

A quota-based GHG emissions quantification model for the construction of subway stations in China

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ABSTRACT

Subway construction in China has experienced a surge during the past decade. Though subway is often viewed as a clean commute mode, the construction of its stations and tunnel sections requires large quantities of energy consumption, generating multiple pollutants, among which the Green-house gas (GHG) emissions would be a major issue in the context of a worldwide plea for carbon reduction, and it has to be quantified for the interest of a comprehensive assessment with regard to the GHG emissions of subway system. This paper proposed a GHG emissions quantification model for the construction of the subway stations based on a quota. A quota-based GHG emissions quantification model is able to estimate GHG emissions during the planning stage of subway projects, providing designers with the environmental consciousness on their design choices, as well as a reference for reduction potential of GHG emissions within or among schemes. Specifically, GHG emissions in the construction of subway stations are attributed to the contribution of each sub-project, a database for the GHG emissions of those sub-projects is established through their construction quota. Case study for an open-excavation station shows 69% of the GHG emissions come from the construction of main structures. In terms of emission sources, embodied emissions account for 90.72% of the totality, of which concrete and steel components are the two major contributors. Besides, parameter on the buried depth of top slab shows that GHG emissions from each sub-projects increase with buried depth.

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1. Introduction

Public concerns on the GHG emissions of transportation sector has been growing these years, it is a major contributor to GHG emissions in developed and developing countries (Glassom, 2007; Francois et al., 2017; Gangwar and Sharma, 2014; Alkhatlan and Javid, 2015). In 2010, 23% of anthropogenic GHGs are from the emissions of passenger and freight vehicles (IPCC, 2014). While it varies a lot between countries, the growing economy of developing countries are likely to change the distribution in the future (Taptich et al., 2016). As the largest developing country in the world, China's transportation sector is responsible for 15.9% of the total final CO₂ emissions in 2008 and will contribute about one-third of CO₂ emissions in 2030 (Zhou et al., 2013).

Some work has been done to investigate the GHG emissions from urban transit rail (UTR), of which a majority chose to focus on the GHG emissions from its operation phase, such as GHG

emissions from traction (Doll and Balaban, 2013; Wang, 2016), that from lightening and power consumption in stations (Hong and Kim, 2004; Li et al., 2018) and equipment spoilage (Baron and Martinetti, 2011). In other studies, efforts have been made on the exploration of GHG emissions reduction methods in its operation stage i.e. changing level-of-service (Cheng et al., 2016), optimizing network (Mandanat et al., 2016) and operation optimization (Grisword et al., 2013; González-Gil et al., 2013). UTR's efficiency in terms of mitigating GHG emissions were justified by quantifying the reduced carbon print due to mode shift from other commute types (Chen et al., 2017; Huang et al., 2015; Saxe et al., 2017; Saxe et al., 2017), congestion relief (Andrade and D'Agosto, 2016) and change of land use (Andrade and D'Agosto, 2016; Saxe and Denman, 2017). Nonetheless, the validity of the quantification of GHGs mitigation is hinged on the uncertainty in ridership prediction, and a more holistic assessment scope including GHG emissions from UTR's infrastructures.

GHG emissions from the construction of UTR's infrastructures, especially those in underground sections, are more intensive as it involves large quantities of energy consumption and building materials. Data show that GHG emissions from the construction of

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1 km subway projects are 79468 t CO₂ eq. in Shenzhen, 46 times higher than that from 1 km highway construction (Mao, 2017). Therefore, to appropriately assess the emissions-mitigating superiority of urban transit to alternative commute modes, it is necessary to take into account its infrastructure-related GHG emissions (Chester and Horvath, 2009).

Along with the adoption of life-cycle methodology, the infrastructure-related GHG emissions in rail projects have received more attention. GHG emissions from the construction of high speed railway has been investigated (Saxe et al., 2016; Chang, 2009; Chester and Horvath, 2010), the results varies as the composition of a HSR line would significantly affect the GHGs investment. For example, GHG emissions from tunnel construction have a disproportionate contribution of the totality (Saxe et al., 2016; Chang and Kendall, 2011). In cases of underground UTR projects, GHG emissions are more intensive for the large quantities of GHGs emitted from the construction of its tunnel sections. GHG emissions from the construction of underground sections and stations of Crossrail in London are estimated to be 1.7 Mt CO₂, contributing about 20% of life-cycle totality (Crossrail, 2014). Similar case studies in Asia show that construction-related GHG emissions (those from building materials and construction machine) account for 4.9% of life-cycle totality in Shanghai metro (Li et al., 2018), 10%, 20% and 30% for urban transit in Kunming, Ho Chi Minh City and Bangalore respectively (Clean Air Asian Cooperates, 2015). The variation in these percentages is dictated by assessment duration, which might belie the fact that GHG emissions from urban transit's infrastructures are huge in absolute volume.

However, the environmental-efficient thinking in construction section is still lacking, and one of the major objectives for the sustainable construction is to establish the environmental-consciousness among engineers and designers, making them aware of the environmental implication of their choices on materials, design, construction methods and facility siting (Horvath, 1999). The existing criterion of economics and safety in engineering should be incorporated with 'the third bottom line'- environment, and a design code with environmental consideration would benefit this process greatly.

A GHG emissions database on the basis of Chinese quota system provides us the chance to do so. Quota system in China has a wide range of adaption, thousands of specified quotas have been issued for each industry. By definition, a quota is an officially-issued database that decomposes the production into many standardized element processes with specific technical routines, quality standards and range of applicability, prescribing the average consumption of manpower, materials and machine shifts and frequently updated unit price of production factors involved in each element process. The standardization of routine and resource input in one element process is achieved through a long-term maturity process of its technology as it is adopted by many individual manufacturers, therefore a statistically-average database for consumption can represent the production level within a region. In practice, the consumption data in quotas serves as the benchmark in bidding from which any significant deviation would cause potential quality problems or, on the other side, less economical competitiveness of a proposal. As for the construction industry, quota is indispensable in that it is the common language among different roles throughout the project. Design schemes and inventory should be compiled in accordance with the element processes in quota, and construction plan is also organized in the form of the combination of these elements. Moreover, acceptance check and payment are also performed on the basis of quota.

In this paper, the standardized element processes and their consumption data are utilized to construct a quota-based GHG emissions database to quantify the GHG emissions from the

construction of subway stations. Such a database is capable of estimating the GHG emissions from different schemes of UTR engineering, providing reference to scheme selections. Besides, it is inherent with the convention of contractors, owners and designers, thus being helpful in improving their perception of the environmental implication of their choice such as scheme selection and construction plan. The major differences between quota-based method and traditional method are listed in Table 1.

The layout of this paper is as follows: In section 2, the decomposition for the construction of open-excavation subway stations is defined, following which the GHG emission quantification model for the construction of subway stations is constructed by integrating the GHG emissions from labor force, construction materials and construction machines in each element process and upscaling them to each level of sub-projects. The established model is used in section 3 for the case study of an open-excavation subway station in Beijing, GHG emissions among different sub-projects and emission sources are analyzed. Section 4 gives a demonstration on the quota-based model's role in scheme selection. Parameter analysis is made on how the buried depth, the most essential parameter for the construction, affects the GHG emissions from construction. Some implication of the results is discussed in section 5.

2. Modelling the GHG emissions qualification model of subway station during its construction period

2.1. Methodology

The quota-based GHG emissions quantification model follows the procedure of ISO/TS 14067 (ISO/TS, 2013), in which the single impact category of GHG emissions is assessed. A few modifications were made to serve the goal of this study:

Scope: Referring to the notion of Partial CFP (Carbon Foot Print) in ISO/TS 14067, this study aims to quantify GHG emissions from all unit processes ahead of the operation of a subway station, which are classified into two categories: (I). GHG emissions from construction material and (II). those from construction machine. System boundary is defined as in Fig. 1. The post-construction GHGs impacts of the infrastructure, i.e. GHG emissions from operation and its impacts on commuters' behaviors are not within this scope.

Common practice in quantification of GHG emissions takes the equivalent CO₂ emissions as a benchmark, equivalent carbon dioxide emissions of gas *i* can be calculated through global warming potential of gas *i*

$$CO_2eq_i = M_i \times GWP_i \quad (1)$$

The quantification of GHGs focuses on the three major GHG sources, i.e. CO₂, CH₄ and NO_x. Global warming potentials are updated according to the latest IPCC report (IPCC, 2013) (see Table 2).

2.2. Modeling

2.2.1. Decomposition of the construction process of open-excavation subway station

Open-excavation method, characterized by high efficiency and

Table 1
Major differences between quota-based method and traditional method.

	Quota method	Traditional method
Element unit	Element process	Material/energy
Function	Estimation	accounting
Input data	Engineering quantities	Material/energy quantities
Functioning stage	Pre-construction stage	Post-construction

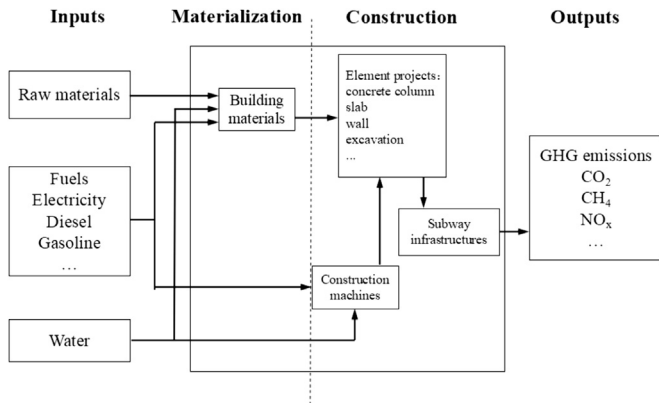


Fig. 1. System boundary.

Table 2

GWP of 4 green-house gas in 100 years (IPCC, 2013).

GHG	CO ₂	CH ₄	N ₂ O
GWP	1	28	265

low cost, is the most common method in the construction of subway stations in China. One typical form of open-excavation method is the consequent method, whose construction process is decomposed into three levels of sub projects. The secondary projects include station parts such as main structure of station, entrance and exit and ventilation. Construction of each part consists of sub-divisional projects like structures, earthwork, supporting work and waterproofing work that can be further decomposed into integrated processes like open-excavation earthwork, backfill and supporting.

2.2.2. Quota-based quantification model of GHG emissions

The quantification model of GHG emissions is established based on the 'Quota for the Construction of Metro Stations in Beijing' (Beijing Municipal Commission Housing and Rural-Urban Development, 2012a, b).

As mentioned above, the construction of subway stations can be decomposed into a set of element processes. Average consumption of material and machine shifts for unit quantity of each process is prescribed in this quota. Then, combining the GHG emissions factors of each type of investment involved in the process, GHG emissions for unit quantity of this element process can be calculated

$$C_m = \sum p_i C_{mat,i} + \sum q_j C_{mach,j} \quad (2)$$

where C_m is the GHG emissions of element process m . $C_{mat,i}$ and $C_{mach,j}$ are the GHG emissions factors of material i and machine j

respectively. p and q are the quantities of material i and machine j respectively.

$C_{mat,i}$ are adopted from Chinese Life Cycle Database (CLCD). CLCD is a local LCA database which includes over 600 LCA data sets of materials (IKE Environmental Technology Ltd.).

$C_{mach,j}$ can be traced down to the GHG emissions of each kind of fuel consumed in unit shift (8 h' working for one single machine).

$$C_{mach,j} = \sum r_{fi} C_{fi} \quad (3)$$

in which, r_{fi} is the consumption of fuel i in one shift, Kg. C_{fi} is the GHG emissions factor of unit consumption of fuel i . Similarly, a national quota prescribed the average consumption of each fossil fuel of certain machine in one shift (Ministry of Housing and Rural-Urban Development of the P.R. China/General Administration of Quality Supervision, Inspection and Quarantine of P.R. China, 2012a, b).

C_{fi} is calculated on the basis of the carbon-emissions factors of C_{ci} issued by IPCC, in combination with modifications that accommodates for incomplete combustion (Chinese National Development and Reform Commission, 2011)

$$C_{fi} = C_{ci} \times \eta_i \times Q_{net,i} \times 44/12 \quad (4)$$

where C_{ci} is the carbon-emissions factor of fuel i . η_i is the Carbon oxidation factor, taken from the Chinese standard 'Guidelines for the Preparation of GHG Inventories' (Chinese National Development and Reform Commission, 2011). $Q_{net,i}$ is the average net calorific power of fuel i , issued by Chinese standard 'General Principles for Calculation of Total Energy Consumption' (Chinese National Standardization Administration, 2008).

The other part of GHG emissions in construction comes from electricity energy that is dependent upon the composition of electricity utilization of a certain region. Seven regions are defined in Chinese standard 'Guidelines for the Preparation of GHG Inventories' (Chinese National Development and Reform Commission, 2011), and average GHG emissions factors of electricity in those regions are present in Table 3.

Table 4 gives an illustration of the breaking down of GHG emissions from one element process-the manufacturing and installation of concrete formwork, which is a part in the construction of concrete column.

Designers' behaviors have counterpart items in the quota. For instance, when they choose between the schemes of concrete column, they are actually choosing between a couple of element processes including the diameter of steel bars, precast concrete or cast-in-site concrete. These element processes, together with other element processes such as concrete formwork and concrete pumping, make up an integrated process as follows

Table 3

GHG emissions factors of electricity in different regions of China.

Region	Coverage area	GHG emissions factor kg CO ₂ /kw.h
North China	Beijing, Tianjin, Hebei, Shanxi, Shandong, West of Inner Mongolia	1.246
Northeast China	Liaoning, Jilin, Heilongjiang, East of inner Mongolia	1.096
East China	Shanghai, Jiangsu, Zhejiang, Anhui, Fujian	0.928
Central China	Henan, Hubei, Hunan, Jiangxi, Sichuan, Chongqing	0.801
Northwest China	Shaanxi, Gansu, Qinghai, Ningxia, Xinjiang	0.977
South China	Guangdong, Guangxi, Yunnan, Guizhou	0.714
Hainan	Hainan	0.917

Table 4

Breaking down of the GHG emissions from the element process of concrete formwork.

Type of emissions	Source of emission	Unit	Quantity	emission factor	Summation
Material	Wood slab	m ³	p_i	$C_{mat,i}$ (CO ₂ eq.kg/unit quantity)	$\sum(\text{CO}_2 \text{ eq.kg})$
	Steel support	kg	0.002	83.870	4.133
	Steel formwork	kg	0.492	3.778	
			0.696	3.027	
Machine shift	Gantry crane (Less than 20t)	Shift	q_j	$C_{mach,j}$ (CO ₂ eq.kg/unit quantity)	
Summation			0.012	35.383	1252.849

Tips: no consideration on the reuse of concrete formwork.

$$C_n = \sum C_m q_m \quad (5)$$

where q_m is quantity of the element project m . Taking the integrated process of cast-in-place concrete column as an example, Table 5 presents the decomposition of its GHG emissions.

Repeat the calculation in Table 5, GHG emissions of the whole station are obtained following the bottom-up route of Fig. 2.

$$C_i = \sum C_n \quad (6)$$

$$C = \sum C_i \quad (7)$$

where C_i, C_j are GHG emissions of the construction of the whole project, secondary project i and third level project j respectively.

The bottom-up feature of a quota-based GHG quantification model has the implication that the distribution of GHG emissions among the secondary or the third level projects can be easily obtained as a reference for the recognition of reduction potential.

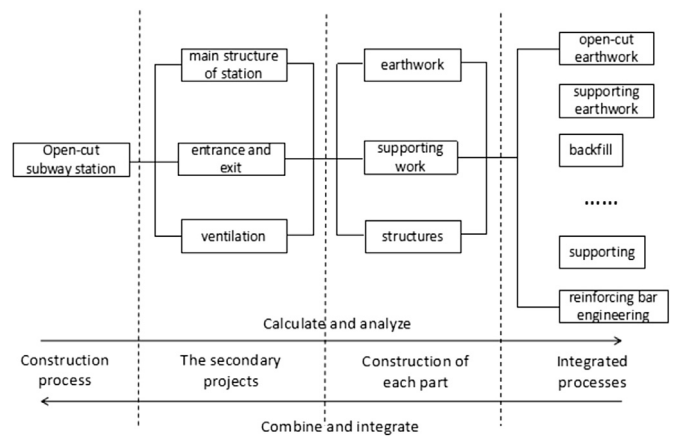
3. Case study

In this section, the proposed quota-based GHG quantification model is applied in the GHG emissions analysis of an open-excavation subway station of Beijing Subway during its construction stage.

Table 5The inventory of 1 m³ cast-in-place column.

Type of emissions	Source of emission	Unit	Quantity	emission factor	Summation
Material	Steel bar ($d < 10$ mm)	kg	p_i	$C_{mat,i}$ (CO ₂ eq.kg/unit quantity)	$\sum(\text{CO}_2 \text{ eq.kg})$
	Steel bar ($d < 10$ mm)	kg	25.500	3.182	1219.198
	Galvanized low-carbon steel wire	kg	234.000	3.182	
	Electrode for low-carbon steel	kg	1.155	3.974	
	Wood slab	kg	1.620	3.027	
	Steel support	m ³	0.014	83.870	
	Steel formwork	kg	3.630	3.778	
		kg	4.754	3.027	
	C30 Concrete ^a	m ³	1.020	347.643	
Construction machine			q_j	$C_{mach,j}$ (CO ₂ eq.kg/unit quantity)	$\sum(\text{CO}_2 \text{ eq.kg})$
	Concrete transportation vehicle	Shift	0.014	35.383	33.651
	Gantry crane (Less than 20t)	Shift	0.125	167.015	
	Low-speed winch	Shift	0.025	50.836	
	Steel binding machine	Shift	0.067	10.427	
	Steel cutting machine	Shift	0.023	25.910	
	Steel straightening machine	Shift	0.025	9.543	
	Circular sawing machine	Shift	0.001	19.384	
	Butt welder 75 kV A	Shift	0.02	98.581	
	AC welder	Shift	0.101	74.099	
Summation					1252.849

^a Grade C30 in Chinese Standard (Chinese National Development and Reform Commission, 2011), the 28-day compressive strength is 30Mpa.

**Fig. 2.** Decomposition of the construction of an open-excavation subway station.

3.1. Case description

Object of GHG emissions analysis in the case is a two-story island-platform station with two columns and three spans in the cross-section. Basic parameters of the station are presented in Table 6.

The main structure of this open-excavation station was constructed in a sequential method. The combination of bored pile and steel tube is used as slope supporting system. Three rows of steel tube were installed successively. Cross-section is illustrated as Fig. 3.

Table 6
Dimensional parameters of the station.

Width of platform	12.00 m	Depth for the top of track	16.23 m
Length of station	299.90 m	Width of standard section	21.10 m
Thickness of earth above top slab	3.50 m	Depth of bottom slab	17.86 m
Area of major building	13450.00m ²	Total area	21850.00m ²

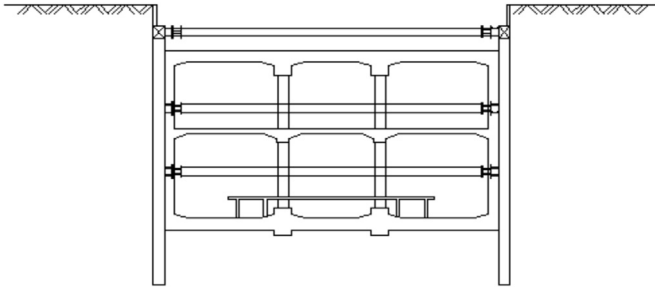


Fig. 3. Diagram for the cross-section of the case station.

There are six entrances, two of which are reserved for future construction. And the station is equipped with two low-open pavilions.

3.2. Result and analysis

Integrated projects involved in the construction of the investigated station are listed in Table 7. Using the quota-based GHG quantification model, GHG emissions factors of each integrated project can be obtained.

GHG emissions of each integrated project can be quantified through the inventory. A bottom-up integration of these integrated projects is conducted following the classification in Fig. 2, then we can obtain how GHG emissions distribute among sub-projects as illustrated in Table 8 and Fig. 4. As a result, total GHG emissions of this open-excavation station are 55075.279t, averaging 3.81t for unit area of station. The construction of main structure accounts for about two thirds of total GHG emissions, two times the volume of other affiliation projects combined (see Table 8).

As shown in Figs. 5 and 6, further analysis was made on distribution of GHG emissions among third-level projects in main structure for the reason that it is not only the largest GHG emissions

Table 7
GHG emissions factor of integrated projects.

Element projects involved	Unit	GHG emissions from building material (kg CO ₂)	GHG emissions from construction machine (kg CO ₂)	GHG emissions factor (Kg CO ₂ /unit)	Amounts
Bored pile (Mechanical drilling)	m	276.862	110.321	388.162	15069.381
Bored pile (Mechanical drilling, Intermediate columns)	m	398.840	115.589	515.592	2442.077
Spray concrete between columns	m ²	37.970	10.134	48.317	20207.989
Concrete loop girder	m ³	295.229	8.608	304.585	792.089
Concrete retaining wall	m ³	295.229	0.940	296.273	295.416
Non-prestressed reinforcement Bar (For bored piles)	t	3273.970	293.365	3569.339	2446.876
Glass fiber bar (Supporting pile of foundation)	t	3273.970	533.391	3811.004	4.257
Non-prestressed reinforcement Bar (Concrete beams)	t	3304.240	82.887	3388.777	95.050
Non-prestressed reinforcement Bar (Retaining wall)	t	3304.240	82.887	3388.777	35.450
Demolished reinforced concrete structure	m ³	1.200	50.266	53.069	295.416
General earthwork	m ³	0.000	1.097	1.155	147.603
Earthwork with supporting system	m ³	0.000	6.246	6.292	187373.022
Backfilling (General soil)	m ³	0.000	1.340	1.405	29351.383
Backfilling (Lime soil)	m ³	290.400	1.339	291.997	3951.106
Concrete cushion	m ³	244.140	2.290	246.712	262.728
Concrete bottom slab	m ³	441.563	0.942	442.578	471.309
Concrete side-wall	m ³	440.936	0.950	442.005	470.700
Concrete slab in-between (Concrete grade C40 in Chinese standard)	m ³	440.936	1.500	442.516	471.243
Concrete slab in-between (Concrete grade C45 in Chinese standard)	m ³	427.706	1.500	429.287	457.155
Concrete top slab (Concrete grade C40 in Chinese standard)	m ³	440.936	1.500	442.511	471.238
Concrete top slab (Concrete grade C45 in Chinese standard)	m ³	427.706	1.500	429.282	457.150
Concrete columns	m ³	575.020	1.510	576.676	614.112
Concrete beams	m ³	440.936	1.510	442.581	942.624
Concrete slabs on platform	m ³	440.936	2.850	444.014	472.838
Concrete walls (Under the platform)	m ³	440.936	28.180	469.642	500.130
Concrete of ventilation	m ³	438.774	4.540	444.138	472.971
Concrete stairs	m ³	107.147	4.026	111.308	118.534
Non-prestressed reinforcement bar (Major structure)	t	3304.240	82.887	3388.777	3608.768
Embedded iron	kg	3.288	0.290	3.590	3.823
Planting bars (Diameters 14 mm)	1	2.031	2.380	4.530	92.000

Table 8
GHG emissions of sub projects (t.CO₂).

	Main structure	Entrance	Emergency passageway	Ventilation	Summation
Support	11664.235	2352.240	1507.144	2105.722	17629.341
Earthwork	1738.184	253.481	146.984	258.262	2396.910
Structure	24602.781	5650.592	1370.001	3425.654	35049.028
Summation	38005.200	8256.313	3024.129	5789.637	55075.279

Table 9
GHG emissions from the earthwork in main structure.

Integrated process	GHG emissions from building material(t.CO ₂)	GHG emissions from construction machine (t.CO ₂)	Total amount (t.CO ₂)
Excavation using manpower	0.00	18.90	18.90
Supporting excavation	0.00	1006.23	1006.23
Backfill(Ordinary soil)	0.00	33.56	33.56
Backfill(Lime soil)	982.16	4.50	986.71

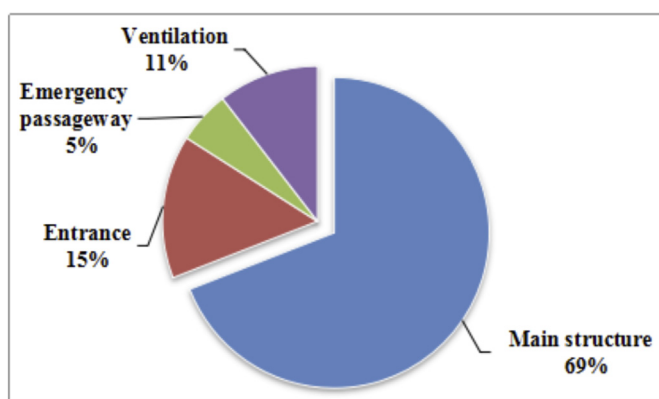


Fig. 4. Distribution of GHG emissions among secondary projects.

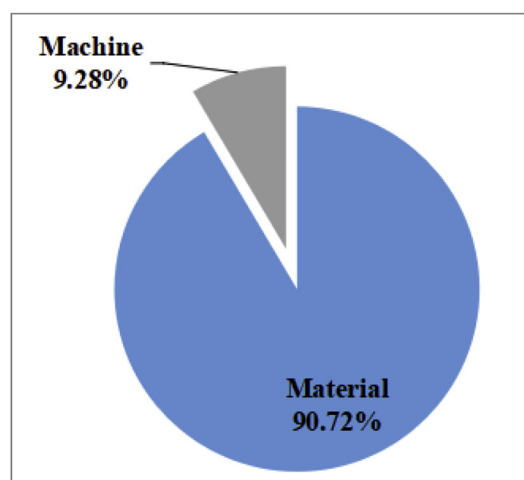


Fig. 6. Distribution of GHG emissions between two stages in the construction of main structure.

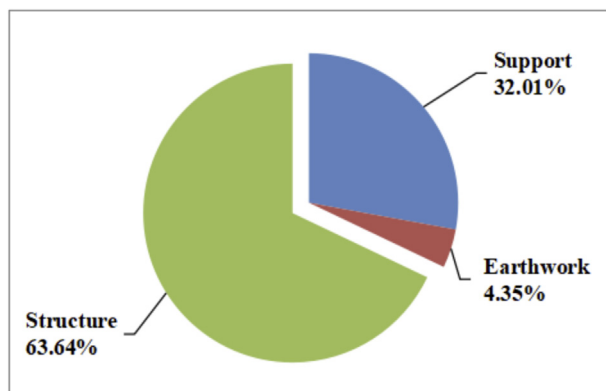


Fig. 5. Distribution of GHG emissions among third-level projects in main structure.

contributor but also more susceptible to design schemes, thus making it a more possible part for potential reduction of GHG emissions. Results show that over two thirds of its GHG emissions stem from the construction of structures, over 90% of which can be attributed to the embodied emissions of building materials in its process. This can be explained by the fact that construction of station structure involves extensive use of concrete and reinforcement bars, both are highly energy-intensive building materials.

Analysis of the integrated projects of station structures in Fig. 7 shows that approximately 60% of the GHG emissions from main structure can be assigned to the production and installation of

reinforcement bars, leaving concrete structures like concrete slab, concrete sidewall, concrete columns and concrete beams making up the rest 40%.

Similar conclusion was drawn for supporting systems of main structure. As shown in Fig. 8, GHG emissions of reinforcement bars

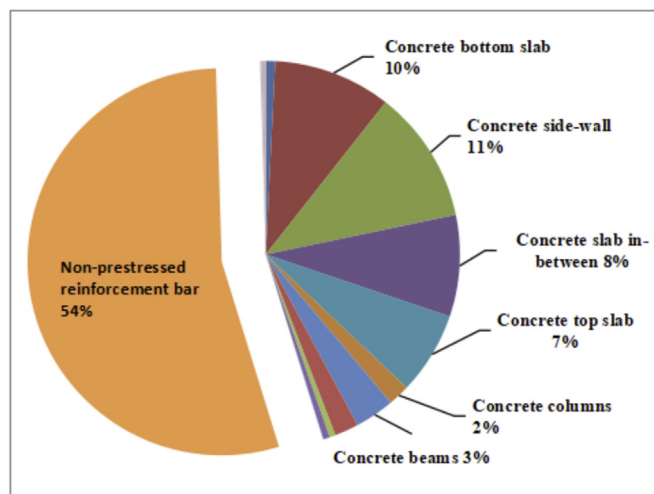


Fig. 7. GHG emissions of integrated projects of structures.

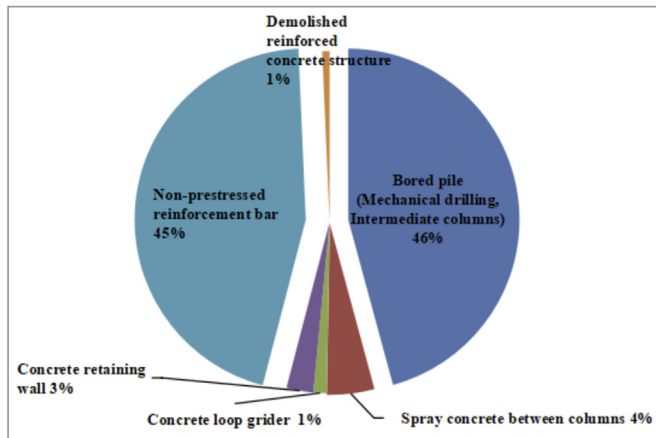


Fig. 8. GHG emissions of integrated projects of supporting system.

and concrete caisson piles both account for 45% of total emissions. It is noteworthy that 18% GHG emissions of supporting system are produced by construction machine, a much higher percentage than structures (1.67%). Integrated projects in supporting system, like caisson piles and shotconcrete, are highly mechanized, as the data in Table 5 suggests, machine-induced GHG emissions make up a considerable part of their total quantity.

Even more mechanized is the earthwork projects, machine-based GHG emissions of which account for 51.97% of the totality (see Table 9). Support-excavation is the most commonly adopted excavation method which uses reusable steel brace to assist excavation. Therefore, as a major integrated process in the case station, almost no building materials are consumed in this integrated process, and this helps to limit the whole GHG emissions of earthwork.

Excavation using manpower seems much cleaner than the supporting-excavation, however, construction of temporary dormitory and living facilities for these workers are not considered. With regard to backfill, unit GHG of lime soil backfill are 29 times higher than ordinary soil. Materialization and mixing of lime and clay produce large quantity of GHG emissions, nearly the same as the integrated projects of concrete structure.

For main structure as a whole, GHG emissions from construction machine account for 9.28% of total amount. This is a much smaller percentage than GHG emissions from building materials, but has to be given corresponding attention in terms of emissions reduction as its emissions are highly concentrated in both scopes of time and space. Unlike the production and transportation of building materials, which can be dissembled into several sub-processes and thus scattering its emissions over different locations, GHG emissions from construction machine are more localized and generated over a shorter period of time, making it a more pronounced part of the whole process than what the data suggests.

4. Influence of buried depth on GHG emissions

4.1. Identification of influencing factors

GHG emissions of an open-excavation station are correlated with the volume of projects that can vary greatly from different design schemes. There are four basic parameters that can determine the structural form of station and sizes of structural components, namely buried depth, station height, station width and station length. Station height is related to the number of station floors which is prescribed according to station type and geological

conditions. In the case of a certain cross-section form, quantity of the whole project increases linearly with station length. In addition, width of station is related to the width of platform, which is specified under certain volume of passenger flow. Hence investigations into these three parameters are of little importance.

In light of previous analysis, construction of main structure is the biggest contributor of total GHG emissions, also more variable with different design schemes. Therefore, GHG emissions of main structure under different buried depth are investigated in this section.

Buried depth of a typical open-excavation station lies between 2 m and 6 m, and the open-excavation method loses its economic superiority when buried depth exceeds 9.5 m (Song, 1994). In this study, buried depth of the case station is set to be 2 m, 2.5 m, 3 m, 3.5 m, 4 m, 4.5 m, 5 m, 5.5 m and 6 m, and GHG emissions from earthwork, supporting system, and structure of main structure are quantified respectively under these buried depth. To keep a single variable, other parameters of station dimension stay unchanged.

4.2. Influence of buried depth on earthwork

Earthwork of main structure can be divided into three parts: general excavation, supporting-excavation, and backfill. Provided that the depth of first steel-support remains invariable and that so do GHG emissions from general excavation, GHG emissions of both increase linearly with buried depth:

$$C_1 = C_{se} \times B \times L \times (H - h_0) \quad (8)$$

$$C_2 = C_b \times B \times L \times h_1 \quad (9)$$

where, C_1, C_2 are the GHG emissions from the construction of excavation and backfill respectively, B and L are the width and length of foundation pit respectively, H and h_0 are the depth of the pit and depth of general excavation, h_1 is the buried depth of the station. C_{se} and C_b are GHG emissions from integrated projects of supporting-excavation and backfill respectively.

For each 1 m increment of buried depth, GHG emissions from excavation increase 19.14 t, 4.25 t from backfill using ordinary soil, and 890.00 t from backfill when using lime soil.

4.3. Influence of buried depth on supporting system

In light of previous analysis, GHG emissions from caisson piles and its reinforcement bars account for 91% of that of supporting system, therefore investigation into its variation from different buried depth is necessary.

Lateral pressure from earth and water increase with the buried depth, exerting larger momentum and shear stress on caisson piles, thus demanding for caisson piles with larger diameter, reinforcement ratio, and embedded depth. Common pile diameters are 600 mm, 800 mm, 1000 mm and 1200 mm, and at the buried depth of 2 m, 2.5 m, 3 m, 3.5 m, 4 m, 4.5 m, 5 m, 5.5 m and 6 m, each of diameter is adopted. For each combination of pile diameter and buried depth, pile length and reinforcement ratio can be determined using the elastic-support method recommended by Chinese national code 'Technical specification for retaining and protection of building foundation excavation' (Ministry of Housing and Rural-Urban Development of the P.R. China, 2012a, b). As illustrated in Fig. 9, this method presumes that connection point of beams and piles are elastic, and passive earth pressure embedding range is also simplified as an array of elastic supports. Adopting the M-method, coefficient of subgrade reaction is assumed to change linearly with depth (Ministry of Housing and Rural-Urban Development of the P.R. China, 2012a, b).

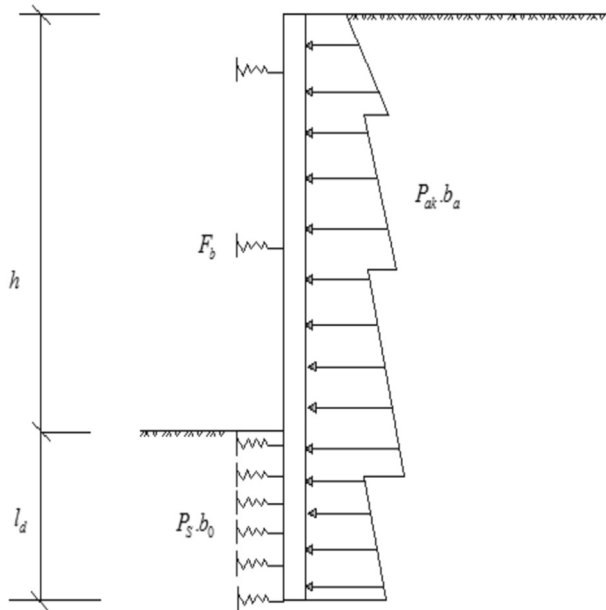


Fig. 9. Elastic design scheme of caisson pile.

Earth pressure that exerts on the outer and inner edges of caisson piles, defined as active and passive earth pressure of layer i , can be quantified as

$$p_{pi} = \sigma_p K_{pi} - 2c_i \sqrt{K_{pi}} \quad (10)$$

$$K_{a,i} = \tan^2 \left(45^\circ - \frac{\phi_i}{2} \right) \quad (11)$$

$$p_{pk} = \sigma_n K_{ni} + 2c_i \sqrt{K_{ni}} \quad (12)$$

$$K_{p,i} = \tan^2 \left(45^\circ + \frac{\phi_i}{2} \right) \quad (13)$$

where, p_{ai} , p_{pi} are positive and negative earth pressure of layer i respectively; σ_p , σ_n are the vertical pressure that exerts inside and outside piles respectively; K_{pi} , K_{ni} are the positive and passive coefficient of subgrade reaction of layer i ; c_i , ϕ_i are the cohesion and internal friction angle of layer i . According to Chinese standard 'Code for Design of Metro' (Ministry of Housing and Rural-Urban Development of the P.R. China/General Administration of Quality Supervision, Inspection and Quarantine of P.R. China, 2011), ground overload is set to be 20 kN in this study. The excavation of case study involved dewatering process, and the ground water level

dropped to 0.5 m below the bottom of foundation pit.

Physical properties of each soil layer are present in Table 10.

Following the routine, schemes of reinforcement design under each combination of pile diameter and buried can be determined. Fig. 10 shows how the GHG emissions of caisson pile varies with these two parameters. For each pile diameter, GHG emissions of piles increase almost linearly with buried depth, linear regression fits all four sets of data with deviation larger than 0.95, in which GHG emissions increase averagely 690.98 t, 447.50 t, 284.48 t and 131.67 t for each 1 m depth increment for the 600 mm, 800 mm, 1000 mm and 1200 mm diameter piles respectively. Larger buried depth means greater lateral earth pressure that requires higher ratio of reinforcement and larger embedded depth, consuming more reinforcement bars and concrete.

Also suggested in Fig. 10 is the range of applicability of pile diameters in terms of GHG emissions. Adopting the 600 mm-diameter or 800 mm-diameter piles emit less GHG emissions when buried depth are less than 3 m. However, GHG emissions from piles with smaller diameters are more susceptible to buried depth since larger quantity of reinforcement bars are required to compensate for the lack of concrete's load-bearing capacity. As a result, the 600 mm-diameter pile lose its superiority in terms of GHG emissions when buried depth exceeds 3.5 m, at buried depth smaller than which, little disparity exists between the 600 mm-diameter pile and 800 mm-diameter pile, the latter remains as an optimal choice until buried depth exceeds 5.5 m.

4.4. Influence on structures

Loads exerting on the structures of main structure can be

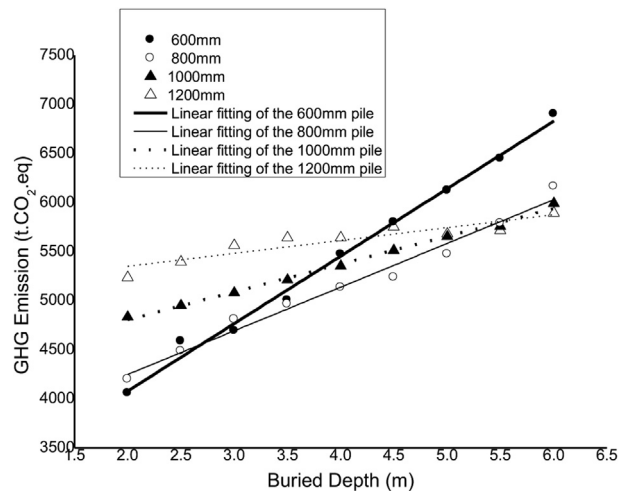


Fig. 10. GHG emissions from caisson piles with different diameters and buried depth.

Table 10

Geographical properties of each soil layers.

Soil type	Layer depth	Bulk density (Kg/m ³)	Buoyant density (Kg/m ³)	Cohesive strength (kN)	Internal friction angel	Friction On anchor (kN)	Cohesive strength beneath water (kN)	Internal friction angel beneath water
Miscellaneous fill	3.0	19.0	—	10.0	10.0	0.1	—	—
Clay	3.4	19.7	—	37.0	15.0	60.0	—	—
Silt	2.8	19.0	—	16.0	22.0	30.0	—	—
Pebble	2.8	22.0	—	0.0	45.0	220.0	—	—
Pebble	10.6	23.0	13.0	0.0	52.0	260.0	0.0	42.0
Strongly weathered rock	8.2	23.4	13.0	—	—	220.0	300.0	45.0
Moderately weathered rock	0.9	22.1	12.1	—	—	110.0	25.0	40.0

classified into eternal loads, variable loads and incidental loads (Ministry of Housing and Rural-Urban Development of the P.R. China/General Administration of Quality Supervision, Inspection and Quarantine of P.R. China/Ministry of Housing and Rural-Urban Development of the P.R. China and General Administration of Quality Supervision, 2013). Some of these loads, such as vertical and lateral earth pressure and buoyancy on bottom slab vary with buried depth, causing a change in the quantity of projects and thus a change in the GHG emissions from station structures. According to previous analysis, GHG emissions from concrete structures like top slabs, bottom slabs, inter-layer slabs, sidewall, columns, beams and their reinforcement bars account for over 95% of total, therefore, variation of GHG emissions from these parts against buried depth is investigated.

The case station adopts a frame-type, totaling 35 spans in the length dimension. A FEM model was established, which constructed the 7 spans in the middle.

Distribution of loads on the cross section of the frame is illustrated in Fig. 11. Loads from land surface, equipment and passengers adopt the values prescribed in Chinese National Code 'Code for Design of Metro' (Ministry of Housing and Rural-Urban Development of the P.R. China/General Administration of Quality Supervision, Inspection and Quarantine of P.R. China/Ministry of Housing and Rural-Urban Development of the P.R. China and General Administration of Quality Supervision, 2013). Structural frame and supporting system are joint together, and lateral earth pressure calculated in the previous part is adopted here.

As presented in Fig. 12, GHG emissions of station structures grow almost linearly with buried depth, increasing about 588.08t CO₂ for each 1 m increment of buried depth. This increase is almost exclusively the contribution of the GHG emissions of reinforcement bars as the predetermined size parameters for the majority of concrete structures meet the requirement of increasing buried depth.

Figs. 13–16 show the variations of GHG emissions of structural

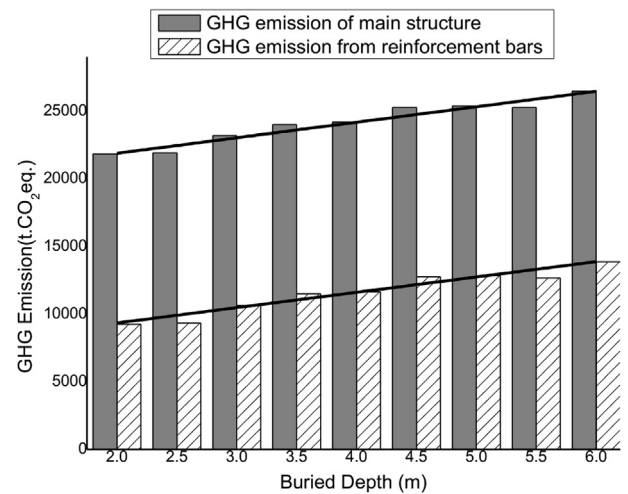


Fig. 12. GHG emissions of station structures under different buried depth.

components with buried depth. GHG emissions from both concrete and reinforcement bars of sidewalls and slabs do not change with buried depth which means the initial sizes and reinforcement ratio of those two components are capable of bearing loads at each depth. Conversely, initial sizes and reinforcement ratio of beams and columns cannot provide adequate bearing capacity as buried depth increases. Mass of reinforcement bars in 1 m³ concrete beams increases by 16.07 t for each increment of 1 m in buried depth. Original cross section of rectangle columns increases by 10%, 20% and 35% for the buried depth of 4 m (4.5 m), 5 m and 5.5 m (6 m).

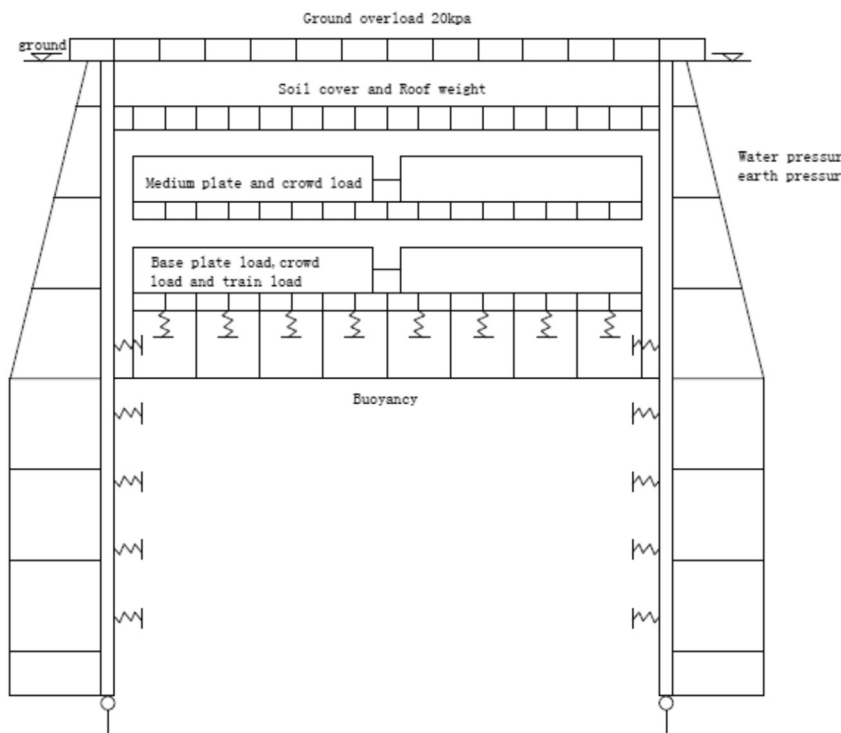


Fig. 11. Distribution of loads.

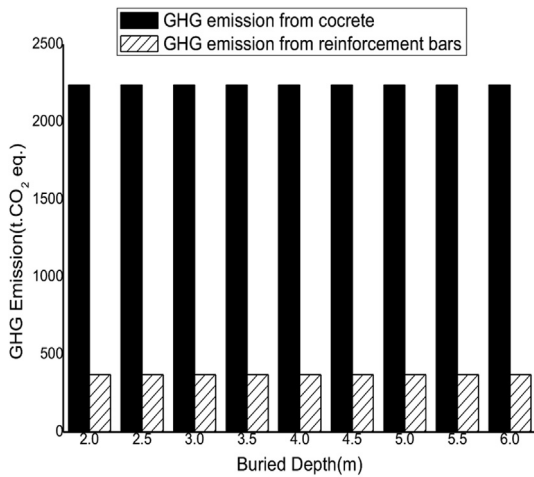


Fig. 13. GHG emissions from sidewall.

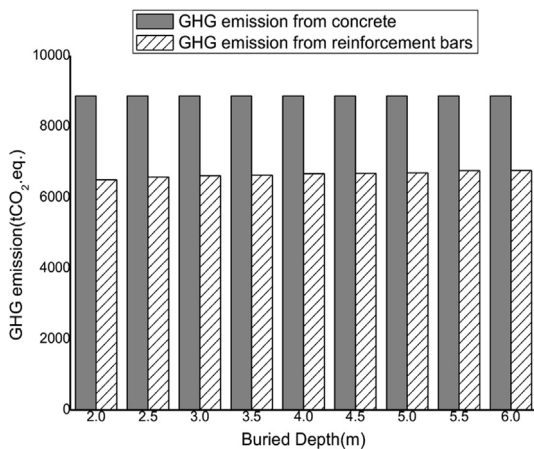


Fig. 14. GHG emissions from slabs.

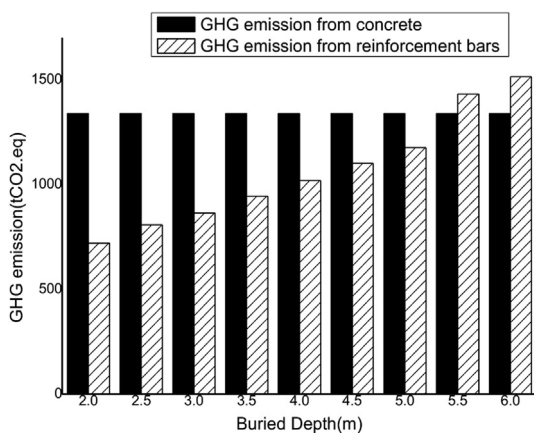


Fig. 15. GHG emissions from beams.

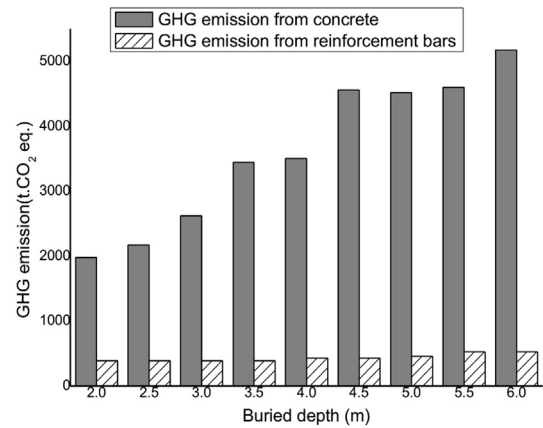


Fig. 16. GHG emissions from columns.

emissions of an open-excavation station are analyzed in this study, major conclusions are as follows:

1. 69% of the GHG emissions come from the construction of main structures, of which 95.65% are the contribution from the construction of structures and support. Only 4.35% of the total emissions in main structures are excavation related, but 51.97% of the emissions are machine-based. GHG emissions from construction machine are more localized and generated over a shorter period of time, making it a more pronounced part of the whole process than what the data suggests.
2. For station as a whole, embodied emissions from building materials account for 90.72% of totality, of which concrete and steel components are the major contributors. Therefore, emissions reduction schemes in the construction of subway stations could be laid out around these two GHG-intensive contributors. For example, Crossrail planned to utilize fly-ash concrete with replacement ratio higher than 50% in their efforts to reduce construction-related GHG emissions by 8% (Crossrail, 2014). On the other hand, the steel mould of concrete and steel-support in excavation can be reused.

Though the machine-based GHGs only account for 9.28% of the totality, it is also a source of emissions reduction. For example, hybrid construction equipment was utilized in Crossrail to reduce GHG emissions from this category (Crossrail, 2014).

3. A parameter analysis was made on the influence of buried depth on GHG emissions of a subway station. In general, it suggests an approximately linear relationship between buried depth and GHG emissions from main structure or its sub-projects, despite some nonlinearity exists because of the discontinuity in size variation of some components with buried depth. In addition, optimal diameters for caisson piles under each buried depth should be specified.

5.2. Uncertainty

The quota method is technically an estimating method that can be utilized in the design process to estimate the GHG emissions from different schemes. The uncertainty in those consumption data are within acceptable range for the reason that.

1. Those data are statistically derived from thousands of constructors' input on an element process that has been

5. Discussion

5.1. Conclusions and discussion

This paper proposes a quota-based GHG quantification model for the construction of subway stations. Using this model, GHG

ameliorating for years and the investments on which are supposed to be stabilized;

2. Those data serves as a benchmark that has implications for safety and quality control, investments significantly below the benchmark might have safety and quality issues. On the other hand, a bidding proposal will lose competitiveness when its investments are significantly higher than the benchmark.

Together with localized GHG intensity factors, these data can provide a reliable reference to the GHG emissions of a design scheme.

5.3. Outlook

This paper investigated on the GHG emissions from the construction of subway station projects. To complete a LCA of the infrastructures, emissions from maintenance and end-of-life activities need to be supplemented. GHG emissions from these activities were less investigated for lack of reliable data and uniform work content, and the quota method based on the quotas for maintenance and dismantle (regional quotas, like 'Quota for maintenance and dismantle of building in Beijing' (Beijing Municipal Commission Housing and Rural-Urban Development, 2012a, b)) have the potential to fill the gap by its reliable consumption data of the standardized maintenance and dismantle behaviors.

The quota-based method in this paper can be utilized to assist scheme selection in the design stage. In the even earlier planning stage, only some of the basic parameters (i.e. buried depth, station size and section length) of a UTR line can be confirmed. As illustrated in this paper, changes in buried depth would significantly affect the GHG emissions from an open-cut station and exhibits a linear relationship with the GHG emissions from most sub-projects. Therefore, an estimation of GHG emissions in the planning stage of a UTR line can be achieved by deriving some rougher GHG intensity indicators (such as GHG emissions per station area or per section length) which should be a function of station/section geometry, geological and load conditions, etc. In the context of quota-based method, these indicators can be regarded as GHG intensity factors of more integrated sub-projects, and the derivation of them needs ample quantification of GHG emissions from existing infrastructures, which would benefit the feasibility study greatly.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at <https://doi.org/10.1016/j.jclepro.2018.07.067>.

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