Quantitative Methods for Predicting Underground Construction Waste Considering Reuse and Recycling

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Quantitative methods for predicting underground construction waste considering reuse and recycling

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Abstract

The construction industry has been greatly developed in the past few decades, especially in the extensive use of underground space. The increasing amount of waste (e.g., soil, sludge, and rock) generated in the underground construction constitutes an important part of construction and demolition waste (CDW) but the related problems are rarely addressed in an independent quantitative study. In order to facilitate recycling of underground construction waste (UCW), quantitative methods for predicting UCW are proposed based on mass conservation in this study. Through on-site investigation and literature review, the source characteristics of UCW and corresponding recycling potential are firstly analyzed. Secondly, the corresponding quantitative mothed is proposed for predicting each type of UCW according to the principle of mass conservation. Finally, the proposed quantitative methods are applied in two real underground infrastructure projects to verify the accuracy. The results show that the accuracy of quantitative methods for predicting shield sludge and engineering soil is 82.03%-95.79% and 94.49% respectively. In addition, detailed geological and geotechnical analysis is the key to accurate management of waste generated in underground civil and infrastructure projects. In both cases, underground construction produced a large amount of construction waste with great recycling potential. UCW can theoretically reach 100% recycling, and full reuse and recycling of UCW will bring huge economic value and be conducive to the sustainable development of the construction industry.

Keywords: Quantitative methods; Underground construction waste; Recycling; Source characteristics; Engineering verification; Mass conservation;

1 Introduction

Because of the large-scale underground construction in the recent years and the inevitable earthwork in the construction process, a large amount of waste excavated in underground construction has become a problem that cannot be ignored (Shang et al. 2013). Excavated waste is inert material that is not normally considered to cause a major problem on environment and society. However, more and more studies prove that excavated waste has a strategic impact on resource efficiency and the sustainable environment. Construction industry is a major contributor to the decrease of natural resources, especially the resources of sand and rocks (Kirthika et al. 2020). With the increasing demand of protecting the environment and building a sustainable society, the constraints on the exploitation of natural sand and rock are becoming increasingly tight (Magnusson et al. 2015; Rana et al. 2016). Therefore, it is of practical significance to supplement the channels of acquiring construction sand and gravel by means of various wastes recycling (Rana et al. 2016). Disorderly disposal and invalid utilization of an enormous amount of excavated waste will add to the cost of the project (Bellopede et al. 2011). Numerous untreated engineering soil will encroach on land and pollute soil and water (Kalbe et al. 2008; Lee et al. 2008). The random dumping of soil may also threaten the safety of human life and bring serious social problems, for example, a landslide killed 77 people and engulfed an industrial park of over 100,000 m^3 in Shenzhen in 2015 (The Xinhua News Agency 2016).

Different from the practices of developed countries, excavated waste mainly buried at landfill sites in China (Zhang et al. 2020), while the recycling rate of the excavated soil and rock in western countries such as Ireland is more than 90% and that in Germany is more than 80% (European Commission 2016). Information such as classification and quantity of excavated waste cannot be accurately obtained in the early stages of construction, which is not conducive to the orderly and coordinated development of excavated waste reuse, recycle, and disposal (Diana et al. 2015; Riviera et al. 2014). It is of great significance for the whole construction industry to realize low-carbon and environmental protection development to fully recycle the excavated waste.

Large underground construction projects often overlap with civil and infrastructure projects. Civil and infrastructure construction will produce a lot of CDW (de Magalhães et al. 2017), but previous researchers have paid little attention to it because of such difficulties as incomplete data and the huge workload. Wu et al. (2014a) summarized 57 papers related to the quantification of CDW, of which only 5 papers are related to civil and infrastructure work. The focus of scholars on the quantification of civil and infrastructure waste is usually at a regional level (Cochran and Townsend 2010; Hashimoto et al. 2007, 2009; Martínez Lage et al. 2010). De Guzmán Báez et al. (2012) developed a quantitative method for calculating the amount of waste generated in the construction of Spanish railways. This method is more accurate than previous ones of calculating the annual production of CDW in a region. Since the work of Wu et al., the study of civil and infrastructure construction waste and the precise quantification of certain types of waste have increased but still account for a very small proportion of quantitative works of CDW (Povetkin and Isaac 2020; Wu et al. 2019). Accurate estimation of waste generated in civil and infrastructure can lead the way in improving waste management in the entire construction industry.

Methodologies for estimating CDW fall into six major categories (Guerra et al. 2019; Masudi et al. 2010; Wu et al. 2014b): site visit, generation rate calculation, lifetime analysis, classification system accumulation, variables modelling and other methods. The recent trend is that more and more computer technologies have been applied to the quantification of CDW (Cha et al. 2020; Chen and Lu 2017; Cheng and Ma 2013; Guerra et al. 2019). The amount of UCW is related to geotechnical properties and construction conditions. Due to this complexity, its calculation requires a combination of multiple quantitative methods to calculate like those of site visit, material flow analysis, principal factor analysis, etc. Traditionally, the prediction of the amount of sludge production was mainly through experience method. For example, 1:4 (sand) ~ 1:7 (cohesive soil) of the excavated volume being used as the predictive generation rate of the amount of sludge generated in sludge shield. The method of experience generation rate for predicting the volume of shield sludge usually has great uncertainty, which brings difficulties for the subsequent development of detailed waste planning.

Most of current research on quantifying CDW has been done at a broader level, ignoring the significance of precise quantification to CDW management. Less research focus on civil and infrastructure construction, ignoring a very important part of the construction industry, not to mention ignoring the quantification of inert construction waste excavated from underground construction. Although there have been many studies on the quantitative methods for calculating the amount of CDW, the validity of the proposed methods has been ignored (Wu et al. 2014b). In order to bring convenience to the precise management of UCW and promote the clean and sustainable development of the whole construction industry, this study proposes a relatively accurate quantitative methodology to predict the amount of UCW considering its reuse and recycling. The quantitative methods enable project stakeholders to predict the amount of UCW at the design and the early construction stage, and provide effective data support for the source reduction, consumption, transfer, and resource utilization of construction waste. In this study, two tunnel infrastructure construction cases are used to validate the proposed quantitative methods, which also provides reference data for estimating the amount of waste produced by other tunnel construction.

The remainder of this paper is as follows. After this introductory section is material and methods used in this study. Two cases study is then presented in Section 3. Section 4 shows findings of the study, and the source characteristics, factors affecting the yield and the possible recycling direction of UCW are involved in this section. It is followed by Section 5, which is an in-depth discussion on both quantitative methods and cases study. Conclusions covering limitations and further research are given in Section 6.

2 Material and methods

Although it is widely accepted that CDW includes excess material from construction, demolition, and renovation, not all countries include excavated waste in their definition of CDW (Lu et al. 2011). In China, CDW is the general term for engineering soil, engineering sludge, construction waste, demolition waste, decoration waste, etc. (MOHURD 2019), and engineering soil and engineering sludge are what we focus on in this study.

The whole research method and process of this study are shown in Fig. 1. Firstly, the source characteristics, factors affecting output, potential recovery value and recycling directions of UCW were analyzed through on-site investigation and literature review. Secondly, the quantitative methods for predicting various UCWs are put forward according to the principle of mass conservation. Based on the geological data and geotechnical information, two cases are finally used to verify the accuracy of the quantitative methods of typical UCW.

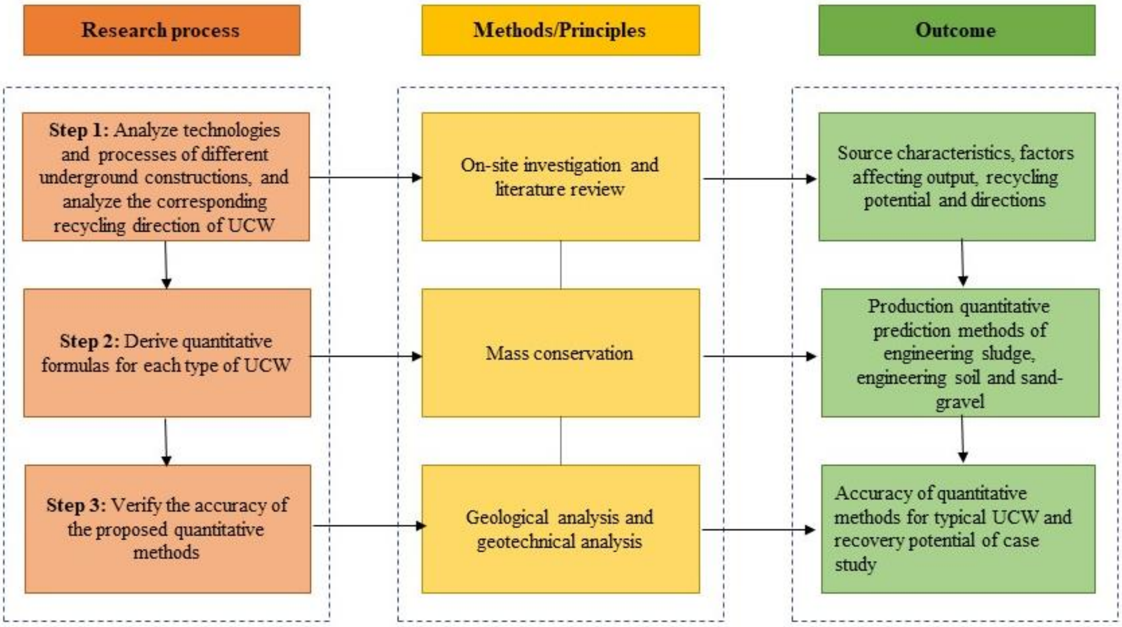

Fig. 1 Research framework

2.1 On-site investigation on source characteristics and recycling status

Source characteristics refers to the UCW in what geological properties, construction conditions generated. Because of the strong regional characteristics of UCW, considering the geological conditions and construction technology is the premise of accurate estimation. Classifying and quantifying UCW according to its possible future recycling routes will bring great convenience to the management of UCW. On-site investigation is a common method to obtain the data of CDW (Thanh et al. 2010), and it is also an important channel to fully understand the actual situation.

All underground construction will inevitably produce engineering soil and engineering sludge. In China, engineering soil includes abandoned soils generated during foundation excavation of all kinds of buildings, structures, and pipe networks. Engineering sludge includes the sludge generated during the construction of bored cast-in-situ pile foundation, underground diaphragm wall, sludge shield, horizontal directional drilling etc. Engineering sludge is required differently in different constructions. In this study, shield construction, underground diaphragm wall construction and pile foundation construction are selected as the typical underground construction.

2.2 Quantitative methods based on principle of mass conservation

Calculating the volume of waste has more practical significance for CDW management. According to the principle of mass conservation, the excavated material eventually become waste before it can be reused and recycled. Construction can lead to changes in the physical state of these materials, which will lead to changes in density. Therefore, the calculation of the volume of UCW converted by raw soil inevitably uses the principle of mass conservation.

2.2.1 Quantitative method for predicting production of engineering sludge

2.2.1.1 Shield sludge

The formation of shield sludge has a complex mechanism. The construction of shield tunneling is carried out according to the ring. After each tunneling ring, the work such as pipe paving and sludge adjustment will be carried out. We use the ring as the basic unit of derivation, and the volume of soil that can form sludge (V_{sl}, m^3) produced during each ring driving is calculated as is shown below:

$$V_{sl} = \varepsilon \bullet \sum V_i \bullet \lambda_i \tag{1}$$

Where $V_i$is the volume of *i* soil layer in each tunneling ring (m^3), $\lambda_i$is the proportion of soil that can form sludge (named sludge soil in later chapter) in *i* soil layer (%) and ε is the loss coefficient.

In the shield sludge system, the total volume and specific gravity of the sludge in the pool are determined, and thus set the initial specific gravity of the sludge as ρ_0 (kg/m^3), and the volume of sludge in the pool as V_0 (m^3). The sludge after being driven has a specific high gravity, part of the sludge needs to be abandoned and adjusted with water to the value of ρ_0, and the process also requires keeping the sludge volume equal to the pre-driven gross volume. The average density of the sludge soil particle is ρ_s, and the density of water is ρ_w. Mass conservation calculation is carried out within the system of sludge tank:

$$V_S\rho_0 = \rho_w V_W + \rho_s V_{sl} \tag{2}$$

$$V_W = \alpha V_{sl} \tag{3}$$

Where V_S is the volume of sludge added after shield driving (m^3), Vw is the volume of added water (m^3), and α is the correction factor determined by engineering practice.

Finally, we get the total shield sludge output of the whole shield project (V_{TS1},m^3) as is shown below:

$$V_{TS1} = \sum_{\mathrm{n}}^{\mathrm{N}} (\rho_s+\alpha\rho_w)/\rho_0 \bullet \varepsilon \bullet \sum V_{ni} \bullet \lambda_{ni} + V_0 \tag{4}$$

Where n≥1, N ≤ the total number of driving rings.

2.2.1.2 Bored cast-in-situ piles sludge

The amount of sludge converted from the pile foundation itself (V_1, m^3) should be equal to the volume of pile foundation (V, m^3). The calculation formula is as follows:

$$V_1 = \mu * V \tag{5}$$

Pore broadening coefficient (μ) refers to the ratio of the actual volume of pouring concrete and theoretical volume (the volume calculated according to the design pile diameter).

The amount of sludge in the hole before being concrete-poured (V_2, m^3) is equal to the amount of sludge formed by the pile foundation itself, and the total amount is calculated as follow:

$$V_2 = V_1 \tag{6}$$

Additional V_3 m^3 sludge is needed to turn 10 m^3 excavated soil into sludge is calculated as follow:

$$V_3 = V_1/10 \tag{7}$$

Therefore, the total amount of sludge of bored cast-in-situ piles foundation (V_{TS2}, m^3) is calculated as follow:

$$V_{TS2} = V_1 + V_2 + V_3 \tag{8}$$

2.2.1.3 Underground diaphragm wall sludge

The index of underground diaphragm wall sludge is closely related to the geotechnical properties of the soil layer it is in. The production of underground diaphragm wall sludge (V_{TS3}, m^3) is:

$$V_{TS3} = \mu V \tag{9}$$

As it passes through the clay layer, the pore broadening coefficient is small, usually 1.1. When the excavated stratum is sandy soil, the pore broadening coefficient is 1.3. V is the construction volume (m^3).

2.2.2 Quantitative method for predicting production of engineering soil

The major factors to predict the yield of engineering soil are the loose coefficient.

The volume of engineering soil (V_{TS}, m^3) is calculated as follow:

$$V_{TS} = \sigma \bullet V \tag{10}$$

The loose coefficient σ refers to the ratio between the volume of excavated soil and the natural volume, which can be obtained by field measurement. V is the construction volume (m^3).

2.2.3 Quantitative method for predicting production of sand-gravel

Sand-gravel is the most economically valuable material in excavated waste, and the volume of sand-gravel (V_{sg}, m^3) which can be separated as reclaimed aggregate is calculated as follow:

$$V_{sg} = \sum V_i \bullet \tau_i \tag{11}$$

τ_i is the proportion of sand-gravel that can be screened out during pre-treatment in *i* soil layer.

2.3 Engineering verification based on geological and geotechnical analysis

The geology of the construction site has a great influence on the yield of UCW. In actual engineering analysis, the overall geological conditions are evaluated according to the geological prospecting report, and the quantity and proportion of all kinds of soil layer involved in the actual project are preliminarily counted. Targeted analysis of the physical and mechanical properties and particle analysis are carried out on the relatively large soil layers. Through geological and geotechnical analysis to obtain the amount of slurry soil, sand-gravel, and other soil.

The following formula is used to measure the accuracy of the quantitative prediction methods:

$$\delta = 1\text{-}|V_r - V_p|/V_r \tag{12}$$

V_r is the actual value of waste volume (m^3), V_p is the predicted value of waste volume (m^3). Basic data are derived from construction design drawings, geological information reports, Chinese construction standards and the experience of field staff to ensure the reliability of the prediction results. The real waste output datasets of the cases study are provided by the waste transporters and on-site workers.

3 Cases study

Among all types of excavated waste, shield waste constitutes the largest part, and its occurrence source characteristics and prediction methods are more representative. Therefore, two typical shield construction projects are analyzed to validate the quantitative method of shield sludge and the quantitative method of engineering soil.

3.1 Project Overview of Hangzhou Boao Tunnel

The total length of Boao tunnel is 2800 m, the length of the cross-river tunnel is about 1680 m. The slurry shield of 11.7 m in diameter is adopted to excavate Hangzhou Boao Tunnel. The sludge-water treatment site is arranged on the west side of the structure, covering an area of about 5000 m^2, with 1200 m^3 sludge in the pool of an initial density of 1.3×10^3 kg/m^3. The propulsion distance of each ring is 5 m.

In the preliminary work, we have obtained the actual production of part of the shield sludge in the Boao Tunnel, the data of which are respectively those of ring 551, ring 563 and ring 572 on the western line, ring 243, ring 250 and ring 255 on the eastern line. These six rings will verify the quantitative method of shield sludge.

During the site investigation prior to construction, constructors will perform geotechnical and/or geophysical tests. Before construction, drilling samples should be analyzed to obtain basic information about complex geological conditions. The detailed geological survey report is illustrated in Fig. 2.

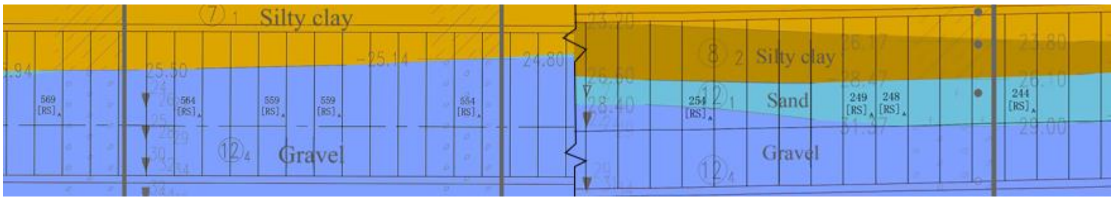

Fig. 2 Part of the soil layer map of the Boao tunnel

We can see from Fig. 2 that ring 551, ring 563 and ring 572 of the western line mainly involve the stratums of gravel layer and silty clay layer, among which the gravel layer takes up a large proportion. Ring 243, ring 250 and ring 255 on the Eastern line mainly include silty clay layer, sand layer and gravel layer. The physical properties of the soil layers involved in the six rings are listed in Table 1.

Table 1

Physical properties of the soil layers involved in the six rings.

Geotechnical name	Water content (%)	Void ratio (%)	Plasticity index (%)	Liquid index (%)	Soil particle composition (mm)						
					>20.00	20.00-2.00	2.00-0.50	0.50-0.25	0.25-0.075	0.075-0.005	<0.005
Silty clay⑦1^a	26.20	0.74	4.90	1.57			0.30	5.70	47.40	42.80	3.90

Silty clay$_{⑧2}$[a]	25.10	0.69	9.90	0.51						91.20	5.80
Sand	22.90	0.66	4.20	1.61		0.60	4.10	14.90	44.90	32.10	3.40
Gravel					48.40	24.20	8.10	7.70	5.20	4.80	1.60

[a] According to China's Code for Geotechnical Engineering Investigation, Silty clay$_{⑦1}$ and Silty clay$_{⑧2}$ are classified into the same category, but their physical properties are not the same.

In the separation system of shield slurry and sand-gravel, the screen mesh is 0.25 mm in size. Particles larger than 0.25 mm in the soil will be screened out. The sludge consists of 1 volume of soil and 1.1 volume of water, and the average density of the slurry soil is 2.7×10^3 kg/m^3. The loss coefficient ε is 0.95 in this study.

3.2 Project Overview of Changsha Metro Line 5

The construction method of earth pressure balance (EPB) shield is adopted for the tunneling of Changsha Metro Line 5. The diameter of the tunnel is 6.3 m and the length of EPB shield construction area is 1600 m. The geotechnical properties and construction information of two tunnel projects was provided by the construction party. The loose coefficient σ is 1.04.

4. Result

4.1 Source characteristics of UCW

4.1.1 Source characteristics of shield waste

Shield construction refers to the method of tunnelling and dredging by using shield tunnelling machine while controlling the excavation face and surrounding rock without collapse and instability. Because of its advantages of fast digging speed, excellent quality and relatively high construction safety (He et al. 2020), in the case of poor stratum conditions and complex geological conditions, etc., the shield method has become the preferred construction method for tunnel construction in China (Yu et al. 2020).The types of shield machines can be divided into open face shield machine, sludge shield machine and EPB shield machine etc. When the permeability coefficient of the geological layer is greater than 10^{-4}, sludge shield is adopted; When the permeability coefficient of geological layer is less than 10^{-7}, EPB shield is adopted; When the permeability coefficient is between the above two numbers, both types can be adopted. The waste products of EPB shield construction are mainly engineering soil, and the products of sludge shield are mainly engineering sludge and soil. The shield tunnelling machine builds the tunnel without disturbing the surrounding rock due to the linings assembled from the pipe pieces on the machine, and the wall behind which grouting is implemented. The residue under the knife disc is dissolved into the sludge and the sludge discharge system continuously discharges the sludge from the sludge tank to ensure that the pressure of the sludge film is in equilibrium.

4.1.2 Source characteristics of pile foundation waste

Pile foundation passes the superstructure loads to the deep stability soil or rock, reducing the non-uniform settlement of ground and foundation. Pile foundation can be classified into precast driven piles and bored cast-in-situ piles (Luo et al. 2018). Construction of bored cast-in-situ piles will generate hole-wall-protecting sludge, which is made by artificial pulping with original soil. Through circulating sludge, the earth blocks cut by the drill bit are carried out of the hole, and then the steel cage tied up is installed in the hole, and concrete piles are poured underwater by the catheter method. During the drilling process, the hole-wall-protecting sludge shall meet the requirements (relative density of sludge is 1.1~1.3, viscosity is 10~25s, sand content <6%, etc.) to play the role of wall protection and fixation, preventing caving hole.

4.1.3 Source characteristics of underground diaphragm wall waste

An underground diaphragm wall is a narrow and deep underground trench formed by grouting, which has the functions of waterproof, seepage proof, bearing and retaining (Li et al. 2013). Sludge and soil are produced in the construction process of the underground diaphragm wall. The sludge plays the role of wall protection, and the soil is produced at the bottom of the sludge with the digging of the mechanical grab, and the sludge is used in circulation during the whole construction process. Geological exploration is also needed for underground diaphragm wall construction. For the different conditions of sandy soil and cohesive soil in the construction stratum, the allocation index of sludge is different, and the specific data should be prepared according to the actual situation of the project.

4.2 Factors affecting yield

The amount of UCW depends mainly on the construction scale. Underground construction usually passes through one or more strata, the geological conditions and geotechnical properties of different strata will affect the yield of waste. The operating parameters of machine and special construction requirements also affect the actual output of excavated waste. Construction scale and geological conditions are the main factors affecting the amount of UCW.

4.2.1 Geological and geotechnical conditions

For engineering soil, the looseness coefficient is the main factor. The soil mass in the construction area is a compact volume and the volume of engineering muck after loosening (i.e., transport volume) is greater than its dense volume.

According to the source characteristics of shield sludge, and the principle of the residue separation in the separation system, the cohesive muck is partly separated from circulating sludge in the form of chunks during the cutting process. The sand-gravel that can be recovered for use as reclaimed aggregate is also separated. So, the amount of shield sludge is related to the content of cohesive soil and sand-gravel in stratum. According to the key physical parameters of stratum selected from geotechnical survey data for quantification, the transformation indexes of shield sludge are summarized and quantified in Table 2. Table 2 can be used to calculate the proportion of sand-gravel, sludge soil and other soil.

Table 2

Geotechnical conversion indexes of shield sludge formation.

Key geotechnical properties	Sludge transformation indexes (%)
W (%): Water content	
Rv (%): Void ratio	K_1: Porosity $K1 = Rv/(1+Rv)$
Ip (%): Plasticity index	K_2: Proportion of cohesive muck $K2 = \sqrt{3} \bullet Ip/IL$
IL (%): Liquid index	τ: Proportion of sand and gravel to be screened out $\tau = \sum_{d > \text{mesh size}} k$
K (%): Soil particle composition	λ: Sludge Soil proportion $\lambda = 1 - \mathrm{K1} - \mathrm{K2} - \tau$

4.2.2 Construction scale and strata volume

The construction depth of pile foundation is determined by the bearing capacity. Generally, the construction area is below 40 m underground. The construction depth of the underground diaphragm wall is determined by the water table and is generally less than 20 m underground. The two types of construction will go through a variety of strata. The construction area of shield tunneling is generally below 10 m underground. The diameter of most shield tunnels is larger than 10 m, so the tunnels will pass through one stratum or more during the shield construction. Geotechnical properties of different strata have a great impact on the type and amount of waste to be generated. Therefore, we should not only know the overall scale of construction, but also calculate the volume of each geological layer that goes through. For the variety and instability of the terrain, we can adopt an idealized model, and then use integral method to calculate the volume of each layer.

4.3 Reuse and recycling of UCW

The high valued composition and characteristics of UCW make it necessary to have the waste reused and recycled in place of natural resources like sand, gravel, and rock (Haas et al. 2020). Excavated waste can be used directly on site (reused), or transported off-site for either recovery (recycled) or disposal. Excavated waste can be used as substitute for other earthworks (landfill covers, trench works, dam works, paving layers, etc.) materials in accordance with construction requirements (Griffiths and Radford 2012).

In light of the source characteristics of the engineering sludge, the composition of the pile foundation sludge and the underground diaphragm wall sludge have constant low sand-gravel content, both types of sludge can be directly reduced to be dry soil (water content less than 35%) with the use of the sludge-water separation system. Shield sludge will carry a large amount of high economic value sand-gravel during the production process. Sand-gravel will be separated with using the sand-slurry separation system, and sludge will be dehydrated into dry soil and transported out of the field. Sand-gravel can be used as recycled aggregate for the construction site and other recycled building products (e.g., reclaimed mortar, recycled cement, recycled concrete) (Zhao et al. 2010). Dry soil can be used as raw material for roadbed, sintered wall materials and sintered aggregate, etc (Weng et al. 2003; Zhang et al. 2020). Parameters that may affect management of UCW include geographic characteristics, geotechnical properties, facility capacity, and demand for recycled materials, etc (Magnusson et al. 2015). According to the primary recycling ways of UCW, quantitative methods of sludge, sand-gravel, and other soil (material other than sludge, sand-gravel) are established respectively, which will greatly facilitate the management and recycling of UCW.

4.4 Accuracy of proposed quantitative methods

4.4.1 Accuracy of quantitative methods for predicting shield sludge

In combination with the geological and geotechnical datasets of Boao Tunnel in Hangzhou and the calculation formula of slurry soil ratio listed in Table 2, we obtained the volume of sand-gravel, cohesive soil, and slurry soil in the unexcavated strata in ring 551, ring 563 and ring 572 of the western line, and ring 243, ring 250 and ring 255 of the eastern line. The results are shown in Table 3 and Table 4 below.

Table 3

Volume of sand-gravel, cohesive soil, and sludge soil particles in the western line.

Ring number	Yield	Gravel	Silty clay⑦1
Ring 551	Volume m³	482.56	55.00
	Sand-gravel m³	426.59	1.32
	Cohesive soil m³	0	26.20
	Sludge soil m³	55.98	3.91
Ring 563	Volume m³	417.29	120.28
	Sand-gravel m³	368.88	2.89
	Cohesive soil m³	0	57.29
	Sludge soil m³	48.41	8.55
Ring 572	Volume m³	393.84	143.73
	Sand-gravel m³	348.15	3.45
	Cohesive soil m³	0	68.46
	Sludge soil m³	45.69	10.22

Table 4

Volume of sand-gravel, cohesive soil, and sludge soil particles in the eastern line.

Ring number	Yield	Silty clay⑧2	Gravel	Sand
Ring 243	Volume m³	191.65	159.07	186.85
	Sand-gravel m³	0	140.61	36.62
	Cohesive soil m³	64.43	0	8.45
	Sludge soil m³	48.97	18.45	67.49
Ring 250	Volume m³	190.51	187.10	159.95
	Sand-gravel m³	0	165.40	31.35
	Cohesive soil m³	64.05	0	7.23
	Sludge soil m³	48.68	21.70	57.77
Ring 255	Volume m³	173.55	240.15	123.86
	Sand-gravel m³	0	212.29	24.28
	Cohesive soil m³	58.35	0	5.60
	Sludge soil m³	44.34	27.86	44.74

By comparing Table 3 and Table 4, we can see that even the same project will have a big difference due to the large geological span. For example, the excavated waste produced by the rings in the western line contains more sand-gravel, which can obtain huge economic value through simple screening; while the rings in the eastern line will produce more sludge, which will increase the difficulty of excavated waste treatment. Therefore, detailed geological and geotechnical analysis is the key to accurate management in underground civil and infrastructure projects.

The forecast yield of the 6 rings is calculated by formula 0, the accuracy of quantitative method for predicting shield sludge are calculated by formula 0. The comparison table between the actual sludge production and predicted production is shown as Table 5.

Table 5

Accuracy table of quantitative method for predicting shield sludge.

Ring number	Forecast yield (m^3)	Actual yield (m^3)	Accuracy (%)
Ring 551 (west)	175	208	84.23
Ring 563 (west)	166	151	89.86
Ring 572 (west)	163	199	82.03
Ring 243 (east)	394	378	95.79
Ring 250 (east)	374	345	91.53
Ring 255 (east)	341	361	94.59

According to the data in Table 5, the accuracy of quantitative method for predicting shield sludge is between 82.03%-95.79%.

4.4.2 Accuracy of quantitative methods for predicting engineering soil

The amount of shield soil generated by Changsha Metro Line 5 can be calculated according to the formula (10). With L=1600 m, α=1.04 and R =3.15 m in the formula, the yield of engineering soil was 103936.35 m^3. In the shield construction process, all the engineering soil was trucked away. We can calculate the actual output of the engineering soil according to the volume of soil truck, the actual output is about 110470 m^3. According to the precision calculation formula 00, the accuracy of the quantitative method for predicting engineering soil is 94.49%.

5 Discussion

5.1 Accuracy specification

According to the current status of construction waste control and management, if the accuracy is ≥80%, we consider the quantitative methods is effective. The principle of various UCWs prediction methods proposed in this study are essentially the same, and they are all based on their source characteristics and mass conservation to predict the possible waste output. The accuracy of quantitative methods of engineering soil and shield sludge has certain representative significance. We can conclude that the quantitative methods for predicting the amount of UCW proposed in this study is effective. The application of this quantitative methodology to the actual project will greatly facilitate the follow-up management.

The accuracy of quantitative method for predicting shield sludge is less than that of the quantitative method for predicting engineering soil mainly because of the lack of data of additives (e.g., bentonite, cellulose, foaming agent) added in construction process. Various additives are added into the sludge to maintain is functions and properties during shield sludge circulation. Agents will also be added during EPB shield construction to make tunnelling proceed safely and smoothly. The operating parameters of shield machine also affect the actual output of excavated waste. The quantitative methods proposed in this study does not consider the machine operation parameters and some special requirements, but only considers the two main factors: construction scale and geological conditions.

Quantitative methods proposed in this study are the sum of the quantitative data of each construction section, which can provide effective data for the precise on-site management of the excavation waste, such as determining the volume and location of the sludge pool, the quantity and distribution scheme of the soil separator, crusher, etc., and the reasonable allocation of transport personnel and vehicles.

5.2 Production and recycling of UCW in case study

According to the overall geological survey report and construction plan of Boao tunnel，we obtained the volume of sand-gravel, cohesive soil and sludge soil in the whole line.

Table 6

The forecast volume of sand-gravel, cohesive soil and sludge soil in the whole Boao tunnel.

Soil layer	Volume (m$^{3)}$	Sand-gravel (m^3)	Cohesive soil (m^3)	Sludge soil (m^3)
Silty clay and sand	4116.46	172.89	1756.08	464.34

Soil layer	Volume (m$^{3)}$	Sand-gravel (m^3)	Cohesive soil (m^3)	Sludge soil (m^3)
interbedding				
Silty soil	27985.74	4365.78	2003.78	9713.85
Sandy silt	27985.74	447.77	1178.20	13421.96
Sandy soil	32541.97	6378.23	1470.90	11754.16
Mucky silty clay	65676.17	1247.85	15827.96	13062.99
Silty clay	154635.80	3711.26	73653.03	109946.10
Gravel	171590.60	151686.10	0	19904.51

According to the data in the Table 6, we can calculate that the total volume of sand-gravel produced during the tunnel construction is 168009.90 m^3, the amount of cohesive muck is 95889.95 m^3, and the amount of sludge soil is 178267.90 m^3. The shield sludge yield is 520542.2 m^3. After the completion of the project, the sludge in the sludge pool is also treated and disposed, so the total disposal amount is 521742.2 m^3.

According to the engineering verification results summarized above, the amount of engineering soil generated by the shield part of Changsha Metro Line 5 is 103936.35 m^3. According to the geological report of Changsha Metro Line 5, we can calculate that the soil contains 51363.12 m^3 of sand-gravel.

The amount of UCW produced by underground civil and infrastructure projects is huge, and the reasonable and full utilization of these UCW will obtain huge economic value. For example, sand-gravel will be used as raw material for the concrete mixing station and construction site. Because the quality of the sand-gravel produced by these two projects is slightly worse than that of the sand-gravel in the market, the price of the sand-gravel recycled in cases is 150 yuan /m^3. The total value of the sand-gravel produced by the Boao Tunnel Project is about 25 million yuan. The net profit is about 22 million yuan after removing transportation cost of about 1 million yuan and the follow-up treatment cost of about 2 million yuan. The net profit of sand-gravel separated from Changsha Metro Line 5 is estimated above 7 million yuan. Dry soil will be used as raw materials for roadbed, other soil will be partially backfilled or transported for off-site use. It is estimated that nearly one billion of economic value can obtain if all the waste in the line could be fully reuse and recycling.

6 Conclusions

Underground construction produces a large amount of waste with high reuse and recycling value, but few quantitative studies focus on it. In order to bring convenience to the management and recycling of UCW, this study established quantitative methods to predict the amount of UCW based on the principle of mass conservation. The source characteristics, factors affecting the yield and the possible recycling direction of UCW were analyzed to provide sufficient theoretical support for the establishment of the method. Through the engineering verification of the actual project, it is concluded that the quantitative method for predicting shield sludge has a valid accuracy with the accuracy range from 82.03% to 95.79%. The accuracy of the quantitative method for predicting engineering soil is 94.49%. It proves that the quantitative methods are effective and workable. Excavated waste generated during the construction of Hangzhou Boao tunnel and Changsha Metro Line 5 were quantified by using the quantitative methods. Recyclable sand-gravel make up a large part of the excavated waste, and the reasonable and full utilization of these UCW will obtain huge economic value.

To improve the accuracy of the quantitative methods, more factors can be taken into account, such as water content of stratum, additives added into sludge and so on. In this study, UCW is only divided into three categories, more categories can be considered according to the actual situation, for example, sand, gravel, sandy soil, silty soil, etc. Sludge dewatering has always been the difficulty and key point of sludge treatment. Accelerating the improvement of the construction method of tunnelling to minimize sludge production is the fundamental solution to sludge treatment problems.

Declarations

Ethics approval and consent to participate- Not applicable

Consent for publication – Not applicable

Availability of data and materials- The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Competing interests- The authors declare that they have no competing interests

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