

Quantitative Methods for Predicting Underground Construction Waste Considering Reuse and Recycling

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32 Engineering verification; Mass conservation;

33 **1 Introduction**

34 Because of the large-scale underground construction in the recent years and the inevitable earthwork
35 in the construction process, a large amount of waste excavated in underground construction has become
36 a problem that cannot be ignored (Shang et al. 2013). Excavated waste is inert material that is not
37 normally considered to cause a major problem on environment and society. However, more and more
38 studies prove that excavated waste has a strategic impact on resource efficiency and the sustainable
39 environment. Construction industry is a major contributor to the decrease of natural resources, especially
40 the resources of sand and rocks (Kirthika et al. 2020). With the increasing demand of protecting the
41 environment and building a sustainable society, the constraints on the exploitation of natural sand and
42 rock are becoming increasingly tight (Magnusson et al. 2015; Rana et al. 2016). Therefore, it is of
43 practical significance to supplement the channels of acquiring construction sand and gravel by means of
44 various wastes recycling (Rana et al. 2016). Disorderly disposal and invalid utilization of an enormous
45 amount of excavated waste will add to the cost of the project (Bellopede et al. 2011). Numerous untreated
46 engineering soil will encroach on land and pollute soil and water (Kalbe et al. 2008; Lee et al. 2008). The
47 random dumping of soil may also threaten the safety of human life and bring serious social problems,
48 for example, a landslide killed 77 people and engulfed an industrial park of over 100,000 m³ in Shenzhen
49 in 2015 (The Xinhua News Agency 2016).

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

58 Large underground construction projects often overlap with civil and infrastructure projects. Civil
59 and infrastructure construction will produce a lot of CDW (de Magalhães et al. 2017), but previous
60 researchers have paid little attention to it because of such difficulties as incomplete data and the huge

61 workload. Wu et al. (2014a) summarized 57 papers related to the quantification of CDW, of which only
62 5 papers are related to civil and infrastructure work. The focus of scholars on the quantification of civil
63 and infrastructure waste is usually at a regional level (Cochran and Townsend 2010; Hashimoto et al.
64 2007, 2009; Martínez Lage et al. 2010). De Guzmán Báez et al. (2012) developed a quantitative method
65 for calculating the amount of waste generated in the construction of Spanish railways. This method is
66 more accurate than previous ones of calculating the annual production of CDW in a region. Since the
67 work of Wu et al., the study of civil and infrastructure construction waste and the precise quantification
68 of certain types of waste have increased but still account for a very small proportion of quantitative works
69 of CDW (Povetkin and Isaac 2020; Wu et al. 2019). Accurate estimation of waste generated in civil and
70 infrastructure can lead the way in improving waste management in the entire construction industry.

71 Methodologies for estimating CDW fall into six major categories (Guerra et al. 2019; Masudi et al.
72 2010; Wu et al. 2014b): site visit, generation rate calculation, lifetime analysis, classification system
73 accumulation, variables modelling and other methods. The recent trend is that more and more computer
74 technologies have been applied to the quantification of CDW (Cha et al. 2020; Chen and Lu 2017; Cheng
75 and Ma 2013; Guerra et al. 2019). The amount of UCW is related to geotechnical properties and
76 construction conditions. Due to this complexity, its calculation requires a combination of multiple
77 quantitative methods to calculate like those of site visit, material flow analysis, principal factor analysis,
78 etc. Traditionally, the prediction of the amount of sludge production was mainly through experience
79 method. For example, 1:4 (sand) ~ 1:7 (cohesive soil) of the excavated volume being used as the
80 predictive generation rate of the amount of sludge generated in sludge shield. The method of experience
81 generation rate for predicting the volume of shield sludge usually has great uncertainty, which brings
82 difficulties for the subsequent development of detailed waste planning.

83 Most of current research on quantifying CDW has been done at a broader level, ignoring the
84 significance of precise quantification to CDW management. Less research focus on civil and
85 infrastructure construction, ignoring a very important part of the construction industry, not to mention
86 ignoring the quantification of inert construction waste excavated from underground construction.
87 Although there have been many studies on the quantitative methods for calculating the amount of CDW,
88 the validity of the proposed methods has been ignored (Wu et al. 2014b). In order to bring convenience
89 to the precise management of UCW and promote the clean and sustainable development of the whole
90 construction industry, this study proposes a relatively accurate quantitative methodology to predict the

91 amount of UCW considering its reuse and recycling. The quantitative methods enable project
92 stakeholders to predict the amount of UCW at the design and the early construction stage, and provide
93 effective data support for the source reduction, consumption, transfer, and resource utilization of
94 construction waste. In this study, two tunnel infrastructure construction cases are used to validate the
95 proposed quantitative methods, which also provides reference data for estimating the amount of waste
96 produced by other tunnel construction.

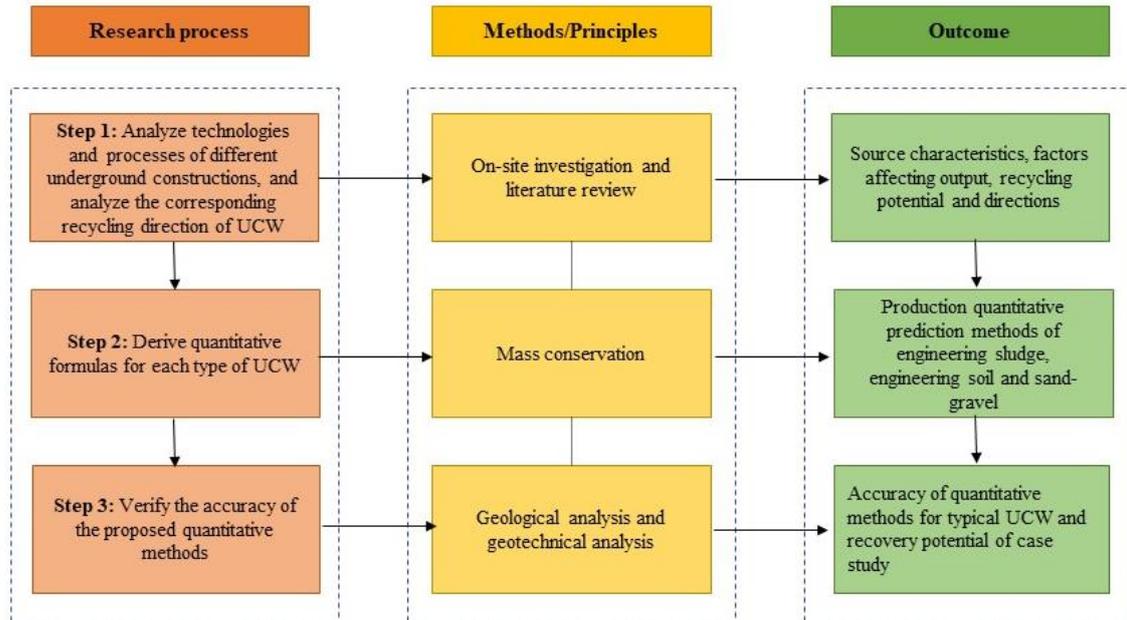
97 The remainder of this paper is as follows. After this introductory section is material and methods
98 used in this study. Two cases study is then presented in Section 3. Section 4 shows findings of the study,
99 and the source characteristics, factors affecting the yield and the possible recycling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

103 **2 Material and methods**

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

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

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Fig. 1 Research framework

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2.1 On-site investigation on source characteristics and recycling status

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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.

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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.

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2.2 Quantitative methods based on principle of mass conservation

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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

136 lead to changes in density. Therefore, the calculation of the volume of UCW converted by raw soil
 137 inevitably uses the principle of mass conservation.

138 **2.2.1 Quantitative method for predicting production of engineering sludge**

139 2.2.1.1 Shield sludge

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

$$144 \quad V_{sl} = \varepsilon \cdot \sum V_i \cdot \lambda_i$$

145 (1)

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

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

$$155 \quad V_S \rho_0 = \rho_w V_W + \rho_s V_{sl}$$

156 (2)

$$157 \quad V_W = \alpha V_{sl}$$

158 (3)

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

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

$$162 \quad V_{TS1} = \sum_n^N (\rho_s + \alpha \rho_w) / \rho_0 \cdot \varepsilon \cdot \sum V_{ni} \cdot \lambda_{ni} + V_0$$

163 (4)

164 Where $n \geq 1$, $N \leq$ the total number of driving rings.

165 2.2.1.2 Bored cast-in-situ piles sludge

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

$$168 \quad V_1 = \mu * V$$

169 (5)

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

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

$$174 \quad V_2 = V_1$$

175 (6)

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

$$177 \quad V_3 = V_1/10$$

178 (7)

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

$$181 \quad V_{TS2} = V_1 + V_2 + V_3$$

182 (8)

183 2.2.1.3 Underground diaphragm wall sludge

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

$$186 \quad V_{TS3} = \mu V$$

187 (9)

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

190 **2.2.2 Quantitative method for predicting production of engineering soil**

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

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

193
$$V_{TS} = \sigma \cdot V$$

194 (10)

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

197 **2.2.3 Quantitative method for predicting production of sand-gravel**

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

200
$$V_{sg} = \sum V_i \cdot \tau_i$$

201 (11)

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

203 **2.3 Engineering verification based on geological and geotechnical analysis**

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

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

211
$$\delta = 1 - |V_r - V_p| / V_r$$

212 (12)

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

217 **3 Cases study**

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

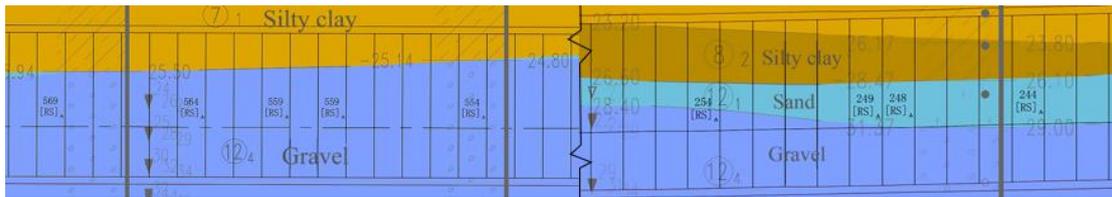
222 **3.1 Project Overview of Hangzhou Boao Tunnel**

223 The total length of Boao tunnel is 2800 m, the length of the cross-river tunnel is about 1680 m. The
 224 slurry shield of 11.7 m in diameter is adopted to excavate Hangzhou Boao Tunnel. The sludge-water
 225 treatment site is arranged on the west side of the structure, covering an area of about 5000 m², with 1200
 226 m³ sludge in the pool of an initial density of 1.3×10³ kg/m³. The propulsion distance of each ring is 5 m.

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

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

234



235

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

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

241

Table 1

242

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 | 0.25-0.075 | 0.075-<0.005 |
| Silty clay _{⊙1} ^a | 26.20 | 0.74 | 4.90 | 1.57 | 0.30 | 5.70 | 47.40 | 42.80 | 3.90 |

| | | | | | | | | | | | |
|--------------------------------------|-------|------|------|------|-------|-------|-------|-------|-------|------|------|
| Silty clay _② ^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 |

243 ^a According to China's Code for Geotechnical Engineering Investigation, Silty clay_① and Silty clay_② are classified
244 into the same category, but their physical properties are not the same.

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

249 3.2 Project Overview of Changsha Metro Line 5

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

254 4. Result

255 4.1 Source characteristics of UCW

256 4.1.1 Source characteristics of shield waste

257 Shield construction refers to the method of tunnelling and dredging by using shield tunnelling
258 machine while controlling the excavation face and surrounding rock without collapse and instability.
259 Because of its advantages of fast digging speed, excellent quality and relatively high construction safety
260 (He et al. 2020), in the case of poor stratum conditions and complex geological conditions, etc., the shield
261 method has become the preferred construction method for tunnel construction in China (Yu et al.
262 2020). The types of shield machines can be divided into open face shield machine, sludge shield machine
263 and EPB shield machine etc. When the permeability coefficient of the geological layer is greater than 10^{-4} ,
264 sludge shield is adopted; When the permeability coefficient of geological layer is less than 10^{-7} , EPB
265 shield is adopted; When the permeability coefficient is between the above two numbers, both types can
266 be adopted. The waste products of EPB shield construction are mainly engineering soil, and the products
267 of sludge shield are mainly engineering sludge and soil. The shield tunnelling machine builds the tunnel
268 without disturbing the surrounding rock due to the linings assembled from the pipe pieces on the machine,
269 and the wall behind which grouting is implemented. The residue under the knife disc is dissolved into

270 the sludge and the sludge discharge system continuously discharges the sludge from the sludge tank to
271 ensure that the pressure of the sludge film is in equilibrium.

272 **4.1.2 Source characteristics of pile foundation waste**

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

282 **4.1.3 Source characteristics of underground diaphragm wall waste**

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

291 **4.2 Factors affecting yield**

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

297 **4.2.1 Geological and geotechnical conditions**

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

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

308 Table 2

309 Geotechnical conversion indexes of shield sludge formation.

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

310

311 4.2.2 Construction scale and strata volume

312 The construction depth of pile foundation is determined by the bearing capacity. Generally, the
 313 construction area is below 40 m underground. The construction depth of the underground diaphragm wall
 314 is determined by the water table and is generally less than 20 m underground. The two types of
 315 construction will go through a variety of strata. The construction area of shield tunneling is generally
 316 below 10 m underground. The diameter of most shield tunnels is larger than 10 m, so the tunnels will
 317 pass through one stratum or more during the shield construction. Geotechnical properties of different
 318 strata have a great impact on the type and amount of waste to be generated. Therefore, we should not
 319 only know the overall scale of construction, but also calculate the volume of each geological layer that

320 goes through. For the variety and instability of the terrain, we can adopt an idealized model, and then use
321 integral method to calculate the volume of each layer.

322 **4.3 Reuse and recycling of UCW**

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

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

342 **4.4 Accuracy of proposed quantitative methods**

343 **4.4.1 Accuracy of quantitative methods for predicting shield sludge**

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

348 Table 3

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

| Ring number | Yield | Gravel | Silty clay ^① |
|-------------|------------------------------|--------|-------------------------|
| | Volume m ³ | 482.56 | 55.00 |
| | Sand-gravel m ³ | 426.59 | 1.32 |
| Ring 551 | Cohesive soil m ³ | 0 | 26.20 |
| | Sludge soil m ³ | 55.98 | 3.91 |
| | Volume m ³ | 417.29 | 120.28 |
| | Sand-gravel m ³ | 368.88 | 2.89 |
| Ring 563 | Cohesive soil m ³ | 0 | 57.29 |
| | Sludge soil m ³ | 48.41 | 8.55 |
| | Volume m ³ | 393.84 | 143.73 |
| | Sand-gravel m ³ | 348.15 | 3.45 |
| Ring 572 | Cohesive soil m ³ | 0 | 68.46 |
| | Sludge soil m ³ | 45.69 | 10.22 |

350

351

Table 4

352

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

| Ring number | Yield | Silty clay ^② | Gravel | Sand |
|-------------|------------------------------|-------------------------|--------|--------|
| | Volume m ³ | 191.65 | 159.07 | 186.85 |
| | Sand-gravel m ³ | 0 | 140.61 | 36.62 |
| Ring 243 | Cohesive soil m ³ | 64.43 | 0 | 8.45 |
| | Sludge soil m ³ | 48.97 | 18.45 | 67.49 |
| | Volume m ³ | 190.51 | 187.10 | 159.95 |
| | Sand-gravel m ³ | 0 | 165.40 | 31.35 |
| Ring 250 | Cohesive soil m ³ | 64.05 | 0 | 7.23 |
| | Sludge soil m ³ | 48.68 | 21.70 | 57.77 |
| | Volume m ³ | 173.55 | 240.15 | 123.86 |
| | Sand-gravel m ³ | 0 | 212.29 | 24.28 |
| Ring 255 | Cohesive soil m ³ | 58.35 | 0 | 5.60 |
| | Sludge soil m ³ | 44.34 | 27.86 | 44.74 |

353

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

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

363 Table 5

364 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 |

365
 366 According to the data in Table 5, the accuracy of quantitative method for predicting shield sludge is
 367 between 82.03%-95.79%.

368 4.4.2 Accuracy of quantitative methods for predicting engineering soil

369 The amount of shield soil generated by Changsha Metro Line 5 can be calculated according to the
 370 formula (10). With $L=1600$ m, $\alpha=1.04$ and $R =3.15$ m in the formula, the yield of engineering soil was
 371 103936.35 m³. In the shield construction process, all the engineering soil was trucked away. We can
 372 calculate the actual output of the engineering soil according to the volume of soil truck, the actual output
 373 is about 110470 m³. According to the precision calculation formula 00, the accuracy of the quantitative
 374 method for predicting engineering soil is 94.49%.

375 **5 Discussion**

376 **5.1 Accuracy specification**

377 According to the current status of construction waste control and management, if the accuracy is
378 $\geq 80\%$, we consider the quantitative methods is effective. The principle of various UCWs prediction
379 methods proposed in this study are essentially the same, and they are all based on their source
380 characteristics and mass conservation to predict the possible waste output. The accuracy of quantitative
381 methods of engineering soil and shield sludge has certain representative significance. We can conclude
382 that the quantitative methods for predicting the amount of UCW proposed in this study is effective. The
383 application of this quantitative methodology to the actual project will greatly facilitate the follow-up
384 management.

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

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

397 **5.2 Production and recycling of UCW in case study**

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

400 Table 6

401 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 |

402

403 According to the data in the Table 6, we can calculate that the total volume of sand-gravel produced
404 during the tunnel construction is 168009.90 m³, the amount of cohesive muck is 95889.95 m³, and the
405 amount of sludge soil is 178267.90 m³. The shield sludge yield is 520542.2 m³. After the completion of
406 the project, the sludge in the sludge pool is also treated and disposed, so the total disposal amount is
407 521742.2 m³.

408 According to the engineering verification results summarized above, the amount of engineering soil
409 generated by the shield part of Changsha Metro Line 5 is 103936.35 m³. According to the geological
410 report of Changsha Metro Line 5, we can calculate that the soil contains 51363.12 m³ of sand-gravel.

411 The amount of UCW produced by underground civil and infrastructure projects is huge, and the
412 reasonable and full utilization of these UCW will obtain huge economic value. For example, sand-gravel
413 will be used as raw material for the concrete mixing station and construction site. Because the quality of
414 the sand-gravel produced by these two projects is slightly worse than that of the sand-gravel in the market,
415 the price of the sand-gravel recycled in cases is 150 yuan /m³. The total value of the sand-gravel produced
416 by the Boao Tunnel Project is about 25 million yuan. The net profit is about 22 million yuan after
417 removing transportation cost of about 1 million yuan and the follow-up treatment cost of about 2 million
418 yuan. The net profit of sand-gravel separated from Changsha Metro Line 5 is estimated above 7 million
419 yuan. Dry soil will be used as raw materials for roadbed, other soil will be partially backfilled or
420 transported for off-site use. It is estimated that nearly one billion of economic value can obtain if all the
421 waste in the line could be fully reuse and recycling.

422 **6 Conclusions**

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

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

441 **Declarations**

442 *Ethics approval and consent to participate*- Not applicable

443 *Consent for publication*- Not applicable

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

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

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455

456 **References:**

457 Bellopede R, Brusco F, Oreste P, Pepino M (2011) Main Aspects of Tunnel Muck Recycling. American
458 journal of environmental sciences 7: 338-347. <https://doi.org/10.3844/ajessp.2011.338.347>

459 Cha G, Moon H J, Kim Y, Hong W, Hwang J, Park W, Kim Y (2020) Development of a Prediction
460 Model for Demolition Waste Generation Using a Random Forest Algorithm Based on Small DataSets.
461 Int J Env Res Pub He 17: 6997. <https://doi.org/10.3390/ijerph17196997>

462 Chen X, Lu W (2017) Identifying factors influencing demolition waste generation in Hong Kong. J Clean
463 Prod 141: 799-811. <https://doi.org/10.1016/j.jclepro.2016.09.164>

464 Cheng J C P, Ma L Y H (2013) A BIM-based system for demolition and renovation waste estimation
465 and planning. Waste Manage 33: 1539-1551. <https://doi.org/10.1016/j.wasman.2013.01.001>

466 Cochran K M, Townsend T G (2010) Estimating construction and demolition debris generation using a
467 materials flow analysis approach. Waste Manage 30: 2247-2254.
468 <https://doi.org/10.1016/j.wasman.2010.04.008>

469 De Guzmán Báez A, Villoria Sáez P, Del Río Merino M, García Navarro J (2012) Methodology for
470 quantification of waste generated in Spanish railway construction works. Waste Manage 32: 920-924.
471 <https://doi.org/10.1016/j.wasman.2012.01.007>

472 De Magalhães R F, Danilevicius D M F, Saurin T A (2017) Reducing construction waste: A study of
473 urban infrastructure projects. Waste Manage 67: 265-277. <https://doi.org/10.1016/j.wasman.2017.05.025>

474 Diana M, Ángel V, Daniel C, Miguel A. C, Aitor C. R (2015) Sustainability in construction works: Reuse
475 of sludge from tunnel boring in lime mortars. Appl Clay Sci 114: 402-406.
476 <https://doi.org/10.1016/j.clay.2015.05.019>

477 European Commission (2016) Construction and Demolition Waste Management Report.
478 http://ec.europa.eu/environment/waste/studies/mixed_waste.htm#links (accessed 13 January 2021).

479 Griffiths J S, Radford T (2012) An introduction to earthworks in Europe. Geological Society, London,

480 Engineering Geology Special Publications 26: 1-4. <https://doi.org/10.1144/EGSP26.1>

481 Guerra B C, Bakchan A, Leite F, Faust K M (2019) BIM-based automated construction waste estimation
482 algorithms: The case of concrete and drywall waste streams. *Waste Manage* 87: 825-832.
483 <https://doi.org/10.1016/j.wasman.2019.03.010>

484 Haas M, Galler R, Scibile L, Benedikt M (2020) Waste or valuable resource – a critical European review
485 on re-using and managing tunnel excavation material. *Resources, Conservation and Recycling* 162:
486 105048. <https://doi.org/10.1016/j.resconrec.2020.105048>

487 Hashimoto S, Tanikawa H, Moriguchi Y (2007) Where will large amounts of materials accumulated
488 within the economy go? – A material flow analysis of construction minerals for Japan. *Waste Manage*
489 (Elmsford) 27: 1725-1738. <https://doi.org/10.1016/j.wasman.2006.10.009>

490 Hashimoto S, Tanikawa H, Moriguchi Y, 2009, Framework for estimating potential wastes and
491 secondary resources accumulated within an economy – A case study of construction minerals in Japan.
492 *Waste Manage* 29: 2859–2866. <https://doi.org/10.1016/j.wasman.2009.06.011>

493 He X, Xu Y, Shen S, Zhou A (2020) Geological environment problems during metro shield tunnelling
494 in Shenzhen, China. *Arab J Geosci* 13. <https://doi.org/10.1007/s12517-020-5071-z>

495 Kalbe U, Berger W, Eckardt J, Simon F (2008) Evaluation of leaching and extraction procedures for soil
496 and waste. *Waste Manage* 28: 1027-1038. <https://doi.org/10.1016/j.wasman.2007.03.008>

497 Kirthika S, Singh S, Chourasia A (2020) Alternative fine aggregates in production of sustainable
498 concrete- A review. *J Clean Prod.* <https://doi.org/10.1016/j.jclepro.2020.122089>

499 Lee J Y, Moon S H, Yi M J, Yun S T (2008) Groundwater contamination with petroleum hydrocarbons,
500 chlorinated solvents and high pH: implications for multiple sources. *Q J Eng Geol Hydroge* 41: 35-47.
501 <https://doi.org/10.1144/1470-9236/07-021>

502 Li Y, Pan Q, Cleall P J, Chen Y, Ke H (2013) Stability Analysis of Slurry Trenches in Similar Layered
503 Soils. *J Geotech Geoenviron* 139: 2104-2109. [https://doi.org/10.1061/\(ASCE\)GT.1943-5606.0000958](https://doi.org/10.1061/(ASCE)GT.1943-5606.0000958)

504 Lu W, Yuan H, Li J, Hao J J L, Mi X, Ding Z (2011) An empirical investigation of construction and
505 demolition waste generation rates in Shenzhen city, South China. *Waste Manage* 31: 680-687.
506 <https://doi.org/10.1016/j.wasman.2010.12.004>

507 Luo W, Sandanayake M, Zhang G (2018) Direct and indirect carbon emissions in foundation construction

508 - Two case studies of driven precast and cast-in-situ piles. *J Clean Prod* [https://doi.org/](https://doi.org/10.1016/j.jclepro.2018.11.244)
509 10.1016/j.jclepro.2018.11.244

510 Magnusson S, Lundberg K, Svedberg B, Knutsson S (2015) Sustainable management of excavated soil
511 and rock in urban areas - A literature review. *J Clean Prod* 93: 18-25.
512 <https://doi.org/10.1016/j.jclepro.2015.01.010>

513 Martínez Lage I, Martínez Abella F, Herrero C V, Ordóñez J L P (2010) Estimation of the annual
514 production and composition of C&D Debris in Galicia (Spain). *Waste Manage* 30: 636-645.
515 <https://doi.org/10.1016/j.wasman.2009.11.016>

516 Masudi A F, Che Hassan C R, Mahmood N Z, Mokhtar S N, Sulaiman N M (2010) Quantification
517 Methods for Construction Waste Generation at Construction Sites: A Review. *Advanced Materials*
518 *Research* 163-167: 4564-4569. <https://doi.org/10.4028/www.scientific.net/AMR.163-167.4564>

519 Povetkin K, Isaac S (2020) Identifying and addressing latent causes of construction waste in
520 infrastructure projects. *J Clean Prod* 266: 122024. <https://doi.org/10.1016/j.jclepro.2020.122024>

521 Rana A, Kalla P, Hk V, JK M (2016) Recycling of dimensional stone waste in concrete: A review. *J*
522 *Clean Prod* <https://doi.org/10.1016/j.jclepro.2016.06.126>.

523 Riviera P P, Bellopede R, Marini P, Bassani M (2014) Performance-based re-use of tunnel muck as
524 granular material for subgrade and sub-base formation in road construction. *Tunn Undergr Sp Tech* 40:
525 160-173. <https://doi.org/10.1016/j.tust.2013.10.002>

526 Shang C, Zhu Y, Zhang Z (2013) A glance at the world. *Waste Manage* 33: 489-492.
527 <https://doi.org/10.1016/j.wasman.2012.12.019>

528 Thanh N P, Matsui Y, Fujiwara T (2010) Household solid waste generation and characteristic in a
529 Mekong Delta city, Vietnam. *J Environ Manage.* 91

530 The Xinhua News Agency (2016) Special major landslide accident investigation Report of “12·20” in
531 muck receiving field of Guangming New District, Shenzhen, Guangdong. *Xinhuanet.*
532 http://www.xinhuanet.com/politics/2016-07/15/c_1119227686.htm (accessed 02/09/2020).

533 Weng C, Lin D, Chiang P (2003) Utilization of sludge as brick materials. *Advances in Environmental*
534 *Research* 7. [https://doi.org/https://doi.org/10.1016/S1093-0191\(02\)00037-0](https://doi.org/https://doi.org/10.1016/S1093-0191(02)00037-0)

535 Wu H, Zuo J, Zillante G, Wang J, Yuan H (2019) Construction and demolition waste research: a

536 bibliometric analysis. *Architectural science review* 62: 354-365.
537 <https://doi.org/10.1080/00038628.2018.1564646>

538 Wu Z, Yu A T W, Shen L, Liu G (2014a) Quantifying construction and demolition waste: An analytical
539 review. *Waste Manage* 34: 1683-1692. <https://doi.org/10.1016/j.wasman.2014.05.010>

540 Wu Z, Yu A T W, Shen L, Liu G (2014b) Quantifying construction and demolition waste: An analytical
541 review. *Waste Manage* 34: 1683-1692. <https://doi.org/10.1016/j.wasman.2014.05.010>

542 Yu C, Zhou A, Chen J, Arulrajah A, Horpibulsuk S (2020) Analysis of a tunnel failure caused by leakage
543 of the shield tail seal system. *Underground space (Beijing)* 5: 105-114.
544 <https://doi.org/10.1016/j.undsp.2018.11.003>

545 Zhang N, Duan H, Sun P, Li J, Zuo J, Mao R, Liu G, Niu Y (2020) Characterizing the generation and
546 environmental impacts of subway-related excavated soil and rock in China. *J Clean Prod.*248: 119242.
547 <https://doi.org/10.1016/j.jclepro.2019.119242>

548 Zhang N, Zhang H, Schiller G, Feng H, Gao X, Li E, Li X (2020) Unraveling the GWP mitigation
549 potential from recycling subway - related excavated soil and rock in China via life cycle assessment.
550 *Integr Environ Asses* <https://doi.org/10.1002/ieam.4376>

551 Zhao W, Leefink R B, Rotter V S (2010) Evaluation of the economic feasibility for the recycling of
552 construction and demolition waste in China—The case of Chongqing. *Resources, Conservation and*
553 *Recycling* 54: 377-389. <https://doi.org/10.1016/j.resconrec.2009.09.003>

554