away from CPT 01 (see Figure 3) in which the soil was artificially wet prior to the test. The soil was flooded for 89 hours (3 days and 17 hours) through four holes approximately 4.5 m deep and 0.30 m diameter. Tapped-water under atmospheric pressure was used. The idea was to emulate a double oedometer test in situ and thus attempt to unveil any trace of collapsibility. The rather rudimentary flooding scheme set up at site is illustrated in Figure 5. The CPT rig is also shown.

Figure 5: Bore holes from where tapped water was poured out (Anjos, 2006).

The values of cone resistance and sleeve friction for both CPTs performed under natural condition and altered moisture condition are compared in Figure 6a, b. The effectiveness of flooding process can be examined from Figure 6c, where water content values obtained from SPT loggings are presented. From these figures we note only a slight decrease in cone resistance and sleeve friction between the two CPT data. That might not be surprising as the water contents before and after wetting process are not very distinct. A reason for the low water content increase may be due to the high permeability and high natural saturation degree (about 78 %) of the soil layers, especially the collapsible zone. As such, the effect of matric suction variation to the soil strength values was small.

The objective here, though, is to classify the soil profile by using Eslami and Fellenius soil profiling chart. For that purpose, data from both CPTs discussed in this section were employed. As pore-water pressures could not be measured, we had to assume $q_E = q_C$; therefore, an error was introduced. However this error is not too critical because the soil layers behave more like sand than clay from a geotechnical viewpoint. Ideally cone penetration testing with pore-water pressure measurements would be preferred as they give a more reliable determination of stratification and soil type than a standard CPT (Eslami and Fellenius, 1997).

After plugging each CPT data into the soil profiling chart, the following results were drawn. For the case with soil under natural condition, collapsible soil was identified at a few depths only (4.65, 5.50, 5.65, 6.45, and 6.60 m).

Differently from that, for the case where the ground was flooded prior to test, soil collapsibility was revealed in many more depths (from 3.25 to 6.35 m), as reported in Table 3. This later result is more in accord with previous researches (Camapum de Carvalho and Mortari, 1994; Camapum de Carvalho et al. 1994, Cardoso, 1995), in which the zone of collapsible soils in the Federal District is shown to extend down to roughly 6m depth. Also, from the undisturbed cubic soil specimens retrieved between 3.2 and 8.0 m depth, a porous collapsible structure is perfectly visible with naked eye. Unfortunately, no laboratory double oedometer test was carried out on the undisturbed samples retrieved at CCUG. Such a test could certainly provide answers to issues not properly addressed in this paper, such as a measure for the soil collapse potential.

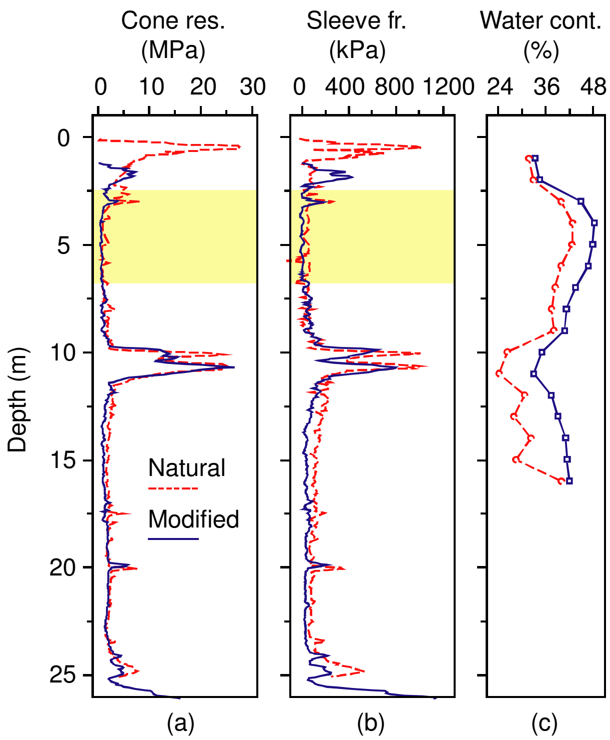

Figure 6: Natural and modified CPT profiles and soil water content (Anjos, 2006)

Table 3: Soil classification based on Eslami and Fellenius (1997) chart and CPT data performed on soil under close-to-saturation condition

z (m)	Soil type
1.50 – 1.55	Sandy-silt
1.60 – 1.95	Clayey-silt and/or silty-clay
2.00	Sandy-silt
2.05 – 2.10	Clayey-silt and/or silty-clay
2.15	Clay and/or silt
2.20 – 2.30	Clayey-silt and/or silty-clay
2.35	Clay and/or silt
2.40	Silty-sand
2.45 – 2.50	Sand to sandy-ravel
2.55	Sandy-silt
2.60 – 2.80	Clayey-silt and/or silty-clay

Table 3: Soil classification based on Eslami and Fellenius (1997) chart and CPT data performed on soil under close-to-saturation condition (continued)

2.85 – 3.20	Clay and/or silt
3.25	Collapsible soil
3.30	Sand and Gravel
3.35	Collapsible soil
3.40	Clay and/or silt
3.45	Collapsible soil
3.50 – 3.80	Clay and/or silt
3.85	Collapsible soil
3.90 – 4.10	Clay and/or silt
4.15 – 4.20	Collapsible soil
4.25	Clay and/or silt
4.30 – 4.50	Collapsible soil
4.55 – 4.75	Clay and/or silt
4.80 – 5.20	Collapsible soil
5.25 – 5.35	Clay and/or silt
5.40	Collapsible soil
5.45 – 5.95	Clay and/or silt
6.00	Collapsible soil
6.05	Clay and/or silt
6.10	Collapsible soil
6.15 – 6.20	Clay and/or silt
6.25	Collapsible soil
6.30	Clay and/or silt
6.35	Collapsible soil
6.40 – 9.35	Clay and/or silt

7 CONCLUSIONS

Results from CPT were used as means to qualitatively assess whether a particular tropical lateritic soil found at the Centro de Convencoes Ulysses Guimaraes, located in the Federal District of Brazil, is collapsible or not. The rather simplistic methodology presented here was based on Eslami and Fellenius (1997) soil profiling chart, which employs CPT data. Two soil conditions were investigated: (a) soil under natural conditions; (b) soil under modified close-to-saturation condition. In the latter case, the ground was artificially flooded prior to test. Under natural moisture condition, collapsible soil was sparsely identified within 3 to 7 m, a result also confirmed by other researches. The wetting process, although not practical at all from an engineering design perspective, helped reveal more spots of soil collapsibility. In conclusion, the soil profiling chart rendered useful in pinpointing the collapse behaviour of the soil investigated.

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