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ORIGINAL ARTICLE

Elimination of loess collapsibility with application to construction and demolition waste during dynamic compaction

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Abstract With the rapid modernization of China's infrastructure construction, disposal of the massive amount of construction and demolition waste (CDW) produced each year has gradually developed into a national concern due to its increasingly adverse effect on the environment. Additionally, in northwestern China, ground deformation triggered by collapsible loess has caused severe damage to local infrastructure. In an attempt to address both problems simultaneously, this paper proposes the novel approach of applying CDW as a pile filler for the down-hole dynamic compaction. The concept, construction process, and design principles of this new method are described, and its efficiency and feasibility are validated in detailed studies of four practical cases in different locations in China. Problems that arise in certain aspects of this method, i.e., code revision with consideration of the variable loess conditions and CDW in different locations, are also discussed. Case studies and relevant discussions indicate a promising future for this environmentally friendly and eco-efficient method that is broadly applicable in many locations.

Keywords Construction and demolition waste · Collapsibility · Loess · Down-hole dynamic compaction

Introduction

Construction and demolition waste (CDW) is generated as a result of infrastructure and demolition activities and primarily includes concrete, brick, and rock materials, among other materials (Aatheesan et al. 2010). With the rapid development of China's construction industry, approximately 1.6–2 million square meters of new urban area are constructed each year, producing a large amount of CDW as construction waste, and more than 100 million tons are produced each year, contributing to 30–40 % of all urban waste (Zhang and Wu 2011). Currently, most CDW is buried in landfills, which not only intensifies the land use pressure on cities but also causes environment problems, such as underground water pollution if buried near rivers. The increasing cost of burying CDW in landfills in many countries (Arulrajah et al. 2013), the growing scarcity of natural resources and other environmental, and social problems associated with the large amounts of CDW have gradually developed into a national concern.

Nevertheless, CDW represents a large resource of recyclable and reusable cement materials that, once put to use, could be both environmentally friendly and eco-efficient. In recent years, many studies have been performed to investigate the possibility of reusing CDW, an option that appears rather fruitful. One possibility is the use of crushed CDW as raw materials for the production of calcium silicate products, i.e., bricks (Schuur 2000), concrete (Rashid et al. 2012; Bazaz and Khayati 2012; Khalaf 2006), and mortar (Silva et al. 2010; Miranda et al. 2013). The CDW also can be directly applied to the construction of pavement (Gabr and Cameron 2012; Herrador et al. 2012; Azam and Cameron 2013) and roof substrates (Molineux et al. 2009; Carson et al. 2012). In addition, recycling management that considers both cost and environmental issues has also been studied (Inyang 2003; Srour et al. 2012).

In northwestern China, loess is an ideal agricultural soil due to its abundant nutrients and low density. However, loess is not sufficiently compacted or completely

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consolidated due to the large voids in the soil that result from the various bridging and bonding systems between the main structural silt particles (Barden et al. 1973). Therefore, loess becomes highly friable and can cause significant ground deformation when exposed to water or destabilization. These soil failures have caused severe damage to local infrastructure due to the rapid expansion of human activities and cities, together with the large demand for water in areas dominated by collapsible loess. In fact, loess collapse can result in a reduction of volume of up to 30 % (Liu 1997).

Therefore, measures must be taken to mitigate or even eliminate the collapsibility of loess prior to construction activities. For decades, extensive in situ and laboratory studies have been carried out to search for efficient reinforcement approaches, including dynamic compaction (Mayne et al. 1984; Lutenegger 1986; Chow et al. 1992), chemical stabilization (Semkin and Ermoshin 1986; Larionova et al. 2012), physical additives (a cement-based method from Li et al. 2007; a soil–cement cushion treatment from Jefferson et al. 2008; a fly ash stabilized method from Parsons and Kneebone 2005; Kolias et al. 2005), partial replacement (Alawaji 2001; Ayadat and Hanna 2005; An et al. 2009), and combined methods (Abbeche et al. 2010).

These approaches can provide eco-efficiency regardless of CDW is utilized as raw materials or directly applied to pavement constructions. Additionally, methods that mitigate the collapsibility of the loess-like loess-cement cushion have proven to be quite effective. However, none of these options are able to address these two urgent problems simultaneously. To address this concern, a novel concept that combines the efficient disposal of CDW and the effective treatment of collapsible loess is introduced and systematically discussed. The remainder of this paper is organized as follows. First, the collapsibility mechanism of loess and different dynamic compaction methods (including the proposed method) are introduced, together with performance evaluation approaches for treated soils. Next, four practical application cases are discussed in detail, and the feasibility and efficiency of this new method are validated. Several existing problems with this method are subsequently discussed in a final section with summaries and future extensions.

Mechanism and methods

Solution to the collapsibility of loess

In engineering practice, approaches used to treat collapsible loess include the lime soil cushion method, dynamic compaction method, chemical consolidation method, and precast concrete pile method, among others. Because loess primarily consists of silt particles that form the pores or void spaces that are the major causes of collapsibility and because the strength of the silt particle framework determines the bearing capacity and other engineering properties of a loess foundation, dynamic compaction is favored in most cases due to its efficiency in increasing the strength of the silt particle framework, thereby reinforcing the soil foundation in an efficient and economical manner.

Classification of the dynamic compaction method

This section introduces a down-hole dynamic compaction (DDC) method that uses CDW in addition to the traditional dynamic compaction method and discusses the different engineering features of these methods.

Traditional dynamic compaction

The traditional method dynamically compacts the soil using a large hammer with a level bottom that falls freely from a height of approximately 20 m directly onto the ground. The impact of this free fall creates stress waves that push on the loess framework and exclude the void spaces between silt particles, thus increasing the density of the soil.

Down-hole dynamic compaction

Conversely, the DDC method applies lateral compaction of soil with the aid of CDW, which is vertically rammed by a tamping machine. The mechanism of the DDC method can be summarized in four steps. First, a hole is dug by either a drilling or tamping machine; second, the bottom of the hole is filled with CDW; third, CDW filler is repeatedly impacted by the tamping machine such that the input energy of the tamping machine is used to compact the loess laterally via the deformation of CDW. Finally, repeated tamping with newly added CDW continues until the entire hole is filled with CDW. Therefore, the hole finally becomes a CDW pile, and the loess around the pile is laterally compacted in an effective manner.

Principles of CDW pile design

For effective CDW pile design, it is essential to involve engineering practice experience and field test conclusions. The basic principles of collapsible loess treatment are summarized in the Chinese national codes, i.e., the code for building construction in collapsible loess regions (GB50025-2004) and the technical code for ground treatment of buildings (JCJ79-2002). According to these codes, the subgrade pressure must be no greater than the

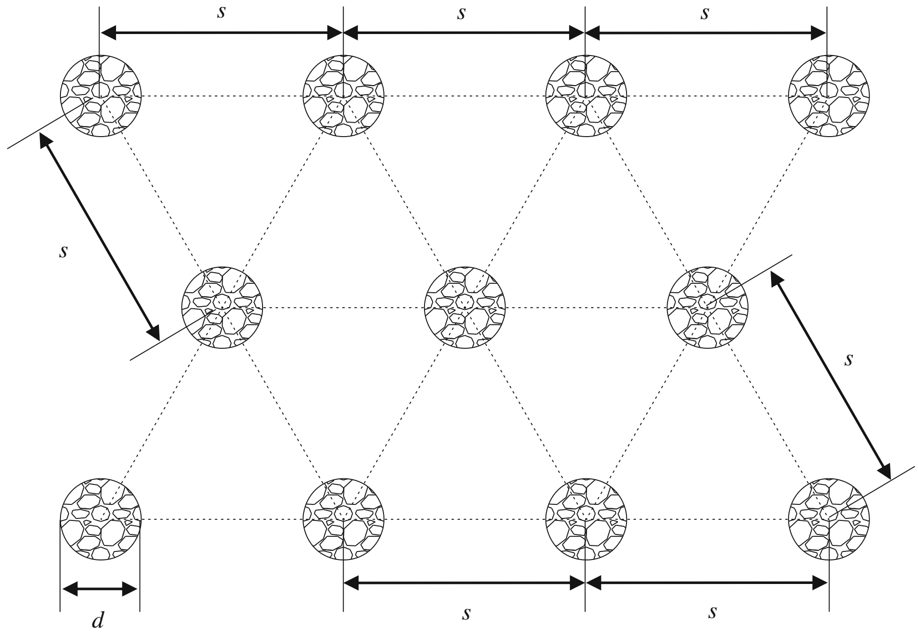

Fig. 1 Collocation of CDW piles. *d* pile diameter, *s* pile space between adjacent pile centers

foundation bearing capacity ($P \leq f$), and the final settlement must be less than the allowable settlement ($S < [S]$). The design of a CDW pile composite foundation should also follow this principle.

Collocation of piles

The collocation of CDW piles follows the relevant criteria in the technical code for the ground treatment of buildings (JCJ79-2002). The diameter of a CDW pile should be determined by the hole-forming equipment or treatment requirement, and the piles should be collocated in a triangular pattern. The space between piles can be determined using the following formulas:

$$s = 0.95d\sqrt{\frac{\bar{\eta}_c \rho_{\mathrm{dmax}}}{\bar{\eta}_c \rho_{\mathrm{dmax}} - \bar{\rho}_d}} \tag{1}$$

$$\bar{\eta}_c = \frac{\bar{\rho}_{\mathrm{d1}}}{\rho_{\mathrm{dmax}}}, \tag{2}$$

where s is the pile space (m); d is the pile diameter (m); ρ_{dmax} is the maximum dry density of soil between piles (t/m^3); $\bar{\rho}_{\mathrm{d}}$ is the average dry density before compaction (t/m^3); $\bar{\eta}_{\mathrm{c}}$ is the compaction coefficient, no <0.93; and $\bar{\rho}_{\mathrm{d1}}$ is the average dry density after compaction (t/m^3).

Figure 1 shows the equilateral triangle collocation of CDW piles. Equation (2) considers the compaction coefficient as the ratio of $\bar{\rho}_{\mathrm{d1}}$ (average dry density after compaction) to ρ_{dmax} (maximum dry density of soil between piles). The value of $\bar{\rho}_{\mathrm{d1}}$ represents the average compaction effects such that a higher value of the compaction coefficient represents greater compaction effects and a higher relative density of the compacted soil.

To achieve the optimal level of compaction, the following formula is applied to identify the single pile filler volume:

$$G = A_{\mathrm{p}} \cdot L \cdot K, \tag{3}$$

where G is the single pile filler volume (m^3); A_{p} is the pile cross-sectional area (m^2); L is the pile length (m); and K is the filling coefficient.

The filling coefficient K is a ratio of the CDW amount actually filled in the pile to the calculated amount of CDW designed prior to construction. According to engineering experiences, the value of K varies between 1.05 and 1.20 depending on the specific site condition. Finally, an independent foundation or strip foundation is efficient for treating ordinary soils, but for collapsible loess, treatment should be upgraded such that one or two rows of protective piles should be placed at the outer edges of the box and raft foundation.

Construction process

The construction process for the DDC method using CDW filler can be divided into three steps: (1) hole formation, (2) CDW fill, and (3) tamping and reinforcement. A detailed description of each step is given below.

Hole formation

Hole formation can be carried out using either drilling or tamping machines, and a schematic of the tamping machine is shown in Fig. 2a. In the case of collapsible loess, the tamping approach is better suited to the

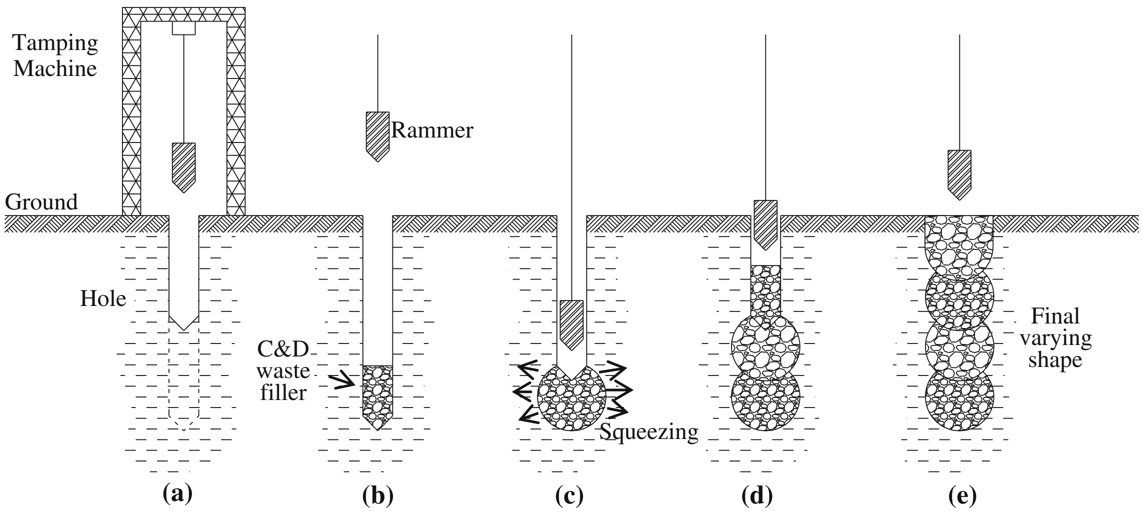

Fig. 2 Construction process of CDW pile. **a** Hole formation, **b** filling, **c** tamping, **d** repeating process, **e** final pile

formation of a hole. The drilling approach uses helical drills, but the tamping method adopts a special heavy columnar hammer, which operates as follows: the hammer is hung on a cable car and is repeatedly pulled up by the work machine on the car after it is released from a certain height and falls freely into the hole until the design depth is reached. Additionally, the position and depth of the hole should be examined after tamping and before filling with CDW.

Fill process

The main compositions of CDW include slag brickbats, concrete residue, gravel, and dry mortar residue, among others. Generally, as a pile filler, CDW is required to contain little or no organic matter. Further discussions of these composition requirements are found in "Requirements fo CDW filler" section.

After the hole is formed, an amount of CDW filler is first placed into the hole, as shown in Fig. 2b. The tamping machine tamps the filler with its hammer, as shown in Fig. 2c. Additional CDW is continually added to the hole and tamped until the last tamping is finished, and the entire hole is filled with CDW. Construction of a CDW pile is finally completed after all processing, leading to a longitudinally varying pile shape (Fig. 2e).

Tamping and reinforcement

During the tamping process, considerable lateral stress is generated to dynamically compact the surrounding soil layers. Additionally, as the CDW deforms, it laterally expands and dominates in certain places where loess was initially located. As a result, the void ratio of the soil is reduced together with an increased density and improved physical and mechanical properties, and thus, the collapsibility of the loess is efficiently eliminated.

In addition, the components of CDW, which include slag brickbats, concrete residue, gravel and dry mortar residue, are primarily loose substances with a strong tendency toward water absorption, which turns the CDW pile into effective drainage channels that release the pore pressure and accelerate the consolidation process. As a result, this method eliminates the collapsibility and liquefaction of the soil and greatly improves the bearing capacity of the loess foundation.

Calculation of the foundation bearing capacity and foundation deformation

Calculation of the foundation bearing capacity

The CDW pile is constructed under dynamic compaction within the hole, which leads to significant interaction between the soil and pile filler. The pile tends to swell laterally because it is vertically compacted. Therefore, the foundation bearing capacity calculation should follow the composite foundation rules, according to which the standard bearing capacity of a composite foundation should be determined using field tests. However, in the preliminary design stage, this value can be estimated by referring to the characteristic bearing capacity of a single pile and the soil between the piles using the following formulas:

$$f_0 = mf_\mathrm{p} + (1 - m)f_\mathrm{a} \quad (4)$$

$$m = A_\mathrm{p}/A_\mathrm{e} \quad (5)$$

$$A_\mathrm{p} = \pi \cdot d^2/4, \quad (6)$$

where f_0 is the basic value of the bearing capacity of the composite foundation (kPa); m is the area replacement ratio, generally taken as $m = 0.1$–0.3, for the total replacement, $m = 1.0$; A_p is the cross-sectional area of a pile (m^2); d is the design diameter of a pile (m); A_e is the treatment area of a single pile (m^2); f_p is the basic value of the pile bearing capacity determined by the reference table according to the average heavy dynamic sounding blow count of the pile or from comparative tests (kPa); and f_a is the basic bearing capacity of the soil between piles after reinforcement determined by the reference table according to the average dynamic sounding blow count for the soil between the piles or from comparative tests (kPa).

Calculation of the foundation deformation

The deformation calculation should follow the Chinese national code for the design of building foundations (GB50007-2002). The approaches for deformation computation for composite foundations and natural foundations are the same, but the deformation modulus should be altered using the following formula:

$$s = \psi_s s' = \psi_s \sum_{i=1}^{n} \frac{P_0}{E_{\text{spi}}} (z_i a_i - z_{i-1} a_{i-1}), \tag{7}$$

where s is the final foundation deformation (mm); s' is the foundation deformation derived from the layer-wise summation method (mm); ψ_s is the empirical coefficient of the settlement calculation obtained from experience with measurements of settlements from previous engineering cases; n is the number of soil layers considered in the deformation calculation; P_0 is the additional stress of the base under a quasi-permanent load effect (kPa); E_{spi} is the compression modulus of soil layer i under the building foundation (MPa) obtained from the curve between the self-weight stress and the additional stress of the soil; z_i, z_{i-1} are the distances from the base to the bottom of soil layers i and $i-1$, respectively (m); and a_i, a_{i-1} are the coefficients of the average superimposed stress from the base to the bottom of soil layers i and $i-1$, respectively.

The deformation modulus E_{sp} is obtained using the following formula:

$$E_{\text{sp}} = [1 + m(n-1)]E_s, \tag{8}$$

where E_{sp} is the deformation modulus of the composite foundation (MPa); m is the area replacement ratio; E_s is the compression modulus of the soil between the piles after reinforcement (MPa); and n the pile-soil stress ratio, taken as 2–4 if no field measurements are available; a lower strength of soil between piles denotes a larger n value, and a higher strength of soil between piles denotes a smaller n value.

Post-construction assessment methods

When the construction of the CDW pile cluster is completed, the piles and soil should be examined. Post-construction examination methods include the field static load test, penetration test, dynamic sounding test, and laboratory soil test.

The field static load test determines the bearing capacity of the foundation using a load plate with a certain size that is subjected to a step-wise increasing load. The load plate can be a circular plate with a diameter of 1.30 m (area = 1.33 m^2), 1.15 m (area = 1.05 m^2), or 0.90 m (area = 0.636 m^2) or a square plate with a side length of 0.50 m, as in this study. Because the settlement of the foundation was measured during the test, the Q–S curve can be obtained together with the determination of the foundation bearing capacity. Therefore, the eligibility of the foundation bearing capacity can be reasonably evaluated via the field static load test.

The goal of the standard penetration test and dynamic sounding test is to count the number of hammer blows to obtain a certain penetration depth using a hammer with a certain weight that falls freely from a certain height into the soil. The blow number can be subsequently used to determine whether the compactness and bearing capacity of soil foundation meet the requirements. The laboratory test is used to obtain the collapsibility coefficient from dozens of soil samples and thereby determine whether the treatment has eliminated the collapsibility of the loess.

Case study: four application cases in practical engineering

Soil treatment using CDW piles is particularly suitable for urban loess foundation reinforcement. This section introduces four cases in practical engineering. "Case I" section describes the foundation reinforcement project for Xi'an Defu Lane, which suffers from large ground settlements. "Case II" section presents the foundation reinforcement project for public teaching building D at the Xi'an Institute of Engineering Science and Technology. "Case III" section describes a project for block B in the Xi'an Yinkai residential area, and "Case IV" section discusses the foundation reinforcement of the second plant building in the relocation project of Zhengzhou's cable company.

Requirements for CDW filler

Components of CDW

Not all CDW can be used as pile filler. Generally, waste components can be classified as originating from either the

Table 1 Components of CDW in HK

Waste components	CDW composition (%)	
	Construction waste	Demolition waste
Crushed concrete	19.89	9.27
Fractured reinforced concrete	33.11	8.25
Lumpy concrete	1.11	0.9
Soils and dashes	11.91	30.56
Crushed rocks and stones	11.78	23.78
Asphalt	1.61	0.13
Bricks	6.33	5.00
Bamboo and wood	7.46	10.83
Glasses	0.2	0.56
Sands	1.44	1.70
Metal	3.41	4.36
Others	2.02	4.56
Total	100	100

construction process or the demolition process, as suggested by the names. Construction wastes include excess or useless materials produced during the construction process, including scattered mortar, fractured concrete, refused steel, and discarded bricks. The main components of demolition waste are produced during the demolition process, i.e., fractured bricks, rubble, and removed concrete waste. The European Waste Catalogue (EWC) classifies CDW into the following eight categories: (1) concretes, bricks, tiles, and ceramics; (2) woods, glasses, and plastics; (3) bituminous mixtures, coal tars, and tarred products; (4) metals (including their alloys), (5) soils (including excavated soil from contaminated sites), stones, and dredged spoils; (6) insulation materials and asbestos-containing construction materials; (7) gypsum-based construction materials; and (8) other construction and demolition waste (Lu et al. 2011). Table 1 places the components of Hong Kong CDW into 12 different categories and lists the corresponding proportion of each component (Chen et al. 2004).

As shown in Table 1, concrete materials account for the majority of CDW. Additionally, approximately 1.5 tons of waste concrete will be generated for every 100 tons of concrete production. Due to the massive concrete production of China's construction industry, the waste concrete supply is clearly substantial. Apart from the main components, the waste will inevitably contain organic substances, pollutants, and other impurities as well, which are not suitable for pile filler. Therefore, it is necessary to exclude these ineligible and harmful components before the tamping and filling process, i.e., CDW must be screened a priori.

Screening process for CDW

The screening process for CDW consists of four steps: (1) preliminary screening, (2) smashing, (3) sieving, and (4) mixing. First, the waste is divided into several different categories, i.e., concrete, stone, soil, steel, wood, glass and plastic, of which only concrete and stone materials can be used as pile filler. Second, the qualified materials are crushed into pieces by a crushing machine. Based on the second step, the materials are grouped according to different grain diameters (materials are stacked in different places after the sieving and post-sieving processes). Finally, materials with different diameters are proportionally mixed together after calculation. Two photographs are presented in Fig. 3 to show the CDW materials and the manner in which they are stacked separately according to different grain sizes.

Other components, i.e., steel, organic matter, toxic substances, and highly radioactive fly ashes, should all be excluded. However, it is impossible to remove all of the undesired components. Therefore, further research efforts are imperative to provide reliable criteria for the upper limit content of organic matter as well as the grain size and composition of pile fillers.

Estimation of the use ratio of CDW

In addition to studies on the composition and screening process of CDW, research on estimating the use ratio of CDW is also necessary. Considering the uncertainty of CDW output, different waste batches may have different contents, and thus, the use ratio will vary from one batch to another. In addition, secondary waste will be produced if large amounts of CDW are not properly utilized. Therefore, it is necessary to estimate the use ratio of the input CDW before and after the construction of CDW piles. Currently, no relevant criteria exist for determination of the lower limit of the CDW use ratio, which is an urgent need for further research.

Case I

The topography of this site is largely flat, and the geomorphic unit belongs to the Weihe River II level terraces. Geological investigation to a depth of 18 m shows that the ground is primarily composed of Quaternary Holocene and Upper Pleistocene fill, loess, ancient soil, and silty clay. Phreatic water exists as well due to the permeation of meteoric water and drainage of domestic water. The stable groundwater level is located 10.9 m below the natural ground level. The superstructure of the seven-story residential building was designed by Dadi Design Office, and the building foundation consists of a reinforced concrete

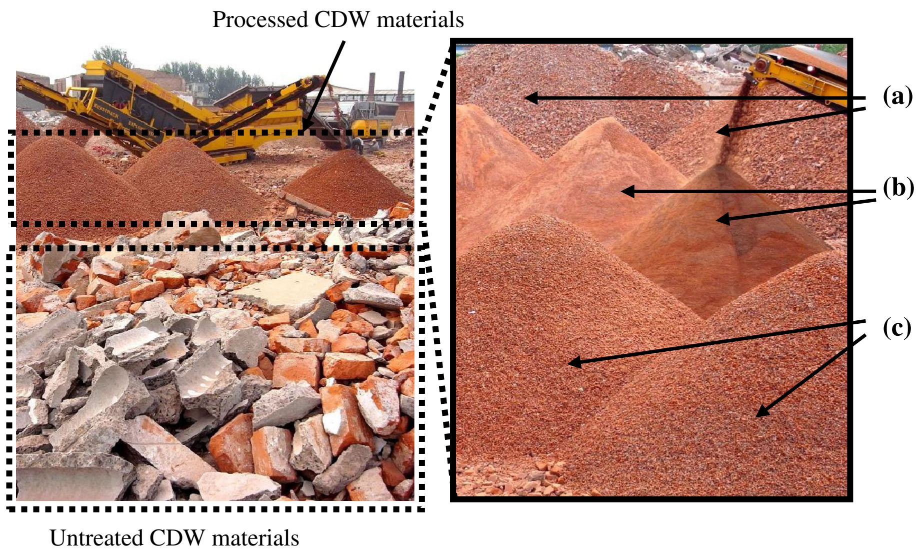

Fig. 3 Processing and stacking of CDW materials. *a* Grain size >35 mm; *b* grain size >5 mm; *c* grain size between 5 mm and 35 mm

strip foundation with an underlying 1.0-m lime soil cushion layer (the proportion of lime to soil is 3:7).

The DDC method is applied in this case, and the pile filler is screened CDW. The depth of the hole (the length of the pile) is 6 m from the bottom of the lime soil cushion to the top, and the diameter of the hole is 400 mm. The pile diameter is 600 mm after completion, and the piles are collocated in an equilateral triangle form with a distance of 1.2 m between each two piles. The bearing capacity of the foundation is required to be >200 kPa.

Two points (located in soil close to the nearby piles) in the site are selected for static load tests, and the load plate used is a steel circular rigid load plate with a diameter of 1.30 m (area = 1.33 m^2). Six points (located on the piles) are chosen for dynamic sounding tests. After the analysis, the Q–S curves are obtained from static load tests of the two points (p I, p II) in the soil (the Q–S curve is shown in Fig. 4). The bearing capacity from the Q–S curve of the load plate test could be obtained using the three methods according to three different curve forms: (1) inflection point method—if there is a notable inflection point in the Q–S curve, the inflection point of the curve is chosen as the proportional limit pressure p_0, and the load value corresponding to the proportional limit pressure p_0 is the bearing capacity value; (2) ultimate load method—the ultimate pressure p_u should be determined first, and if p_u is lower than twice the load value corresponding to the proportional limit pressure, then the bearing capacity value is half of the ultimate pressure p_u; (3) relative settlement method—for a situation in which the Q–S curve changes slowly, the bearing capacity value could be estimated as a foundation bearing capacity corresponding to a certain settlement value. In this case, the standard composite foundation bearing capacity value is determined by the second method

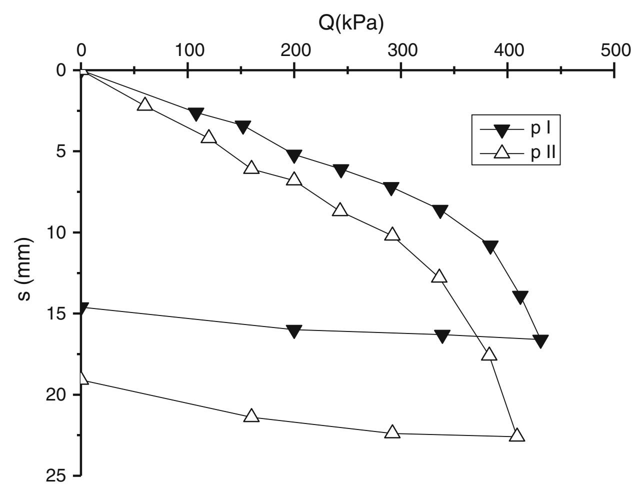

Fig. 4 Load-settlement curves (Case I)

as 210 kPa. In the following three case histories, the bearing capacities are obtained by the aforementioned methods as well.

Figure 5 shows the results of the dynamic sounding tests of six piles at the site. The $N_{63.5}$ in Fig. 5 has the same meaning as the N_{60} value obtained from the standard penetration test (SPT). The value of 63.5 in $N_{63.5}$ means that the hammer weighs 63.5 kg, according to Chinese codes, and is dropped from a height of 76 cm at 30-cm penetration depth intervals, and the value of 60 in N_{60} (SPT) indicates that the hammer drops are corrected for 60 % energy. The standard pile bearing capacities of the three piles (p2, p3, and p4) vary smoothly along the pile, whereas those of the other three piles (p1, p5, and p6) tend to shift. Because two out of the six points are close to the static load test points (p1 is close to pI, and p5 is close to p

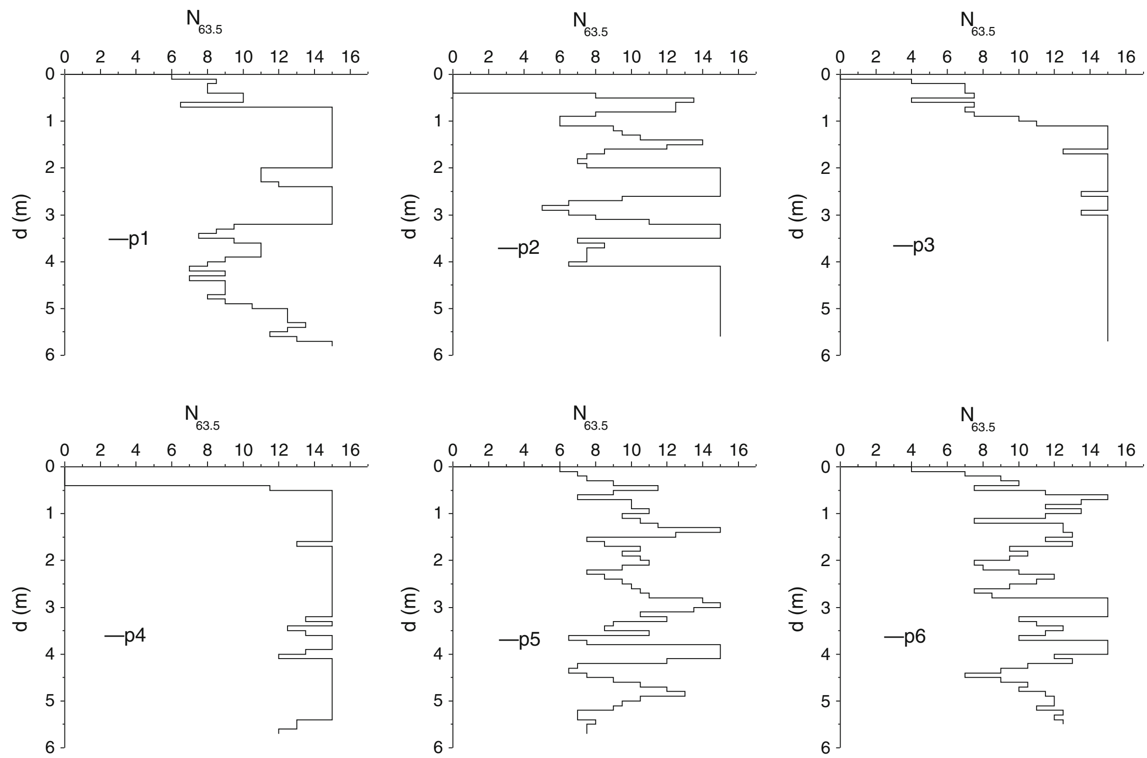

Fig. 5 Dynamic sounding curves (Case I)

II), after comprehensive analysis of the dynamic sounding curves and the results of static load tests, the standard composite foundation bearing capacity is computed as 220 kPa (the standard pile bearing capacity is 300 kPa, and the standard bearing capacity of the soil between piles is 200 kPa). Therefore, this reinforcement proves to be quite effective because each standard bearing capacity is greater than the design value (200 kPa).

Case II

The soil at this site belongs to the non-self-weight collapsible loess category with collapsible grade I according to the *Code for building construction in collapsible loess regions,* showing a mild level of collapsibility. Phreatic water is present with a stable underground water level of 12.00–12.80 m below natural ground, as indicated by the geological investigation. The properties of each soil strata are listed in Table 2 and indicate the remarkable collapsibility of loess in layers ② and ③. In the Tables, α_{1-2} is the coefficient of compressibility and f_{ak} is the natural bearing capacity of the foundation.

The pile filler in this case is screened CDW mixed with lime, and the DDC method is applied. The design diameter of the pile is 600 mm, the effective pile length is 8.5 m (CDW filler from the top down to a depth of 3 m is mixed with lime, the proportion of CDW to lime is 1:9, and the remaining filler is CDW), and the pile spacing is 1.1 m in a fully triangular layout. The bearing capacity is required to be no <300 kPa, and the collapsibility of soil must be eliminated after reinforcement treatment.

After treatment with a steel circular rigid load plate with a diameter of 1.15 m (area = 1.05 m^2) used in the static load tests, the characteristic bearing capacity of the foundation is 300 kPa, as shown in Fig. 6, which meets the design requirements. In the heavy dynamic sounding tests, 36 points were selected, and nine of them (p4, p5, p21, p22, p24, p25, p26, p34, and p35) were picked as representative (Fig. 7); according to these representative points, the pile density is quite satisfactory. In addition to field tests, laboratory tests are also conducted for the soil between piles in this case. Because the sample coefficients of collapsibility are <0.015 according to the test results shown in Tables 3 and 4, the collapsibility of this site's foundation soils has been completely eliminated. The coefficients of collapsibility were obtained in indoor tests by measuring the additional subsidence of loess samples in ring knives of unit thickness, in which the loess samples were immersed in saturated state and tested under certain pressure (Fig. 8).

Case III

The site of this case was originally a soil-sampling pit but was subsequently backfilled by construction and domestic

Table 2 Soil conditions at site of case II

Layer	Soil type	Thickness/m	w/%	e	γ/kN/m^3	I_L	α_{1-2}/MPa	f_{ak}/kPa
①	Fill	0.40–2.50						
②	Loess	2.10–5.30	17.78	1.018	13.23	0.096	0.287	170
③	Loess	2.00–4.60	23.20	0.966	13.54	0.413	0.254	160
④	Loess	2.10–7.60	29.19	0.954	13.61	0.855	0.379	120
⑤	Old soil	4.00–5.10	27.43	0.760	15.10	0.786	0.311	140
⑥	Silty clay	2.60–5.90	23.49	0.664	16.03	0.416	0.211	200
⑦	Medium sand	5.50–10.90						240
⑦$_1$	Fine sand	0.65–3.70						220
⑧	Silty clay	5.00–8.00	23.05	0.651	16.15	0.353	0.224	210
⑨	Silty clay	Unpenetrated	23.70	0.663	16.01	0.451	0.217	220

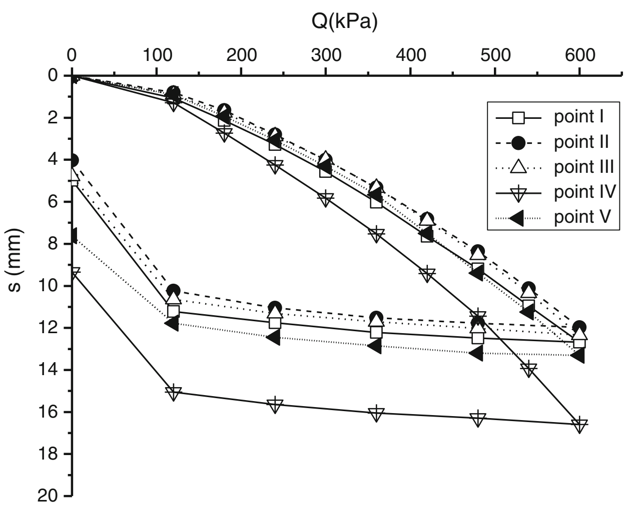

Fig. 6 Load-settlement curves (Case II)

waste. The major obstacle for construction lies in the thick miscellaneous fill with scarps of approximately 8 m in height located in the south and east of the site. The geomorphic unit belongs to the Weihe grade III terraces. Geological investigation down to a depth of 18 m indicates no sign of groundwater. Soil conditions together with the range of pile length are listed in Table 5, and layers ④, ⑥ and ⑥$_1$ are collapsible.

In this case, the DDC method is applied, and the pile filler consists of screened CDW and clay. The ultra-heavy dynamic compaction method is adopted for hole formation. The depth of the hole is 7.00 m, and the treatment depth is 9.00 m. The diameter of the hole is 1.5 m, and pile fillers contain miscellaneous materials (the main components are clay and CDW that contains an amount of lime-ash with <3 % of organic matter content). The filling process together with tamping and compacting are all carried out in a layer-by-layer manner. The layout of the piles follows an equilateral triangle form with a space of 3 m between each two piles. The diameter of each pile is 2 m, and the total number of piles is 833. The characteristic bearing capacity of the composite foundation must be >200 kPa.

Static load tests were conducted using a steel circular rigid load plate with a diameter of 900 mm (0.90 m, area = 0.636 m^2). The results of the static load tests show that the pile's characteristic bearing capacity is 300 kPa (Fig. 8, curves sz1, sz2, sz3, and sz4) and that the characteristic bearing capacity of soil between piles is 200 kPa (shown in Fig. 8, curves st1, st2, st3, and st4). According to the above two values, the characteristic foundation bearing capacity is determined as 240 kPa, which qualifies as no <200 kPa. In addition, heavy dynamic sounding tests (six test points on the piles and six points in the soil between piles) indicate that the pile filler and the soil between piles are both moderately dense in the area from the pile top down to a depth of 2.5 m, and the pile filler is quite dense but the soil between piles is moderately dense in the area down to a depth >2.5 m from the pile top (Fig. 9a, b; dz1 and dz2 are selected as representative of the pile soil test points, and dt3 and dt6 represent the test points for the soil between piles). Therefore, both the pile soil and the soil between piles achieved relative homogeneity.

Case IV

In this case, the site's geomorphic unit can be classified as the Yellow River alluvial plain type. Sand pits and large undulating terrain are common at this site due to human activities. Although the groundwater table is located 2.0 m below natural ground, it has no adverse impact on the reinforced concrete foundation. The building foundation sites are divided into three categories according to the *Code for Investigation of Geotechnical Engineering* established by the Ministry of Construction of the Chinese government. Category I denotes a complex site, category II denotes a moderately complex site, and category III denotes a simple site. The category II sites are those that meet five specific conditions: (1) sites unfavorable for building aseismicity, (2)

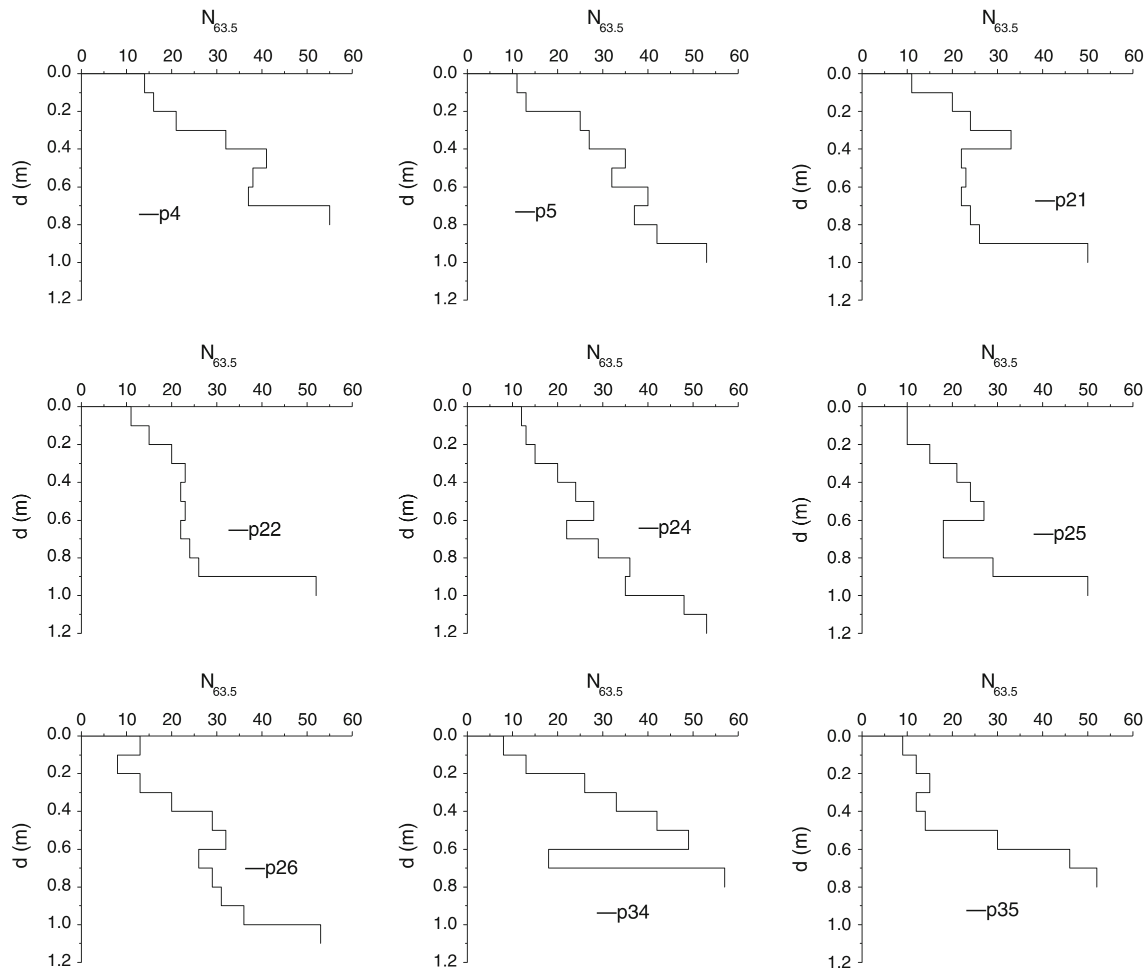

Fig. 7 Dynamic sounding curves (case II, 9 points selected from 36 test points)

sites with adverse geological development at the general level, (3) sites with a geological environment subject to general destruction, (4) sites with complex topography, and (5) sites located below the water table. Considering that the soil in this site is moderately soft and the site of case IV has complex topography, case IV was classified as a category II construction site. An overview of the soil layers from top to bottom is provided in Table 6.

This site is divided into the original area and the filled area, in which soil was filled before reinforcement, and the DDC method is applied. The reinforcement depth is 8 m, and each hole is 1.5 m in diameter. Holes are created by the impact of a hammer weighing 150 kN that falls from a height of 10 m above the ground. The pile filler materials, including CDW and lime soil, are placed into the holes. The proportion of lime soil is <30 % of the entire weight, and <10 % of the CDW mass is organic matter. These materials are placed into the hole in a layer-by-layer manner and tamped at intervals. Finally, the entire site is tamped with a 100 kN hammer from a 6-m drop height over a tamping space of 1.7 m.

In this case, static load tests using a steel square rigid load plate with dimensions of 0.707 m on a side (area = 0.5 m^2) are conducted in both the original and filled areas of the site. According to the results of the field tests (Fig. 10a, b), the design bearing capacity of the composite foundation is 180 kPa after treatment, and the characteristic bearing capacity is >230 kPa. Within the range of reinforcement depth, the compression moduli are all >15 MPa, and therefore, the reinforcement treatment is qualified.

Discussion

Several design criteria

Currently, the design criteria for foundation treatment using the method discussed in this paper generally adhere to those of the compaction design method, which derive from the design criteria of the immersed tube method and the stone column method. Nevertheless, these design criteria differ significantly.

Table 3 Indoor soil tests of Case II (a)

Sample serial	Soil depth/m	Moisture content w/%	Unit weight γ/kN/m^3	Void ratio e_0	Plasticity index	Liquidity index	Coefficient of collapsibility
1-1	1.00–1.15	22.4	18.6	0.746	11.5	0.39	0.001
1–2	2.00–2.15	25.0	18.4	0.802	12.4	0.52	0.001
1–3	3.00–3.15	23.6	18.4	0.782	12.0	0.45	0.002
1–4	4.00–4.15	24.5	18.8	0.757	12.4	0.48	0.001
1–5	5.00–5.15	27.9	18.4	0.844	11.6	0.85	0.001
1–6	6.00–6.15	27.2	18.4	0.834	13.2	0.60	0.001
1–7	7.00–7.15	22.5	19.7	0.646	10.7	0.50	0.001
1–8	8.00–8.15	23.4	19.6	0.672	12.0	0.42	0.001
1–9	8.85–9.00	25.7	19.6	0.692	11.4	0.60	0.001
2–1	1.00–1.15	22.6	17.5	0.860	11.3	0.43	0.001
2–2	2.00–2.15	23.8	18.0	0.817	11.2	0.55	0.004
2–3	3.00–3.15	24.6	17.8	0.855	12.1	0.51	0.001
2–4	4.00–4.15	28.3	18.0	0.890	12.5	0.78	0.002
2–5	5.00–5.15	28.0	18.2	0.865	12.3	0.77	0.001
2–6	6.00–6.15	28.5	18.2	0.872	13.1	0.71	0.001
2–7	7.00–7.15	22.9	19.3	0.691	11.5	0.43	0.001
2–8	8.50–8.65	23.6	19.8	0.658	11.8	0.47	
3–1	1.00–1.15	23.0	18.0	0.812	11.6	0.43	0.001
3–2	2.00–2.15	22.9	17.5	0.871	11.6	0.43	0.001
3–3	3.00–3.15	23.4	17.8	0.848	11.9	0.45	0.001
3–4	4.00–4.15	26.6	18.6	0.806	11.9	0.71	0.001
3–5	5.00–5.15	26.8	18.8	0.790	12.3	0.67	0.001
3–6	6.00–6.15	28.9	18.0	0.808	12.8	0.78	0.001
3–7	7.00–7.15	25.2	18.8	0.767	11.7	0.61	0.001
3–8	8.50–8.65	24.8	19.6	0.684	11.7	0.53	

Diameter of piles

The design of the pile diameter is determined by several factors, i.e., soil conditions before treatment, collocation of piles, and expected treatment effect. In addition, differences between the actual and designed diameter of the pile can occur, depending on the construction parameters (i.e., hammer weight and drop height, blow count, and pile filler properties). The key to eliminating error is to carry out comprehensive field tests before construction and modify the design based on the test results.

Measurement of the compaction effect

If cohesive materials, such as pure or lime soils, are used as the pile filler, the compaction coefficient $\eta_{c,}$ measured by the penetration test should be considered as one of the main indicators for pile quality control. However, because of the enormous tamping energy generated during dynamic compaction, if the construction is carried out under normal circumstances with the maximum dry density measured by the penetration test method, η_c will exceed 1.0, whereas the code requires that η_c is no <0.93, which is in conflict with the requirement for η_c to be no >0.93. This situation means that the advantages of DDC method cannot be fully realized using the current design criteria. Therefore, further studies are required to obtain a more appropriate measurement for the dry density $\rho_{\mathrm{dmax.}}$

If the soil water content is less than the optimal value after compaction, it will still exhibit collapsibility under certain water pressures regardless of the compaction coefficient achieved. Therefore, further investigations should focus on how to determine the optimum water content w_{opt} and how to estimate whether the soil water content after compaction should be regulated in design.

Testing standards of the composite foundation

Quality evaluation

If viscous material filler, i.e., lime or pure soil, exists in the pile, undisturbed soil samples must be collected to measure the compaction coefficient. In certain cases, the unconfined compressive strength can also be measured together with the pile quality as determined by a portable dynamic penetrometer, also known as the light penetration test. N_{10}

Table 4 Indoor soil tests of case II (b)

Sample serial	Soil depth/m	Moisture content w/%	Unit weight γ/kN/m^3	Void ratio e_0	Plasticity index	Liquidity index	Coefficient of collapsibility
4–1	1.00–1.15	21.6	19.1	0.690	12.0	0.28	0.001
4–2	2.00–2.15	20.9	19.1	0.680	11.6	0.23	0.001
4–3	3.00–3.15	23.7	18.1	0.777	11.1	0.33	0.003
4–4	4.00–4.15	24.6	18.8	0.780	11.5	0.77	0.001
4–5	5.00–5.15	26.5	18.7	0.795	11.6	0.73	0.001
4–6	6.00–6.15	28.5	18.8	0.814	12.5	0.75	0.002
4–7	7.00–7.15	27.0	19.0	0.774	12.6	0.66	0.001
4–8	8.50–8.65	25.4	19.6	0.699	11.6	0.65	0.002
5–1	1.00–1.15	19.6	17.4	0.801	11.6	0.15	0.001
5–2	2.00–2.15	20.4	19.4	0.642	11.1	0.26	0.001
5–3	3.00–3.15	19.6	19.4	0.631	11.2	0.18	0.001
5–4	4.00–4.15	20.1	19.2	0.634	11.3	0.22	0.001
5–5	5.00–5.15	25.3	18.8	0.783	11.8	0.69	0.001
5–6	6.00–6.15	25.6	19.2	0.737	12.2	0.59	0.001
5–7	7.00–7.15	24.8	19.4	0.768	12.1	0.54	0.001
5–8	8.00–8.15	24.3	19.3	0.680	11.4	0.68	0.001
5–9	8.85–9.00	22.8	19.8	0.601	11.5	0.51	
6–1	1.00–1.15	22.6	18.9	0.736	11.5	0.50	0.001
6–2	2.00–2.15	23.0	19.6	0.667	11.9	0.41	0.001
6–3	3.00–3.15	23.3	19.6	0.671	11.7	0.41	0.001
6–4	4.00–4.15	23.5	19.8	0.657	11.7	0.46	0.001
6–5	5.00–5.15	25.5	18.9	0.762	11.6	0.66	0.001
6–6	6.00–6.15	26.9	19.0	0.773	11.9	0.74	0.001
6–7	7.00–7.15	26.9	19.2	0.775	12.2	0.69	0.002
6–8	8.00–8.15	23.8	19.2	0.705	11.1	0.57	0.001

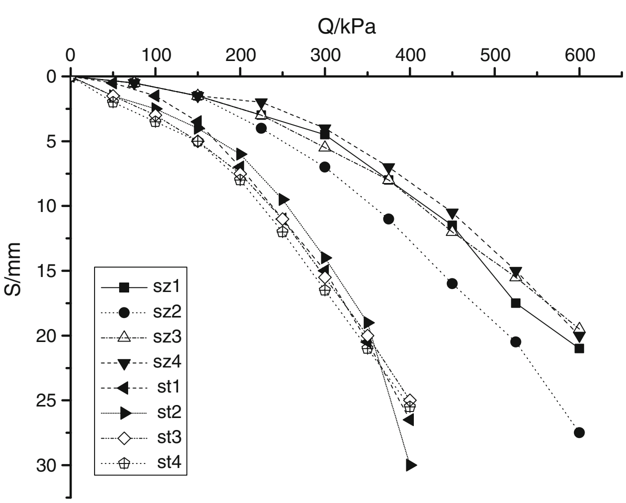

Fig. 8 Load-settlement curves (Case III)

is the blow count for the light penetration test in which the hammer weighs 10 kg, the fall distance is 50 cm, and the penetration depth per count is 30 cm. Because methods for dry density and optimum water content are not fully established, establishment of the relationship between N_{10} and the dry density of the lime soil (under different aging periods and proportions) and between N_{10} and the collapsibility of the soil is essential if the light dynamic penetration test is selected for measurement.

If the CDW primarily consists of sand, stone, and other coarse aggregates, the dynamic penetration test will be the most suitable method. A heavy or ultra-heavy dynamic penetration test also can be applied depending on the compactness of filler. However, because the standards for determining the pile density, bearing capacity, and deformation modulus derive from the research on strata rich in sand and stones (and a relative large range of strata can be defined as rich in sand and stone), direct application of the study to a composite foundation is unreasonable. In addition, the properties of natural gravel strata are associated with not only the density but also the mineral composition and surrounding environment at the time when the strata were formed. Thus, the standard tends to present a feature of localization due to various geographic environments.

Table 5 Soil Conditions at site of Case III

Layer	Soil	Thickness/m	w/%	e	γ/kN/m^3	δ_s	α_{1-2}/MPa	f_{ak}/kPa
①	Fill	4.20–18.80						
④	Loess	0.70	20.0	0.756	18.6	0.003	0.14	160
⑤	Old soil	1.60–3.00	20.2	0.785	18.3	0.002	0.11	180
⑥	Loess		19.3	0.832	17.6	0.005	0.11	180
⑥$_1$	Loess	10.80	24.1	0.900	17.8	0.001	0.12	170

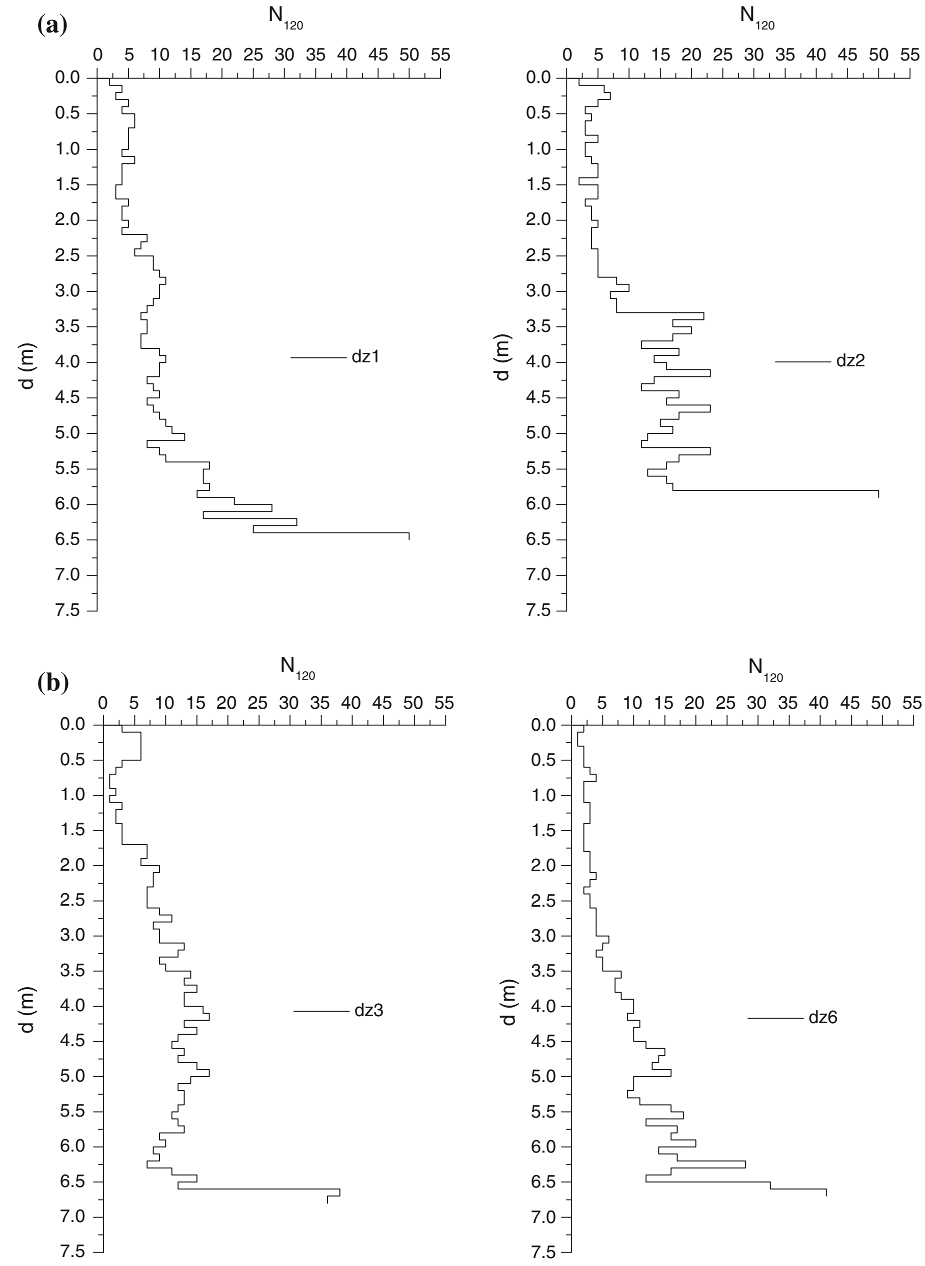

Fig. 9 **a** Dynamic sounding curves of pile soil (case III), **b** dynamic sounding curves of soil between piles (case III)

Evaluation of the quality of soil between piles

A reliable method for determining a reasonable compaction coefficient for the soil between piles has yet to be determined. In certain cases, the penetration test method is adopted, which still remains problematic. One question that remains is how to select the appropriate test points considering that the density of the soil

Table 6 Soil condition at site of case IV

Lithology	Layer bottom depth/m	Bearing capacity standard value/kPa	Compression modulus/MPa
Fine sand	2.8	180	15.5
Silt soil	5.2	165	11.2
Silt soil	9.0	230	15.5
Silty sand	25.6	240	24.0

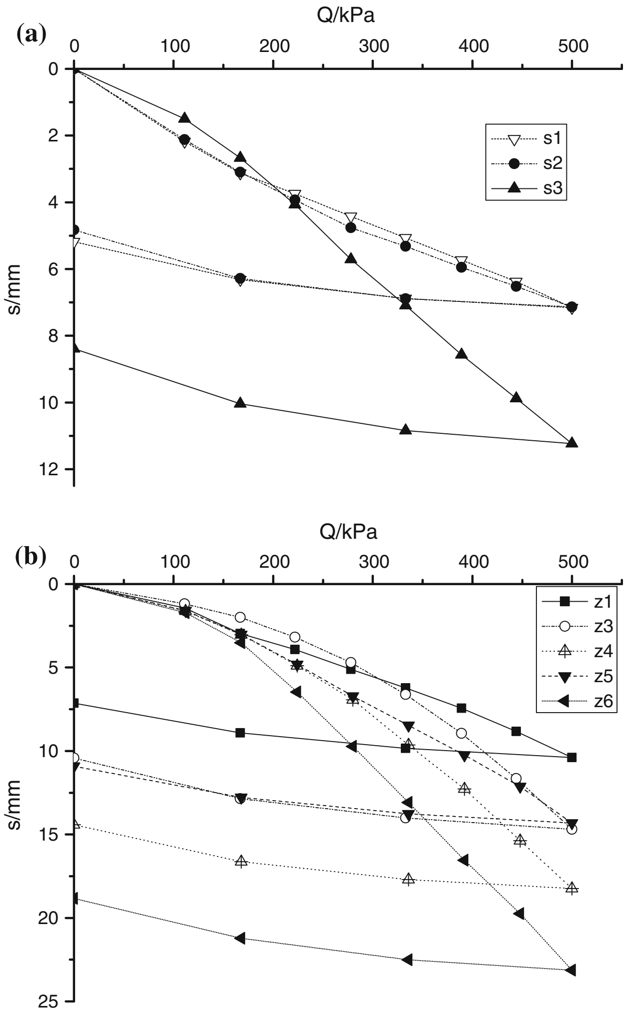

Fig. 10 **a** Load-settlement curves of original area (case IV), **b** Load-settlement curves of filled area (case IV)

between piles varies along the pile. Another problem is that the blow number in the penetration test is related to not only soil density but also the water content and structural properties of the soil. Specification of the range of blow counts that indicates the elimination of the collapsibility of soil cannot be readily realized. Thus, further studies aimed at solving these problems are imperative.

Evaluation of a composite foundation after reinforcement

In general, the field load test is the most reliable method used to evaluate the bearing capacity of a foundation. In addition, the deformation modulus can be obtained by back-calculation through the field test. However, the test plate in the static load test and the actual foundation differ in both size and shape, and therefore, the test results may not be satisfactory in certain cases, especially if conducted on inhomogeneous soils.

In the natural state, collapsible loess has strong structural strength but low water content; thus, in certain cases, it can be directly used for foundations without any need for treatment. However, once treatment is necessary, the existence of groundwater should be considered for a reliable field load test of the composite foundation. However, from a practical perspective, it is unfeasible to broadly apply this method because it will be both costly and time consuming if water immersion is involved. Thus, it is imperative to find a more efficient method for determining the bearing capacity and compression features of a composite foundation immersed in water.

In many cases, the bearing capacity of the composite foundation is still <200 kPa after treatment, which means that the collapsibility of soil between piles has not been sufficiently eliminated as required. Because water pressure is responsible for loess collapsibility, refined treatment can be carried out by considering this pressure.

According to the Chinese code, the collapsibility of loess is evaluated in an immersed condition and under a pressure of 200 kPa (excluding self-weight collapsibility). However, the initial pressure p_{sh} should generally be >200 kPa for a favorable condition that effectively eliminates the collapsibility of loess. Therefore, unless demanding requirements exist for foundation settlement, the bearing capacity of a composite foundation with treated loess between piles should be greater than that for general buildings.

Construction sequence of piles

Because the DDC method is relatively novel for the majority of construction firms, designers, supervisors, and owners, construction with this method is typically addressed empirically; thus, it is not surprising that accidents occur. Therefore, more rigid measures should be implemented to guarantee smooth pile construction. For instance, compaction should be carried out in a timely and step-by-step manner after the hole is formed to improve the compaction effect and ensure that the CDW piles are even and close-grained. The code for building construction in collapsible loess regions (GB50025-2004) recommends that local treatment should be carried out from the inner piles to the outer piles and that full treatment should start from the edges and progress to the middle. In addition, previous batches of piles should be sparsely placed, whereas subsequent batches should be densely placed. Thus, more rigorous provisions of the construction sequence of piles should be added to the codes.

Conclusion

In this paper, a novel approach that simultaneously addresses problems of the disposal of CDW and stabilization of collapsible loess is proposed. This method is validated by four engineering cases. The conclusions drawn from this paper can be summarized as follows:

(1) Stabilization and compaction mechanism: When filled into the hole, CDW is vertically rammed by a tamping machine, and deformation and displacement occur, causing the lateral expansion and consequent dominance of CDW in certain places where loess was initially located. Due to this mechanism, the constraint of the surrounding environment loess is laterally compacted by the compacted CDW.

(2) The design method of CDW piles: The CDW pile design follows the principles of composite foundation design methods according to the relevant codes. In calculating the bearing capacity of the composite foundation, the bearing capacity value is affected by the bearing capacities of both the compacted soil and CDW piles.

(3) This new method has several notable advantages:

   1. It mitigates the pressure to dispose of massive amounts of CDW and thereby alleviates the adverse environmental effects of CDW.
   2. It is neither costly nor time-consuming and greatly reduces the inconvenience to neighboring regions.
   3. It not only satisfies the requirement of soil reinforcement but also increases the shear strength of soil and can be applied to stabilize soil slopes as well.

The major issue with the proposed method lies in the mismatch between the current design code and engineering design practice, as noted in "Discussion" section. Therefore, further studies should focus on improving construction methods and refining the design theory. Thus, further revisions of design codes based on useful information provided by additional engineering practice and research on this dynamic compaction method using CDW materials should be carried out in the future.

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