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Technical Note

Soil-cement mixture properties and design considerations for reinforced excavation

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ABSTRACT

soil-cement is a mixture produced by grouting or mixing cement with soils. This paper reviews and discusses the general classifications of grouting techniques and the suitability of their applications. The mechanical properties of soil-cement mixture and the influence of sodium silicate added are discussed. Design considerations for deep soil mixed wall (DSMW) for excavation support and vault arch for tunnelling stabilisation are presented. Parameters for the numerical analysis of soil-cement mixture are evaluated and recommended.

1. Introduction

Soil-cement is a mixture of cementitious chemical material (usually referred to cement) and natural material (usually referred to soils). The product has a significant increase in shear strength to meet strength requirements of different applications. Soil-cement is best described as fine-grained or coarse-grained soil-cement mixture in accordance with soil classifications, and it presents different mechanical properties accordingly. Grouting or mixing is the mechanical action to produce soil-cement. Grouting may be classified according to the mechanical action, such as jet grouting, permeation grouting, compaction grouting and fracture grouting. On the other hand, grouting can also be classified based on the grouts, e.g. chemical grouting, and cement grouting. In practise, additives, such as fly ash and sodium sulphate solution, are admixed with the cementitious materials to meet different needs.

This paper first reviews the general classifications of grouting and the suitability of their applications. Then, the mechanical properties of the soil-cement mixture and the influence of the sodium silicate added are discussed. Finally, design considerations for the two popular methods, i.e. deep soil mixed wall (DSMW) for excavation support and vault arch for tunnelling, are presented.

2. Grouting categories and suitability of application

Grouting is a mature technology used to inject cementitious materials into fine fissures or small pores. Firstly developed in 1802 (Cambefort, 1977), chemical grouting was applied to dam cut-off and tunnel support (Littlejohn, 1985). Table 1 summarises the grouts used and their applications (Cambefort, 1977).

Chemical grouts are in a state of solution when used to fill the voids of soils, while cementitious grouts are in a state of suspension of particles in a fluid medium (EM1110-1-3500, 1995; EM1110-2-3506, 1995). Chemical grouts react to form a solid, semisolid or gel after a predetermined time, and the difference between chemical and cementitious grouts is arbitrary in which some particulate grouts are composed of suspension of superfine cement with particle size less than 10 μm in diameter. The viscosities of chemical grouts can be in a very low level and no solid particles are contained. Thus chemical grouts have been frequently used to penetrate into the very fine cohesive materials to enhance the strength of the material or into the very fine fissures to prevent water infiltration, when cementitious grout cannot be penetrated. Table 2 summarises the properties of five types of chemical grouts in contrast to Portland cement based grout. US Army Corps of Engineers' manual EM1110-1-3500 (1995) stated that chemical grouts are constantly

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Table 1
Principal grouts employed (after Cambefort, 1977).

Grout type			State		Range of uses		Grouting control
Cement			Suspensions	Unstable	Fissures		Refusal pressure
Bentonite + cement				Stable	Sands and gravels	$k > 5 \times 10^{-4}$ m/s	Limited quantities
Deflocculated bentonite						$k > 10^{-4}$ m/s	
Chemical products	Sodium silicate	Diluted	Liquids			$k > 10^{-5}$ m/s	
		Hard				$k > 10^{-4}$ m/s	
	Organic resins					$k > 10^{-6}$ m/s	

Note: k is the hydraulic conductivity.

Table 2
Grading and assessment of properties of grouts.

Grout material	Properties					
	Ground-penetration characteristics	Durability	Ease of application	Toxicity	Flammability	Costs
Portland cement	Low	High	Moderate	Low	No	Low
Silicates	High	Moderate	High	Low	No	Low
Acrylates	High	Moderate	High	Moderate	Low	High
Lignins	High	Moderate	High	High	Low	High
Urethanes	Moderate	High	Moderate	High	High	High
Resins	Low	High	Moderate	High	Moderate	High

more costly than cement grouts. Moreover, chemical grouts often show significant disadvantages due to potentially toxic effects, and in some circumstances, they are even not allowed to be used in practise. Potential pollution to groundwater by chemical grouts is considered as a main factor that should be avoided in the selection of the type of grouts in many cases. From Table 2, we can see that sodium silicates are among the most widely used chemical grouts due to their safe, environment-compatible nature and relative low costs. In practise, cementitious grout, and sometimes in conjunction with chemical grouts (e.g. sodium silicates), is preferred to grout the large voids.

Grouting can also be categorised by either grouting method or the purpose. For example, jet grouting generates in situ grouted soil body. The jet grout is advanced to the treatment depth, where grout jets (cement grout with optional water and air) are sprayed with high velocity from nozzles under high pressure in the side of the drill chamber. Depending on the application and types of soils, jet grouting can use the single fluid system (slurry grout jet), the double fluid system (slurry grout jet surrounded by an air jet) or the triple fluid system (water jet surrounded by an air jet, with a separate grout port). Different grouting parameters are used for different grouting materials and methods, e.g. grout pressure can be up to 30–50 MPa for single fluid and double fluid (air) systems, higher than 2 MPa for double fluid (water) and triple fluid systems (BS EN 12716, 2001), while some contractors may use 40–70 MPa for single fluid system, 30–70 MPa for double fluid system and 7–10 MPa for triple fluid system, correspondingly with flow rate of grout of 100–300 L/min, 100–600 L/min and 120–200 L/min (Burke, 2004; Wang et al., 2013). With such pressure and velocity, the jets erode and mix the soil in the field as the drill stem and jet grout head are rotated and raised to construct soilcrete panels in full or partial columns, with designed strength and/or permeability.

Deep soil mixing method (DSMM or DMM) is gaining popularity recently. It is a general term to describe a variety of soil mixing techniques to improve in situ soils by mechanically mixing them with cementitious binder slurry. FHWA (2000, 2013) has more details about the technique regarding construction procedure, classification, etc. Table 3 summarises production method, material and suitability evaluation for soil-cement. In this paper, we focus on the mechanical properties and engineering application of cementitious grouting products, i.e. soil-cement mixture, instead of discussing the details related to the construction.

3. Mechanical properties of soil-cement mixture and influence of additive

Engineering practise adopts many empirical methods in addition to theoretical and numerical analyses, especially for ground improvement and pre-support design, which are mostly experience-based. As for using soil-cement in reinforced excavation, unconfined compressive strength (UCS), q_u (at 28 d, and hereafter), is widely adopted as the design and construction quality control standard (Wang et al., 2014a). Parameters used in numerical analysis, e.g. finite element (FE) analysis, have to be interpreted from q_u. The reason for this is that considerable discrepancy is observed for soil-cement mixture between laboratory test results

Table 3
Prodution methods, typically-used materials and suitability evaluation for soil-cement mixture (Leca et al., 2000).

Grouting method	Application	Soil suitablility	Grout	Effect evaluation[a]
Deep soil mixing	Reinforcement	Any soil; soft soils and loose sands are most suitable	Cement	(1), (4)
Jet grouting	Reinforcement and prevention of leaking and seepage	Any soil	Cement/silica	(3), (4), (1)
Permeation grouting	Seepage and leaking prevention, and reinforcement	Loess, fissured rock and gravelly sands	Cement/silica	(3), (4), (1)
Compaction grouting	Reinforcement and settlement control	Poor backfilling, loosened or collapsible soils, sinkhole sites, and liquefiable soils	Cement/flyash/ coarse sand	(2)
Fracture grouting	Leaking prevention, settlement compensation and reinforcement	Clay, silt, gravelly sands and jointed rock	Cement/silica	(2), (3)

[a] Note: (1) Effect on stiffness; (2) Effect on deformation; (3) Effect on permeability; and (4) Effect on strength.

and in situ conditions. On the other hand, considerable uncertainty is observed in the properties of soil-cement mixture. Hence, such uncertainty will affect the design and analysis results. Statistical analysis for in situ testing results can reduce uncertainty, but it is not always suitable to be carried out to obtain sufficient information prior to or during construction period. Some data can be gained after soil-cement mixture hardening, but it is too late to update the design (Wang et al., 2014a). Consequently, how to interpret other properties from q_u of soil-cement mixture for numerical analysis is an important issue in applying this state-of-the-art technique to engineering practise.

3.1. Mechanical properties of soil-cement mixture

3.1.1. Internal friction angle ϕ and cohesion c of soil-cement mixture

Researches on the strength properties of soil-cement mixture started as early as the 1950s. Based on triaxial shear tests, Balmer (1958) firstly found that the internal friction angle ϕ of soil-cement mixture stayed constant roughly regardless of the cement content. The value of the internal friction angle ϕ is 36° for fine-grained soil-cement mixture and 43° for granular soil-cement mixture. To study the effect of testing methods and verify the previous research findings, Li and Liang (2009) carried out a series of laboratory tests on silt-cement specimens with a dosage of approximately 20% cement by weight. Their testing results showed that the range of internal friction angle ranges approximately from 32° to 38°, which is close to the findings of Balmer (1958). Contrary to the findings aforementioned, testing results obtained by Uddin et al. (1997) indicated that the internal friction angle ϕ is not relatively constant, and it varies in a similar fashion as the cohesion c as a function of the cement dosage, soil type, and curing condition and time.

Balmer (1958) also found that the value of cohesion c of soil-cement mixture ranges from approximately 35 psi (241 kPa) to 530 psi (3654 kPa) depending on the cement dosage and the soil type. Mitchell (1976) recommended that the cohesion of soil-cement mixture can be estimated by

$$c = 48.265 + 0.225q_u \tag{1}$$

where the UCS q_u is in kPa.

The above review showed that the strength parameters of soil-cement mixture are influenced by many factors. It seems that the cohesion c increases when q_u increases, while the internal frictional angle ϕ is relatively stable: 32°–36° for fine-grained soil-cement mixture and 38°–43° for coarse-grained soil-cement mixture. It should be noticed that, in these researches, whether c and ϕ are effective values or not was not stated clearly, and we use the effective concept for c and ϕ in this paper.

3.1.2. Elastic modulus of soil-cement mixture

Elastic modulus has a significant influence on the displacement in numerical analysis. Numerous researches have been conducted regarding the elastic modulus of soil-cement mixture previously. Balmer (1958) found that the elastic modulus of soil-cement mixture increases with cement dosage and varies from 100,000 psi (689 MPa) to 2,000,000 psi (13.79 GPa) for granular soil-cement mixture and from 260,000 (1.79 GPa) to 760,000 psi (5.24 GPa) for fine-grained soil-cement mixture. More recent researches on stiffness properties have been carried out by Uddin et al. (1997), Tang et al. (2000), Lee et al. (2005), Yang et al. (2006), Lorenzo and Bergado (2006), and Li and Liang (2009). The laboratory testing results showed that the elastic modulus of the local fine-grained soil-cement mixture has a linear relationship with the UCS. For example, Lee et al. (2005) reported a ratio of $E/q_u = 145$ for slurry-clay-cement mixture, smaller than the lower limit of 175 proposed by Porbaha (1998) and Lorenzo and Bergado (2006).

Soil-cement mixture can be treated as poor concrete with low UCS. Based on full-scale extensive instrumented deep mixing tests conducted in Texas A&M University, Briaud et al. (2000) recommended that the elastic modulus of soil-cement mixture can be estimated by

$$E_{\text{soil-cement}} = 12900q_u^{0.41} \tag{2}$$

where $E_{\text{soil-cement}}$ is the elastic modulus of soil-cement mixture (kPa). Rutherford et al. (2005) stated that Eq. (2) can be considered as a conservative one. To match the field observed deformation, Wang et al. (2014b) proposed that the elastic modulus of soil-cement mixture (admixed with sodium silicate) can be calculated, similarly to concrete, by

$$E_{\text{soil-cement}} = 30000\sqrt{q_u} \tag{3}$$

Numerical analysis for rock masses usually uses a reduced elastic modulus following Bieniawski (1992)'s recommendation to address the weak and jointed rock quality, which is indicated by the rock quality designation (RQD). The core samples of soils treated with chemical grouting indicated that the soil-cement mixture is usually broken. Eq. (3) has used a reduced magnitude to address the breakage and crack of soil-cement mixture and no further reduction is needed when using the elastic modulus for numerical analysis.

Fig. 1 shows the relationship between the elastic modulus and the UCS. It is found that Eqs. (2) and (3) yield the lower and upper boundaries in the range of q_u from 0.5 MPa to 1.5 MPa. With the increase in UCS, the interpreted elastic modulus using Eqs. (2) and (3) has a trend to be lower than that calculated by other methods, but the values calculated by Eq. (3) are slightly larger than the average range of these values. In engineering practise, the typical range of the UCS of soil-cement mixture is 0.5–2.5 MPa when applying the grouting technique to reinforcing and bracing excavation (Wang et al., 2014a). It may be appropriate to use a value between the ranges calculated by Eqs. (2) and (3) for the elastic modulus of soil-cement mixture.

3.1.3. Dilatancy, Poisson's ratio and initial earth pressure coefficient K_0

The dilatancy is related to the peak friction angle and the critical state friction angle using the assumption of Rowe's stress-dilatancy theory (Rowe, 1962). When the internal friction angle of the native soil is less than 30°, the dilatancy of material is zero. When the internal friction angle is greater than 30°, the dilatancy can be evaluated using Eq. (4) with assumption that the critical state friction angle $\phi_{cv} = 30°$ (Schanz and Vermeer, 1996; Yoo, 2002; Yoo and Shin, 2003; Wang et al., 2014a), or simply using $\psi = \phi - 30°$:

$$\sin\psi = \frac{\sin\phi - \sin\phi_{cv}}{1 - \sin\phi\sin\phi_{cv}} \tag{4}$$

where ψ is the dilatancy angle.

Further calculation demonstrates that no difference is observed for the dilatancy of soil-cement mixture calculated with the two methods.

Poisson's ratio ν is usually provided in geotechnical reports for native soils. Given the soil is elastic, Eq. (5) represents a relationship of Poisson's ratio ν with lateral earth pressure coefficient K_0 (Poulos and Davis, 1974):

$$\nu = \frac{K_0}{K_0 + 1} \tag{5}$$

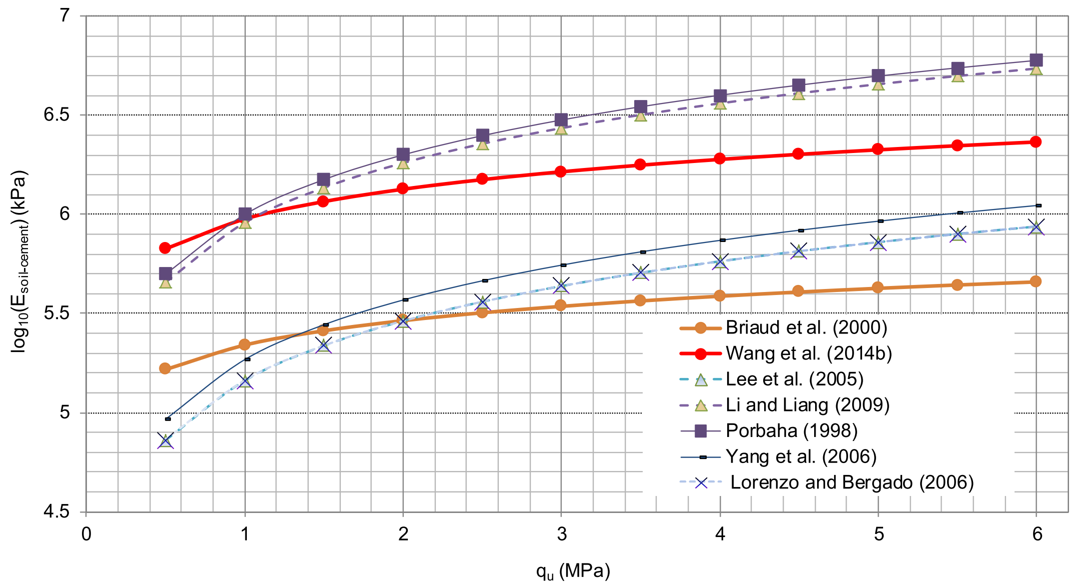

Fig. 1. Relationships between unconfined compressive strength and elastic modulus.

K_0 is also known as initial earth pressure coefficient. Although the elastic-perfectly plastic Mohr-Coulomb constitutive model is nonlinear, Eq. (5) has been used widely for the suitability of the constitutive model (e.g. Yoo, 2002). On the other hand, Eq. (6) (Jaky, 1944; Michalowski, 2005) can be used to evaluate the initial earth pressure coefficient K_0 though it was proposed for cohesionless and normally consolidated cohesive soils:

$$K_0 = 1 - \sin \phi' \tag{6}$$

where ϕ' represents the effective internal friction angle of the soil and herein denotes the interpreted effective internal friction angle of soil-cement mixture. Eqs. (5) and (6) can be used to estimate the parameters of soil-cement mixture for numerical analysis.

3.2. Influences of admixing sodium silicate

Chemicals are frequently used in grouting when the permeability of soils is relatively low (usually less than 10^{-4} m/s) to allow penetration and impregnation by cement grouting. The grouted chemicals form a colloid and then further produce a gel which bonds with soils or fills the voids. Alkaline solution is preferred as hydration product is dissolved in an acid environment. Solutions with pH value less than 9 will produce low level of hardening or even no hardening (Chen and Wang, 2006). Among alkaline solutions, sodium silicate is most widely used.

US Army Corps of Engineers' manuals EM1110-1-3500 (1995) and EM1110-2-3506 (1995) specified chemical grouting and grouting, respectively. MHURD (2010a) issued a guideline for grouting using mixture of cement and sodium silicate. These codes/guidelines focused on material properties, construction procedures, grouting hole spacing and grouting pressure, but no sufficient information regarding the strength increase of improved soils is provided. Kazemian et al. (2011) performed a series of laboratory tests using sodium silicate and cement to treat peat in Malaysia. Fig. 2 shows the relationship of undrained shear strength of treated peat at 30 d with the percentage of grouts by weight. It is found that using 2.5% of sodium silicate, the undrained shear strength of treated peat at 30 d can reach about 105 kPa, corresponding to the shear strength of peat treated using 25% of cement. Faramarzi et al. (2016) found that the alluvial-cement mixture can increase the UCS by 125% through adding resin compared to a laboratory mixed sample of the same material. Their tests further indicated that the grouted cement in sandy soils reduces the permeability up to 98% and the use of resin with different percentages has no significant effect on the permeability of the injected specimen. Azadi et al. (2017) concluded that the sodium silicate is one of the main ingredients of chemical grouting which is also used for increasing the strength of cement-based grouts. This additive may reduce the setting time up to a level in which the grout is set before being injected and is able to inject into much finer fissures or soils than cement. These researches implied that admixing sodium silicate to cement grouting does have many advantages over using cement only. In addition to enhancing the shear strength of improved soils, penetrability to very fine fissures and reducing the setting time shall be considered to meet the specific needs of the project.

4. Design considerations for soil-cement mixture

Deep excavation is a major civil engineering application related to soil-cement mixture. Particularly in populated metropolitan areas, the number of deep excavations is increasing year by year as more skyscrapers, rapid transit systems and other facilities are built. During excavation, support systems have to be built to allow excavation to be cut vertically or near vertically. In this paper, we

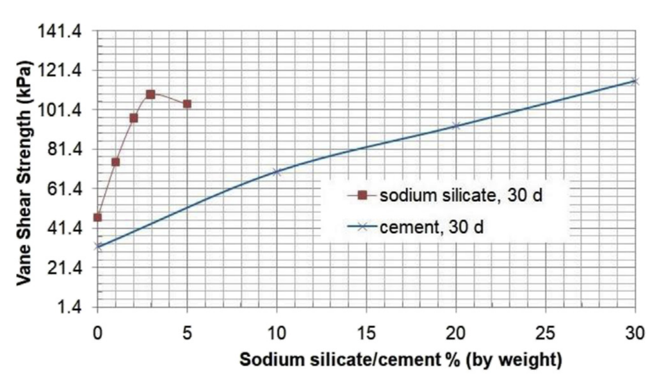

Fig. 2. Undrained shear strength of improved peat using sodium silicate and cement (Kazemian et al., 2011).

focus on two methods, i.e. DSMW for deep excavation, and vault arch for tunnelling.

4.1. Deep soil mixed wall for excavation support

The concept of DSMW evolves from secant pile walls and deep soil mixing. To create a DSMW, the native soils are mixed mechanically with cementitious grout to produce soil-cement mixture. Before soil-cement mixture is fully hardened, H-piles are penetrated into the improved soil. The H-piles and the soil-cement mixture are then working together to stabilise the soil body and to provide support for excavation. Fig. 3 shows the constructed DSMW used in a subway project in Tianjin, China.

Several design guidelines for DSMW are available. For example, Rutherford et al. (2005) conducted a comprehensive research, and their findings were summarised in their design manual. MHURD (2010b) issued a specification for DSMW which mainly focuses on construction and quality control, and the design issues were also included. The two references recommended six items listed below that need to be checked when performing a design:

(1) Internal stress and deformation check for support structural components;
(2) Global stability of the support system;
(3) Overturning stability of the support system;
(4) Stability of soils in excavation bottom;
(5) Seepage analysis; and
(6) Deformation check beyond the excavation pit.

Fig. 4 shows a typical design diagram for DSMW. As shown in Fig. 4, t is the length of soil-cement mixture, w is the width of the flange of the steel, H is the excavation depth, and D is the embedment depth. The design issues are dependent upon the specific construction details, which include the embedment and the support system, ground conditions as well as the structure design. Typically, the soil-cement mixture between the support components is modelled as lagging. The modelled lagging shall be designed to resist and redistribute the horizontal stresses generated by the retained soils and possible surcharge to the adjacent support.

The steel support is designed to resist the bending stress and the shear stress. For bending moment check, it is usually assumed that all tension caused by the moment is resisted by the H-steel only, thus we have

$$\sigma = \frac{1.25\alpha M}{W} \leq [\sigma_{\rm f}] \tag{7}$$

Fig. 3. Photo of a constructed DSMW in Tianjin subway project.

where σ is the calculated tension; $[\sigma_{\rm f}]$ is the allowable bending-induced tension of H-steel; M is the calculated moment in the repeatable length $(w+t)$; and α is a coefficient which can be 1.1, 1 or 0.9 depending on the importance of the facility.

The shear stress τ on H-steel must satisfy the following equation:

$$\tau = \frac{1.25\alpha Q_1 S}{I\delta} \leq [\tau_{\rm s}] \tag{8}$$

where Q_1 is the calculated shear force on H-steel, S is the first moment of the area of the H-steel, I is the inertia of the steel, δ is the thickness of the steel web, and $[\tau_{\rm s}]$ is the allowable shear stress of the steel. It is also necessary to check the shear strength of soil-cement mixture along the H-pile edge. The shear force on soil-cement mixture between the flanges of H-steel can be calculated by

$$Q_2 = pt/2 \tag{9}$$

where p is the lateral pressure exerting on soil-cement mixture from the flange to the flange of H-steels. The calculated shear stress on the edge of soil-cement mixture shall satisfy following equation:

$$\tau = \frac{1.25\alpha Q_2}{d} \leq \frac{[\tau_{\text{soil-cement}}]}{1.6} \tag{10}$$

where d is the effective thickness of the soil-cement wall, and $[\tau_{\text{soil-cement}}]$ is the allowable shear stress of the soil-cement mixture. MHURD (2010b) recommended using 1/3 of $q_{\rm u}$ (at 28 d) for $[\tau_{\text{soil-cement}}]$ calculation.

Several methods can be applied for design either using alone or in combination. FE method has gained great popularity recently in DSMW design with many advantages. It can simulate the construction stages including excavation depth, installation of struts or tiebacks, and dewatering by activating or deactivating the defined elements. Moreover, the structural and geotechnical analyses can be performed simultaneously. Challenges in using FE method also exist. One of them is parameter selection, particularly for the improved ground that this paper aims to address, and these parameters employed in FE method have to be determined in design phase.

4.2. Umbrella arch for tunnelling stabilisation

To stabilise excavation and reduce deformation, grouting technique is frequently adopted to provide pre-support for non-mechanical tunnelling in soils or soft rocks. Typically, steel perforated pipes with a diameter of 32 mm and a length of 2.5 m are installed with upward angles of 10°–15° from excavation circumference to the soil masses. Cementitious grout, more often admixed with sodium silicate, is grouted into the ground through the pipes to form a hardened canopy. Fig. 5 illustrates the vault arch technique for tunnelling pre-support.

Design considerations include excavation method and equipment, site conditions, deformation control criterion, and other aspects. Design guidelines are also available (e.g. BTS, 2010), but details shall be determined by designers with numerical results. In reinforced tunnelling, design parameters from case histories are helpful for new project; however, when comparing two projects, it may be worth noting that different nomenclatures may be used as Oke et al. (2014) argued, e.g. when the pipe length is over the excavation height, the pre-support usually refer to as the pipe roof pre-support.

Three-dimensional FE analysis is ideal for this type of project, as the longitudinal subsidence and stress variation in support components can be analysed during excavation. Software packages such as Plaxis 3D$^{(R)}$ and Midas GTS$^{(R)}$ are user-friendly. A number of

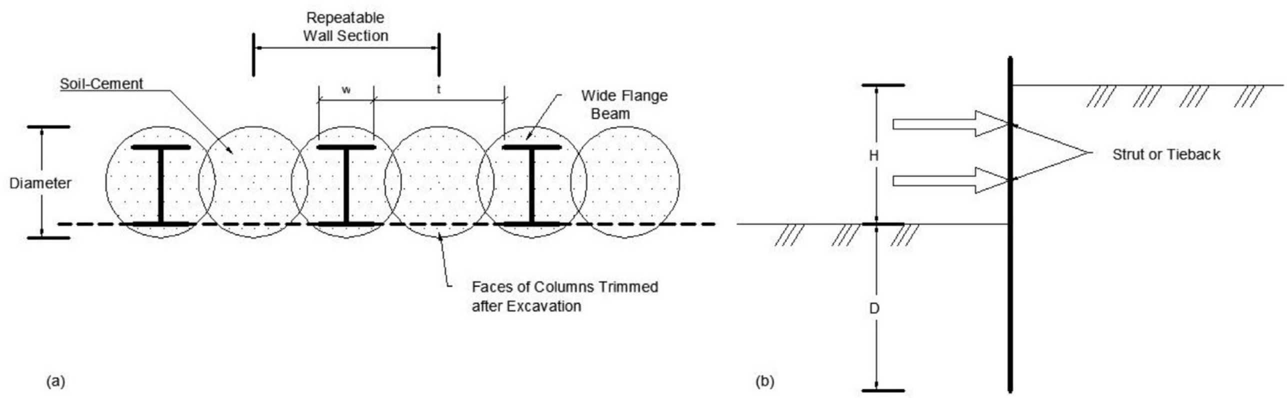

Fig. 4. Typical design diagram for DSMW: (a) Plan view, and (b) Section view.

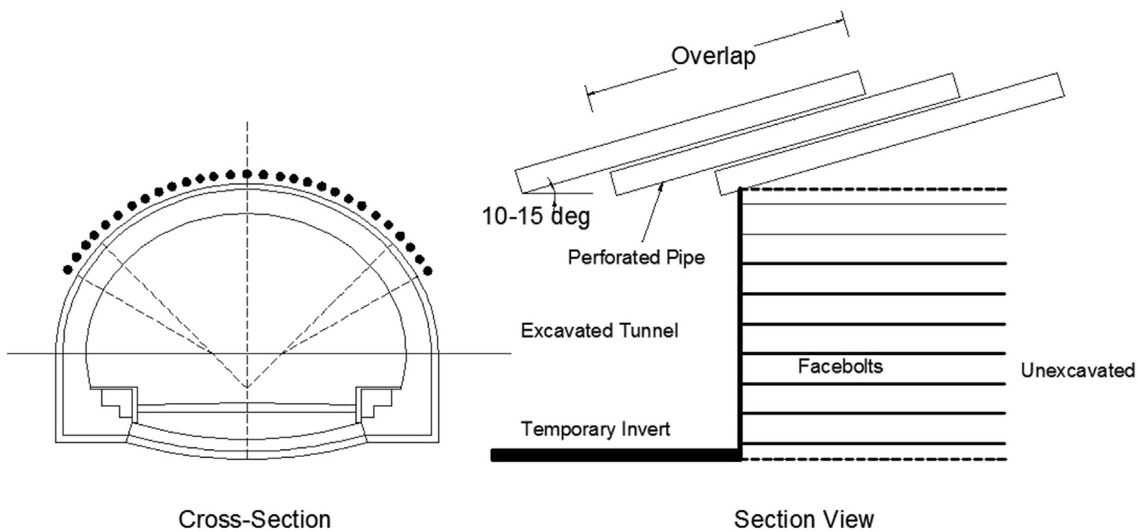

Fig. 5. Illustration of vault arch for tunnelling pre-support.

Table 4
Summary of soil-cement mixture and recommended range for vault arch in FE analysis.

Parameter	Range or interpretation method	Remarks
Cohesion, c	$c = 48.265 + 0.225q_u$	q_u and c are in kPa
Internal friction angle, ϕ	32°–36° for fine-grained soil-cement mixture and 38°–43° for coarse-grained soil-cement mixture	Higher cement content, admixing of sodium silica may help to use higher ϕ value
Elastic modulus, E	Use a value between $E_{\text{soil-cement}} = 12900q_u^{0.41}$ and $E_{\text{soil-cement}} = 30000\sqrt{q_u}$	Higher cement content, admixing of sodium silica may have higher E values. The unit of $E_{\text{soil-cement}}$ is in kPa
Dilatancy angle, ψ	$\psi = \phi - 30^\circ$ when $\phi > 30^\circ$, otherwise $\psi = 0^\circ$	It is also applicable to native soil, but effective internal friction angle shall be used
Initial earth pressure coefficient, K_0	$K_0 = \nu/(1-\nu)$ or $K_0 = 1 - \sin\phi$	It is also applicable to native soil, but effective internal friction angle shall be used

constitutive models are embedded in these software packages. The Mohr-Coulomb failure criterion is often employed for c-ϕ materials. The elastic model is suitable for support components (e.g. initial and final lining). Elements shall be refined carefully, and elements shall be classified as surface load, native soils, improved soils, structural components, etc. Construction stages are simulated by activating or deactivating the packages which comprise related elements. Parameters for stabilised soils shall be checked case by case as uncertainty is involved in the soil-cement mixture and construction process to form the man-made materials. Table 4 summarises the parameters of soil-cement mixture studied in Section 3, and these parameters can be used for vault arch method.

5. Concluding remarks

This paper performs a parametric study on the properties of soil-cement mixture. Further, researches on influences of admixing sodium silicate are reviewed. Design considerations for two popular applications using soil-cement mixture, i.e. DSMW for excavation support and vault arch for tunnelling support, are presented. Some remarks are summarised below:

(1) Soil-cement mixture is a product of cement grouting or mixing with soils. Chemicals, such as sodium silicate, are frequently used in combination to meet specific needs.

Admixing of sodium silicate can enhance the UCS of improved soils with less dosage used, but the most important characteristic is its penetrability to very fine fissures or soil pores. It can also reduce the setting time.

(2) Parameters used in numerical analysis for soil-cement mixture are studied. Comparisons and recommendations are made focussing on the Mohr-Coulomb failure criterion. In summary, the internal friction angle can range from 32° to 36° for fine-grained soil-cement mixture and from 38° to 43° for coarse-grained soil-cement mixture. The cohesion can be interpreted from Eq. (1) and the value interpreted by Eqs. (2) and (3) can be used for elastic modulus.

(3) Design considerations for two popular techniques using soil-cement mixture are discussed. Although different terms may have been refereed for the reinforced excavation techniques, they are essentially the applications of soil-cement mixture, and thus the parameters for soil-cement mixture produced recommended above are valid.

Conflict of interest

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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