Cite this article
Mohammadi D, Shahriar K, Moarefvand P and Farrokh E
Discussion of cutterhead opening design for earth pressure balance machines (EPBMs).
Proceedings of the Institution of Civil Engineers – Geotechnical Engineering,
https://doi.org/10.1680/jgeen.22.00254

Research Article
Paper 2200254
Received 29/12/2022;
Accepted 09/05/2023;
First published online 06/06/2023

Geotechnical Engineering

ICE Publishing

Discussion of cutterhead opening design for earth pressure balance machines (EPBMs)

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Among the various parts of earth pressure balance (EPB) cutterheads, the opening distribution on the cutterhead face plays a crucial role in the success of tunnelling projects in soft ground. The amount of published literature on this subject is very limited, however; as a result, tunnel-boring machine (TBM) manufacturers have developed different cutterheads for soft ground, with varied opening distribution based on their experience. In this paper, as a first step, the results of field studies on cutterheads' opening design for soft ground are expressed. The paper then mainly focuses on numerical studies using the discrete-element method (DEM) to evaluate the adaptability of the EPB system and cohesive and non-cohesive soils' fluidity by changing the opening distribution on the cutterhead. Finally, the optimum opening ratio and its distribution for different soils – by considering the important parameters of the value of the thrust force, cutterhead torque and soil fluidity condition – are proposed based on the analysis results from DEM. Furthermore, the flow characteristics of soil particles inside the EPB chamber are obtained through examination of the velocity field. In addition, practical aspects for further application in the TBM industry are discussed through the consideration of field studies and a real example.

Keywords: cutterhead opening/design/discrete-element modelling/tunnels & tunnelling

1. Introduction

The last two decades of the twenty-first century have seen spectacular advances in the mechanised tunnelling industry for both soft ground and hard rock tunnel-boring machine (TBM) applications. There are various types of TBMs for tunnelling in nearly all different geological conditions ranging from soft soils to hard rocks, and machines ranging in size from under 2 to around 17.5 m in diameter. Past world records in tunnelling progress speed in the last few decades show that these machines have become very efficient and streamlined. Despite these developments, many design issues still require more attention. TBM manufacturers' design philosophies for earth pressure balance (EPB) cutterheads in soft ground are quite different; such cutterheads have unique design features and there is no one ultimate design process. For example, the manufacturer Herrenknecht has designed different soft ground cutterheads for the grand Paris express project in France. Figure 1 shows ten and three different cutterheads, respectively, that have been utilised in the southern lines 15 and 14 of this mega project, which is currently under construction. As can be seen, the centre opening arrangements are different in these cutterheads.

Many advances in cutterhead design are the result of lessons learned from the successes and failures of the technologies in a variety of geologies (Elbaz *et al*., 2018; Grothen, 2015; Warren *et al*., 2018). It is clear that cutterhead design is very much governed by practical aspects of mechanical engineering and has to be in very close cooperation with a TBM manufacturer, but the design of a new cutterhead and its mechanical aspects are not the focus of this paper. Contrary to rock TBMs, soft ground TBM cutterhead design is a new science. It is rather difficult to capture the complex interaction between the pressurised shield drive and the ground (Newman *et al*., 2016; Wu *et al*., 2013). The EPB cutterhead design method has been driven by: (*a*) iterative design based on empirical method; (*b*) analytical design; (*c*) laboratory tests; and (*d*) numerical simulations. Research projects that have been completed recently or are underway on cutterhead design for soft ground machines are demonstrated in Table 1. By way of different research studies, Wu *et al*. (2013) measured the performance parameters indicating the stability of the excavation face, the soil discharge rate, cutterhead system torque and cutter wear by running the discrete-element method (DEM) code in PFC^{3D}. Dang (2018) developed a model based on the

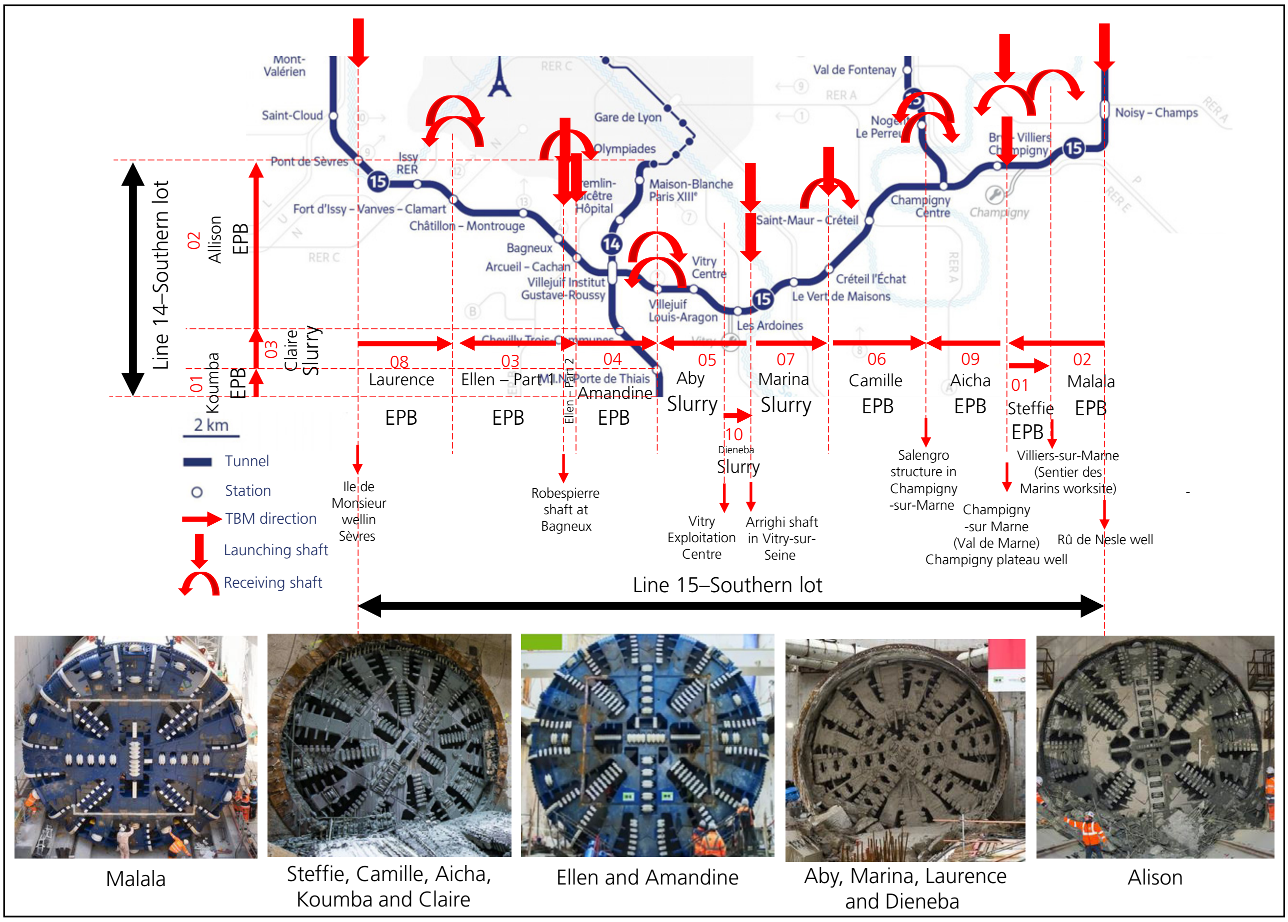


Figure 1. Herrenknecht's cutterheads used in southern lines 15 and 14 of grand Paris express project, France

Table 1. Soft ground cutterhead design methods and researchers

Researcher	Research centre	Analysis and design method
Reilly (1999)	Land transport authority, Singapore	Conventional model
Maynar and Rodriguez (2005)	Coruña University, Spain	Numerical model
Burger (2011)	Herrenknecht Co., Germany	Job site experience
Shi *et al.* (2011)	Zhejiang University, China	Mathematical and laboratory model
Mongillo and Alsaleh (2011)	Caterpillar Corp., Canada	Numerical model
Wang *et al.* (2012)	Zhejiang University, China	Mathematical and laboratory model
Wu *et al.* (2013)	Dalian Jiaotong University, China	Numerical model
Dobashi *et al.* (2013)	Metropolitan Expressway Co., Japan	Numerical model
Guo *et al.* (2014)	Tianjin University, China	Numerical model
Wu *et al.* (2014)	Dalian Jiaotong University, China	Numerical model
Grothen (2015)	Robbins Co., USA	Job site experience
Godinez *et al.* (2015)	Colorado School of Mines, USA	Mathematical model
Cheng *et al.* (2016)	Department of Underground Engineering, China	Job site experience
Li *et al.* (2017)	Beijing Jiaotong University, China	Job site experience
Zhou and Zhai (2018)	Chongqing University, China	Mathematical model
Dang (2018)	Ruhr University Bochum, Germany	Numerical model
Qu *et al.* (2019)	Central South University, China	Numerical model
Zhu *et al.* (2020)	Tongji University, China	Numerical model
Hu *et al.* (2020)	Southwest Jiaotong University, China and Colorado School of Mines, USA	Numerical model
Park *et al.* (2021)	University of Science & Technology (UST), Korea	Numerical model
Rasekh (2022)	R&D section of Tunnel Saz Machine Company, Iran	Numerical model

finite-element method to simulate the excavation of a tunnel using an EPB shield. Zhu *et al*. (2020) assessed the adaptability of the soil chamber system of an EPB machine to be used in a sandy pebble stratum by DEM modelling. Rasekh (2022) developed a DEM model of an EPB cutterhead to evaluate cutterhead wear and soil particle transport in the chamber and screw conveyor.

In this paper, unknown and seldom discussed topics of EPB cutterhead design in soft ground will be considered. The main purpose of this study is to simulate numerically the existing EPB cutterheads used in various tunnelling projects to assess their performance when the soil properties are varied. The results will be used to determine the best cutterhead type and its opening arrangement based on the grain size distribution curve, geotechnical parameters and field studies.

2. Opening distribution on cutterhead face

2.1 A brief overview of field studies

Soft ground cutterhead structure includes opening areas (light sections, Figure 2(a)) and closing areas (dark sections, Figure 2(a)), and the arrangements of these areas determine the cutterhead type. The opening–closing arrangements on the

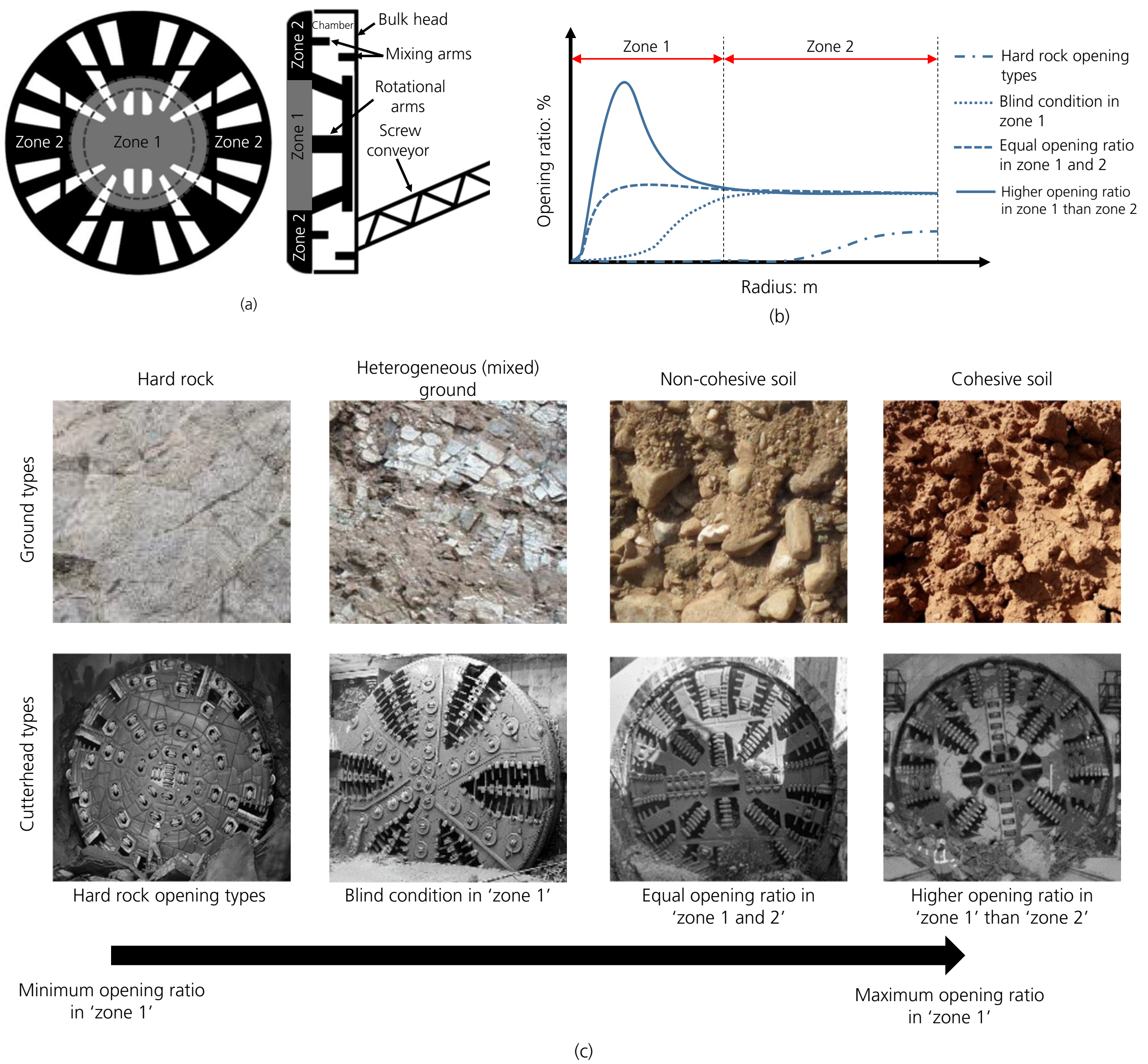
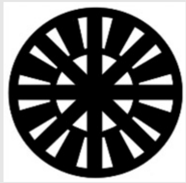
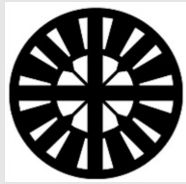


Figure 2. (a) Cutterhead divided into two zones in face and section; (b) opening ratio–radius curve with possible arrangements; and (c) proposed cutterheads for different ground types

Table 2. Different opening distribution in zones 1 and 2 based on different ground types for EPB cutterheads

Ground type	Hard rock	Heterogeneous and mixed	Non-cohesive	Cohesive soils
Opening area percentage in zones 1 and 2	(Zone 1) = zero, blind condition, (zone 2) = semi-blind	(Zone 1) = zero, blind condition, (zone 2) = constant	(Zone 1) = (zone 2)	(Zone 1) > (zone 2)
An example for cutterhead scheme in graphical shape				

cutterhead face (i.e. opening ratio and its distribution) are represented by an 'opening ratio–radius curve', see Figure 2(b). The rotational arms divide the space in the chamber into two zones based on Figure 2(a). 'Zone 1' is the area between the centre of the cutterhead–chamber and rotational arms, and 'zone 2' encompasses the rest of the areas between the rotational arms and the circumference area. Figures 2(b) and 2 (c) show the opening distribution curve of the soft ground EPB cutterheads in zones 1 and 2 in different ground types. Based on Table 2 and Figures 2(b) and 2(c), the opening distribution in zone 1 is divided into three different patterns for soft ground. Generally, the opening area in zone 1 increases from hard rock to cohesive soils. The opening distribution pattern in zone 2 has a constant percentage on the cutterhead according to Figures 2(b) and 2(c). The opening percentage of zone 2 in cohesive soils is usually higher than that in non-cohesive soils.

2.2 Problem statement

A comparison was made among various strategies of EPB cutterhead design adopted by European, American and Japanese TBM manufacturers (e.g. Herrenknecht Corp. in Germany, Robbins Corp. in USA, Wirth-CREG in Germany-China, NFM-NHI in France–China, Mitsubishi Heavy Industries Ltd in Japan, Kawasaki Heavy Industries Ltd in Japan, Lovat (Lovsuns) in Canada and Hitachi Zosen Corp. in Japan) used in different tunnelling projects. Based on the monitored data of various EPB machines through soft ground in different tunnelling projects around the world, it is better that the opening area in zone 1 increases than zone 2 from non-cohesive soils to cohesive soils. There are good reasons behind this statement, as follows: (*a*) a low linear velocity in zone 1 and (*b*) the confinement condition of excavated material in the chamber space around the rotational arms in the EPB chamber in zone 1. The problem statement is to optimise the earth pressure balance machine (EPBM) performance parameters by considering the cutterhead opening configuration, arrangements and ratio when a cutterhead is excavating in similar cases, in terms of soil properties, such as non-cohesive and cohesive soils, the values of conditioning parameters and face pressure. In this regard, to avoid uncertainty and to generate similar ground conditions for different cutterhead schemes, numerical modelling is employed here. In the numerical modelling phase, a partial flow code as a discrete-element framework is employed to assess the optimum cutterhead opening. Output parameters include the optimum opening ratio and its distribution considering the related operational parameters of the cutterhead in various ground conditions. These parameters are obtained through a comparative study of the results of experimental and numerical models. In other words, the best opening arrangement parameters are defined when thrust force, cutterhead torque and geo-hazards are at their minimum levels and penetration rate is at its maximum value. For this purpose, two different Herrenknecht cutterheads with different opening shape and ratio in zone 1 and the same one in zone 2 are adopted for the numerical modelling of excavation in both typical non-cohesive and cohesive alluvium of Tehran, on behalf of Tehran Metro Projects in Iran. The design process of the cutterhead opening for excavating through Tehran alluvium is summarised in Figure 3.

3. Discrete-element model for evaluation of EPB cutterheads

The nature of EPB process modelling is large deformation of particle soil with a freestyle mesh. The finite-element or finite-difference methods are not suitable for simulating tunnel excavation using an EPB shield because they are based on small-strain theory and continuum mechanics. The discrete-element method (DEM), also called the distinct-element method, is any of a family of numerical methods for computing the motion and effect of a large number of small particles, which is appropriate for large deformation problems. The DEM is a numerical model that is capable of handling particles of any shape and was developed by Cundall in 1971 and 1974 (Cundall and Strack, 1979). A DEM simulation is started by first generating a model, which results in spatially orienting all particles and assigning an initial velocity. The forces that act on each particle are computed from the initial data and the relevant physical laws and contact models (Cundall and Strack, 1979). The fundamental assumption of the method is that the material consists of separate, discrete particles. These particles may have different shapes and properties that influence inter-particle contact. The friction, contact plasticity, gravity and attractive potentials may have to be considered in macroscopic simulations in DEM. EDEM is a powerful DEM commercial software released in 2002, which has been widely used in fields such as mining, agriculture and machinery industries (DEM Solutions, 2022).

3.1 Structural element model (cutterhead and EPB system model)

The three-dimensional geometry of cutterhead, soil chamber, shield and screw conveyor system as an EPB system were built with a full-scale model (1 : 1) using Solidworks software as shown in three dimensions, front and side view in Figure 4. The diameter and width of the cutterhead is 9330 mm and 550 mm, respectively. The chamber structure is a cylinder with a height of 1036 mm, and an external and internal diameter of 9330 mm and 9210 mm, respectively. The soil chamber structure includes mixing arms (four fixed mixing arms on the bulkhead and four rotational mixing arms behind the cutterhead), rotational arms (eight rotational arms with a diameter of 508 mm) and a screw conveyor (see side view of Figure 4). The screw conveyor with installation angle of 23° includes shaft, screw blades and conveyor housing such that the screw blades are arranged with a pitch of 630 mm and a diameter of 1000 mm. The different kinds of cutting tools adopted, which are arranged on the cutterhead face, are described in Table 3.

As mentioned in the problem statement (see Section 2.2), two different Herrenknecht cutterheads with different central opening shape and ratio are adopted for the numerical modelling based on Figure 5. Cutterhead no. 2 has a higher opening ratio in the central area than cutterhead no. 1 (see the opening ratio–radius curve in Figure 5). The cutting tools and chamber were considered similar for both cutterheads; additional properties are presented in Table 4. A central cutting tool known as the 'nose' is installed 442 mm ahead of the cutterhead surface, with a different shape for each cutterhead to improve the stirring and cutting process of the soil mass in the central zone of the cutterhead.

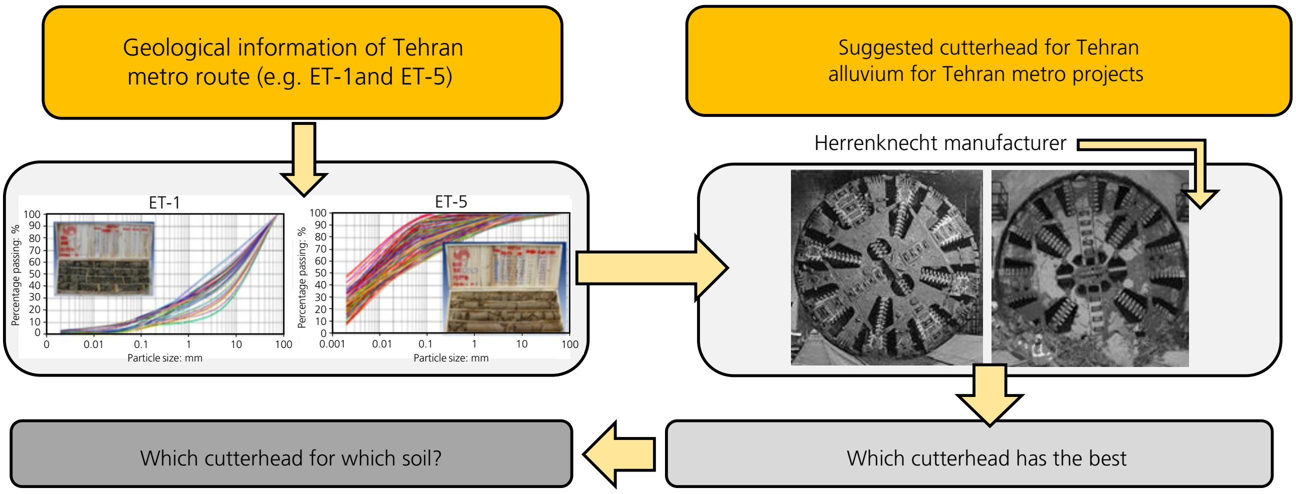


Figure 3. Design process of cutterhead opening through Tehran alluvium for numerical simulation

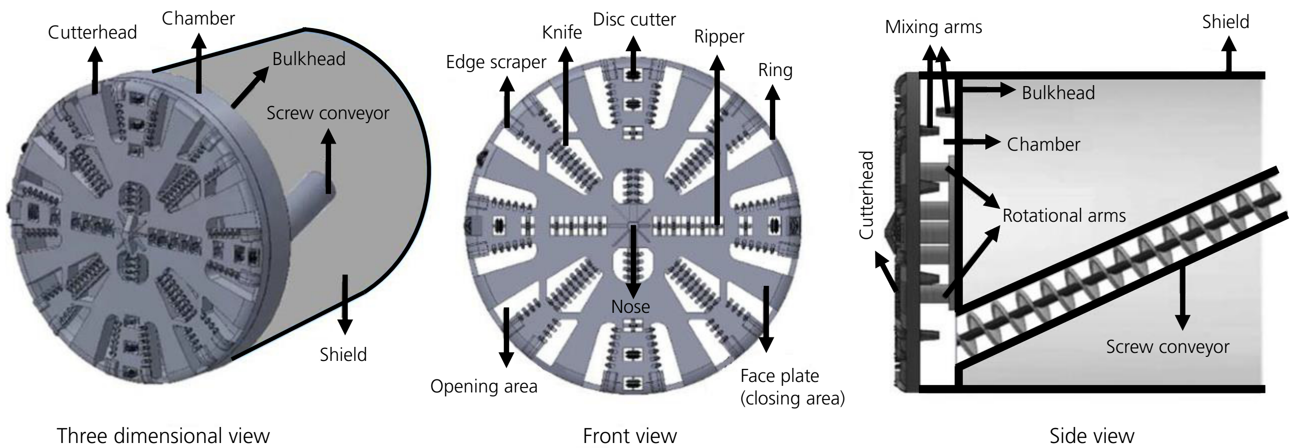
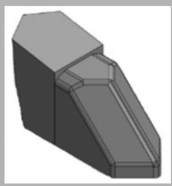
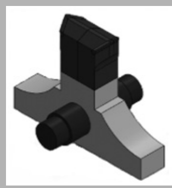
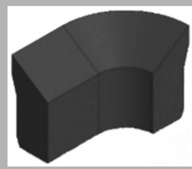


Figure 4. Three-dimensional, front and side views of EPB system in numerical model

Table 3. Cutting tools' geometry and properties for DEM simulation

Cutting tools	Knife 	Ripper 	Disc cutter (double-edged) 	Scraper (edge type) 
Size (width × length × height)/size (diameter × edge spacing)	100 × 280 × 150 mm	100 × 280 × 175 mm	432 mm (17 inch) × 100 mm	165 × 181 × 140 mm

The steel material was assigned to the cutterhead, cutting tools, chamber structure, screw conveyor and shield (see Table 5). Also, the contact parameters of the soil particle–TBM structure is considered in Table 5. The Hertz–Mindlin model is a soft-sphere model, which is used to calculate the particle–particle or particle–wall contact. In both cases the calculations are similar; however, when the particle–wall contact is calculated, the particle radius and mass are considered as equivalent amounts. In this model, the normal force component is based on Hertzian contact theory. The restitution coefficient, static friction coefficient and rolling friction coefficient are the input parameters for this model to calculate the tangential force, normal force and damping. Furthermore, Hertz–Mindlin with JKR (Johnson–Kendall–Roberts) is a contact model that allows users to represent the cohesive nature of fine and moist materials. This model was originally implemented to allow the simulation of Van der Waals forces, which influence the flow behaviour of fine, dry powders. This model may also be used to recreate the influence that moisture content has on the bulk flow of larger-scale materials.

3.2 Defining the particle element model (soil model)

The soil mass for excavating the EPBM should possess high plasticity and fluidity, low abrasiveness, adhesion and permeability, as well as appropriate compressibility (Zhu *et al.*, 2020). As regards the DEM simulation, the most vital activity is the assignment of a reliable DEM model of the soils. It was impossible to define directly the input particle parameters to the DEM model. Therefore, these parameters are estimated using back-analysis from the direct shear test results (EFNARC, 2005). Two typical non-cohesive and cohesive soils of Tehran alluvium in Tehran metro projects were selected to assign the DEM simulation; the soil type is illustrated in Table 6. Three-dimensional direct shear tests based on ASTM D 3080 (ASTM, 2011) were developed to characterise the soil particle parameters and their interactions in the DEM model to verify the geotechnical parameters. The direct shear test was simulated by soil particles and box geometries based on Figure 6(a).

The servo control system controlled the shear displacement rate and shear strain under three different normal loads. The

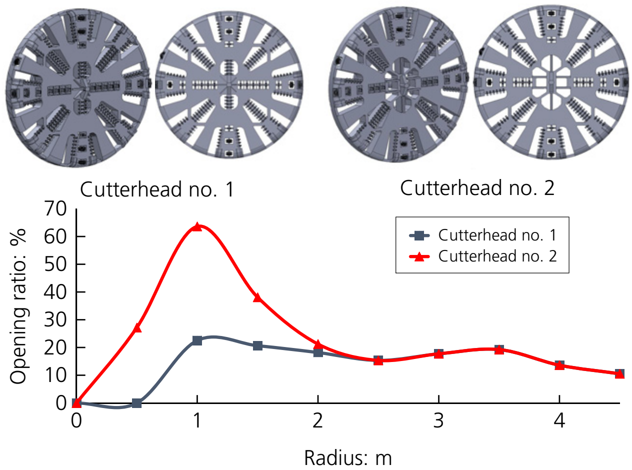


Figure 5. Opening ratio–radius curve for cutterheads no. 1 and no. 2

shear force and its corresponding shear displacement were monitored from the test box through the shear direction in the simulation to calculate the shear stress (Figures 6(b) and 6(c)). While the contact parameters of particles material are calibrated based on Table 7, with those parameters adopted, the direct shear test through DEM simulation is consistent with the results of direct shear tests in the laboratory based on the Mohr–Coulomb failure criteria and linear regression in Figure 7. The cohesion and internal friction angle calculated from the numerical model were about 4.8 kPa and 35.5°, respectively, for ET-1 soil type and 42 kPa and 25° for ET-5 soil type (compare with Table 6).

Given the large number of soil particles and TBM elements as structural elements used in the DEM models, as well as the dynamic interaction between structural elements and soil particles, the computational cost and run time were a major concern in this academic study. In order to improve computational performance, the particle sizes in the DEM simulation were magnified eight times. The capacity of the cutterhead and the screw conveyor were considered in determining the magnification factor. In addition, since it is difficult to interpolate all

Table 4. Cutterhead properties for two Herrenknecht cutterheads adopted for numerical model

Cutterhead	Diameter: mm	Max. opening ratio: % in central area (zone 1)	Opening ratio: % in rest area (zone 2)	Face shape	Opening ratio–radius curve type
No. 1	9330	63	10–20	Flat face and curve corner	Equal opening ratio in zone 1 and 2
No. 2	9330	22	10–20	Flat face and curve corner	Higher opening ratio in zone 1 than zone 2

Table 5. Material parameters for TBM structure and contact parameters of soil particle–TBM structure

Material parameters			Contact parameters of particle-TBM structure			
Density, ρ_s: kN/m^3	G, shear modulus: MN/m^2	Poisson's ratio, ν_s	Contact model[a]	Restitution coefficient, e[b]	Static friction coefficient, μ_s[b]	Rolling friction coefficient, μ_r[b]
7800	7×10^4	0.3	Hertz–Mindlin	0.25	0.7	0.001

[a]Contact model of soil particle–TBM structure adopts Hertz–Mindlin (Hu, 2010)
[b]Contact parameters of soil particle–TBM structure are derived from the literature (Ma, 2016)

Table 6. Particle parameters of Tehran alluvium along Tehran metro tunnel projects (P.O.R. Consulting Co., 2009)

Soil type	Soil type according to USCS standard	Material behaviour	Elastic modulus: MN/m^2	Cohesion: kN/m^2	Friction angle: degrees	Shear modulus, G: MN/m^2	Poisson's ratio	Unit weight: kN/m^2
ET-1	GW and SW	Non-cohesive	80	5	35	30	0.35	21
ET-5	ML and CL	Cohesive	35	40	26	13	0.35	21

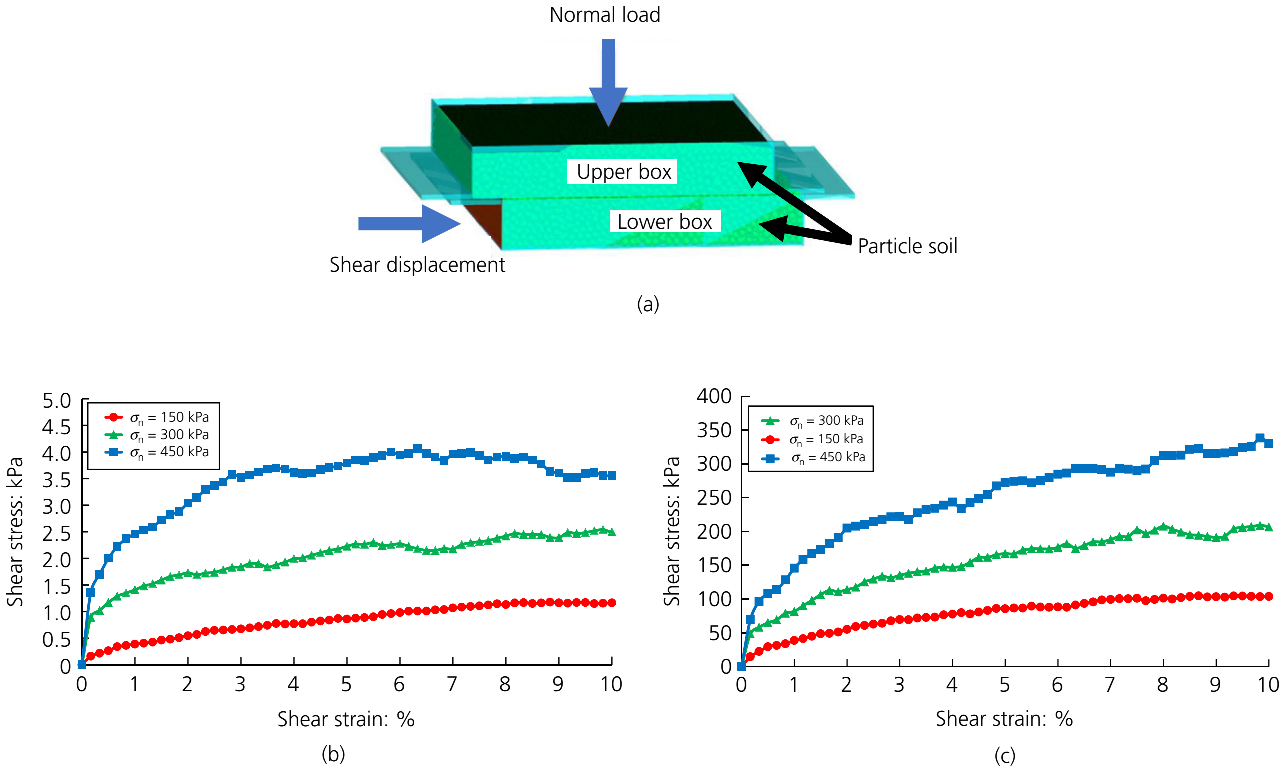


Figure 6. (a) Direct shear test modelled by DEM. (b) Shear test numerical results for (b) ET-1 soil and (c) ET-5 soil under three normal stress values

Table 7. Calibrated contact parameters of Tehran alluvium along Tehran metro tunnel projects

Soil type	Particle shape	Contact model	Restitution coefficient, *e*	Static friction coefficient, μ_s	Rolling friction coefficient, μ_r	Surface energy, *k*: J/m^2
ET-1	Single sphere	Hertz–Mindlin	0.200	0.700	0.10	3.75
ET-5	Single sphere	Hertz–Mindlin with JKR	0.015	0.500	0.55	100

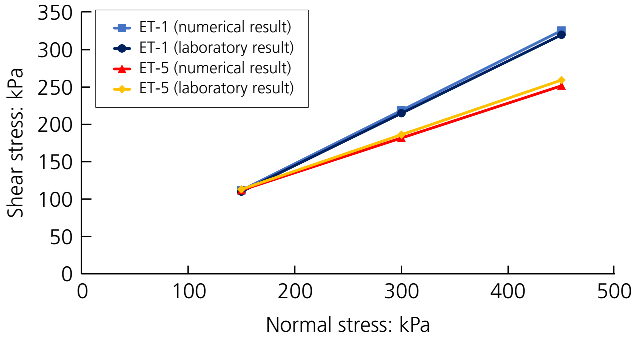


Figure 7. Comparison of laboratory and numerical simulation results based on the Mohr–Coulomb failure criteria

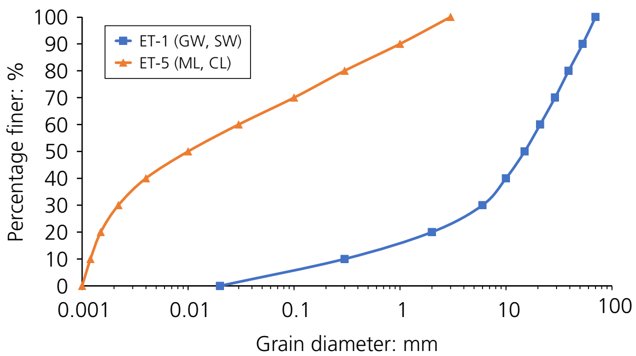


Figure 8. Particle size distribution curves for non-cohesive and cohesive soil particles (P.O.R. Consulting Co., 2009)

particle sizes, only a few representative sizes have been selected according to the particle size distribution curves in Figure 8, but the overall grading has not changed. The spherical soil particles for ET-1 soil with diameters of 168 mm, 232 mm and 312 mm constitute 60.50%, 30.80% and 8.70% and for ET-5 soil with diameters of 8 mm, 2 mm and 1 mm constitute 91.90%, 4.55% and 3.55% of the total mass randomly arranged, respectively.

In order to define the parameters of conditioned soil in the chamber system and screw conveyor in DEM, a series of slump tests was established in DEM models to assess the flow behaviour. Based on the findings from field studies, the foam expansion ratio (FER), foam injection ratio (FIR) and foam concentration (C_f), respectively, was found to be approximately 2.5, 50% and 1.2%. The slump cone test was enlarged eight times with a top diameter of 800 mm, bottom diameter of

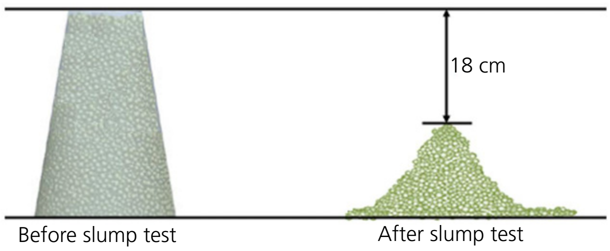


Figure 9. Simulated slump test for conditioned soil to define the soil conditioned parameters

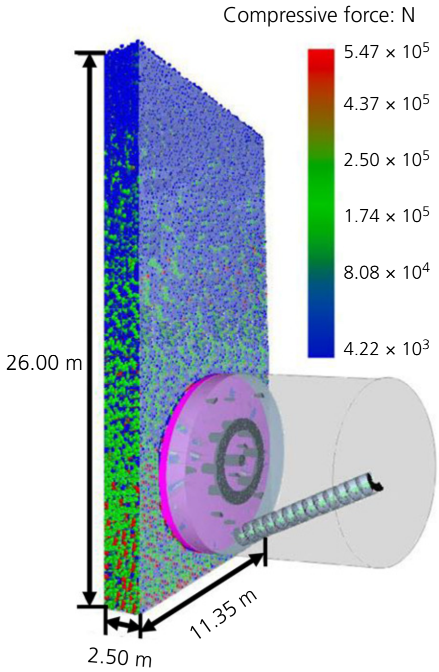


Figure 10. Assembled 3D EDEM model

1600 mm and height of 2400 mm. As shown in Figure 9, the measured slump magnitude was about 180 mm.

3.3 Assembly modelling, validation and collaboration

The DEM simulation model is assembled with a structural element model (cutterhead and EPB system model) and the particle element model (soil model) based on Figure 10. Five wall geometries are placed in the form of a soil box to be filled with spherical soil particle elements as the ground model. The soil box wall in front of the cutterhead and EPB system is 11.35 m long, 2.5 m wide and 26 m high; the wall-related parameters are defined with the soil particle parameters. The bottom, rear and front sides of the soil box in EDEM are constrained with rigid walls, which do not allow the soil particles to escape from the soil box. However, a periodic boundary condition is assigned to the left and right boundaries of the soil box, which means that the boundary condition is just an infinite dimension in the transverse direction equivalently to remove the boundary conditions. It allows the escaped soil particles to enter the soil box from the other side immediately. The front wall was created with a hole of the same diameter as the TBM. The soil particles' surface-normal force is generated according to the sum of compressive force in Figure 10, which increases with the depth of the tunnel (the tunnel overburden depth is 15 m). In the simulation, the entire TBM geometry was moved into the hole to excavate soil at a specific speed; the cutterhead and screw conveyor were also rotated at a specific speed. The operation parameters are considered in Table 8. Excavation was simulated for 180 s.

Table 8. Operational parameters for TBM for running in DEM (SELI Co., 2015)

Advance speed: mm/min	Cutterhead speed: r/min	Screw conveyor speed: r/min	Chamber pressure: bar
33	1.1	4.5	0.9

In order to validate and calibrate the assembly modelling of soil particles (in situ soil and conditioned soil) and TBM structure, the thrust force and cutterhead torque were monitored in the numerical model and on site. Figure 11 shows the variations of on-site and numerical measured thrust force and cutterhead torque when tunnelling in the same conditions. As seen in Figure 11, the thrust force for the numerical model and on site maintained an average level of 1180 t and 1150 t, respectively. The cutterhead torque recorded an average level

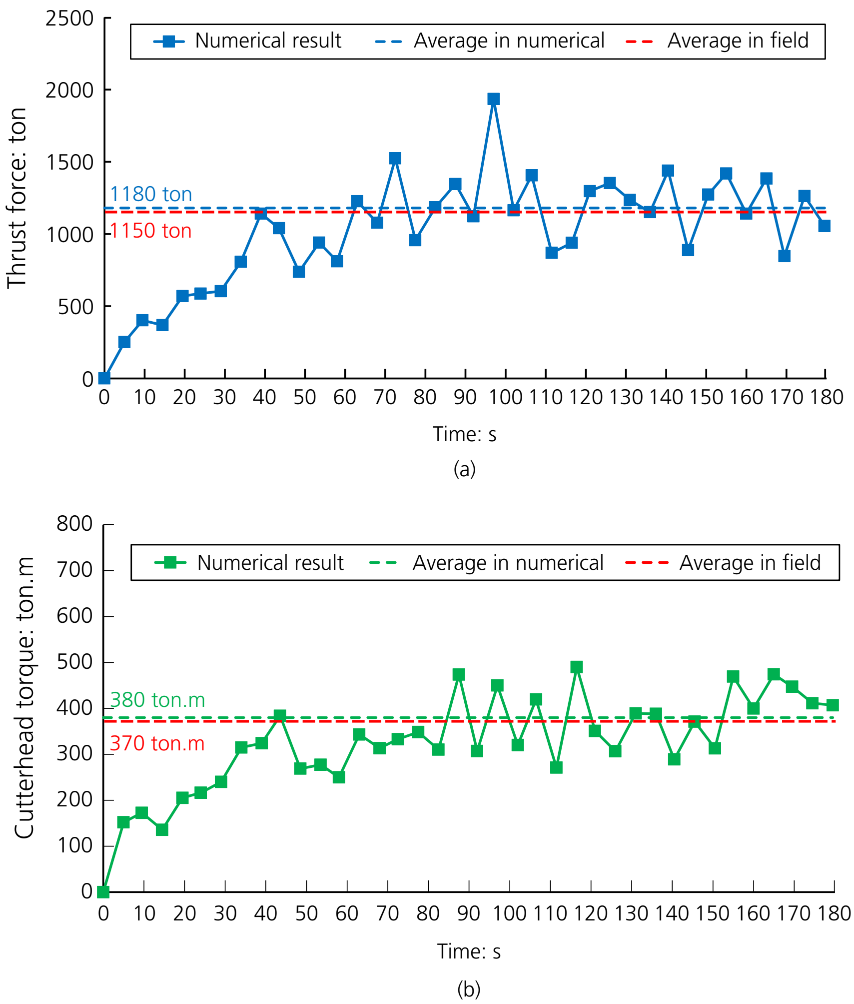


Figure 11. Comparison of the on-site and numerical result for (a) thrust force and (b) cutterhead torque

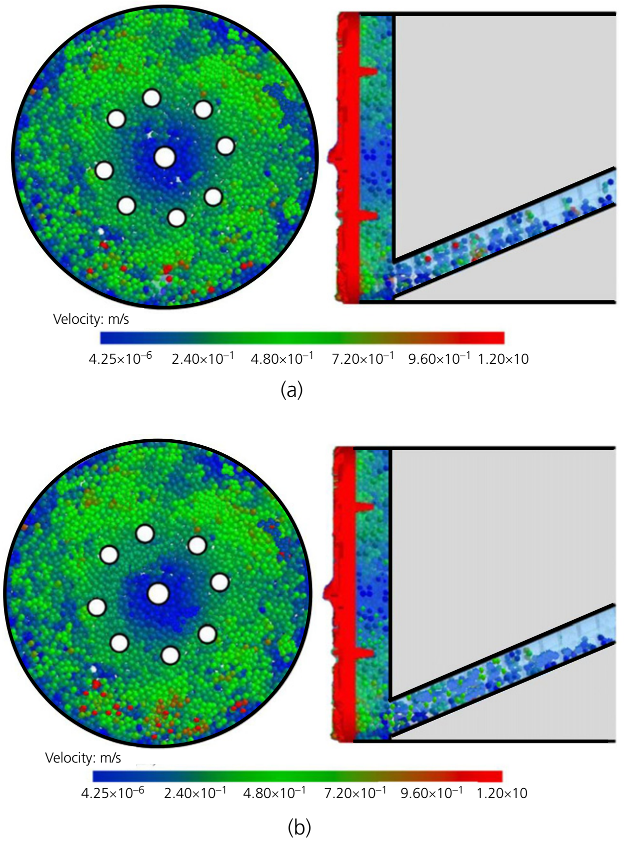


Figure 12. Velocity distribution of soil particles in chamber for non-cohesive soils (ET-1) – transverse and longitudinal sections along the chamber for (a) cutterhead no. 1 and (b) cutterhead no. 2

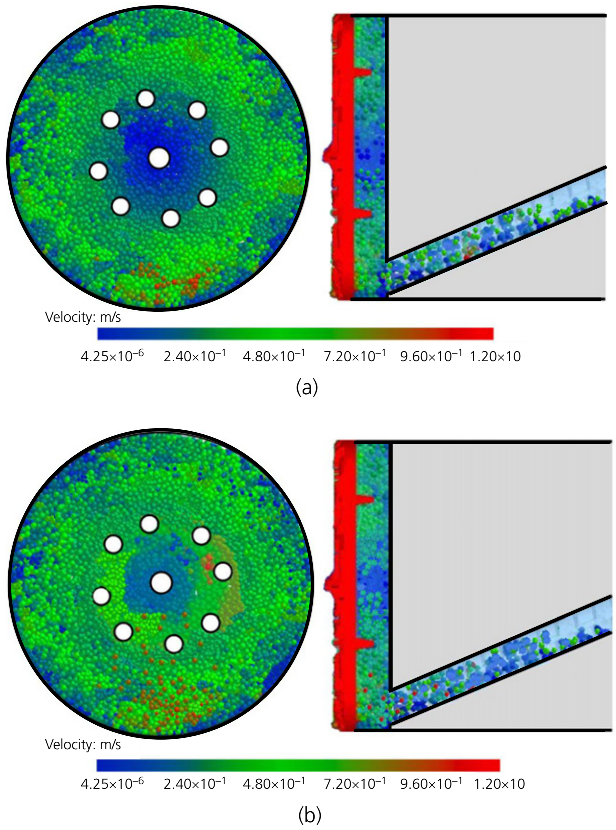


Figure 13. Velocity distribution of soil particles in chamber for cohesive soils (ET-5) – transverse and longitudinal sections along the chamber for (a) cutterhead no. 1 and (b) cutterhead no. 2

of 380 t m and 370 t m, respectively. These results imply good agreement, proving the model validity, and pave the way to apply the numerical model for analysis.

4. Evaluation of adaptability

Many factors are involved in the EPB cutterhead opening design; however, selection of the best cutterhead opening scheme is governed by two important factors: soil particle flow and operational parameters.

4.1 Particle flow characteristics

The performance of an EPB system is governed by the soil particles' flow condition inside the chamber to increase the working efficiency and lower the clogging risk. The particle flow characteristics have a complex interaction with the cutterhead structure, in particular its openings and chamber structure – especially the rotational arms and mixing bars. However, there are very few research studies to assess the soil flow inside the chamber. Among them, Tanaka (2005) presented the velocity and shear rate distribution of soil flow in the EPB chamber. Wang (2012) introduced an analytical solution for the soil flow characteristics from the cutterhead opening to the chamber structure as a laminar flow. The best cutterhead opening scheme in the centre zone of a cutterhead for non-cohesive and cohesive soils is selected through DEM simulation by obtaining the flow condition inside the chamber. Figures 12 and 13 show a cross-sectional view of the velocity distribution of non-cohesive soil particles (i.e. ET-1) and cohesive soil particles (i.e. ET-5), respectively, in different cutterhead openings in chamber space.

As shown in Figures 12 and 13, the rotational arms divide the space of the chamber into two zones, where the soil particles show high fluidity in the chamber apart from those in the central zone, which are encircled by the rotational arms (i.e. zone 1 in Figure 2(a)). By comparing Figures 12(a) and 12(b) for a non-cohesive soil, as well as Figures 13(a) and 13(b) for a cohesive soil, the high opening ratio in the central zone of the cutterhead (i.e. cutterhead no. 2) can increase the fluidity of soil particles in this zone, especially for cohesive soil, which can thereby decrease the clogging risk, standing time of particles, the consolidation condition in this zone, the cutterhead temperature and the energy consumption during the tunnelling process. It is one more example of the effectiveness of the central opening of the cutterhead in improving fluidity and efficiency.

4.2 Cutterhead torque and thrust force

In order to selecting the best cutterhead opening, operational parameters such as the thrust force and cutterhead torque value are investigated. By comparing Figures 14(a) and 14(b) and according to Figures 15(a) and 15(b), it can be found that the value of both thrust force and cutterhead torque is decreased by about 7% and 34% for non-cohesive and cohesive soils, respectively, when using cutterhead no. 2 in numerical modelling. Based on Table 9, cutterhead no. 2 is more suitable for cohesive soils, which shows that the results obtained from numerical studies are consistent with field studies based on Figure 2.

4.3 Comparing the results of numerical models and actual tunnelling practice

The findings regarding particle flow characteristics and reduction in cutterhead thrust and torque form a general recommendation from model outputs. Therefore, further elaboration using a real tunnelling example to required to justify the statement. In order to achieve this, actual tunnelling practice in Tehran metro project line 7, Iran, is introduced here. The tunnel of line 7 was excavated by two Lovat EPBMs with the same mechanical and hydraulic features, but with different cutterheads, especially with regard to the cutterhead opening, with a length of about 23.4 km and excavation diameter of 9.13 m (Figure 16). Figure 17 shows the opening ratio–radius curve for the two EPB machines used in this project: cutterhead no. 1 for south–north lot and cutterhead no. 2 for west–east lot based on Figure 16. Cutterhead no. 1, as a spoke type with inserted face plate, was designed with 35.6% overall opening ratio and 24% as the maximum amount in the central area. The total opening ratio of cutterhead no. 2 is 47.9%, which is of the star type, and 52% is the maximum value in the central area.

The cutterhead torque and thrust force of the two EPB machines in 1010 selected rings for Tehran metro line 7 are shown in Figure 18; the information is summarised in Table 10.

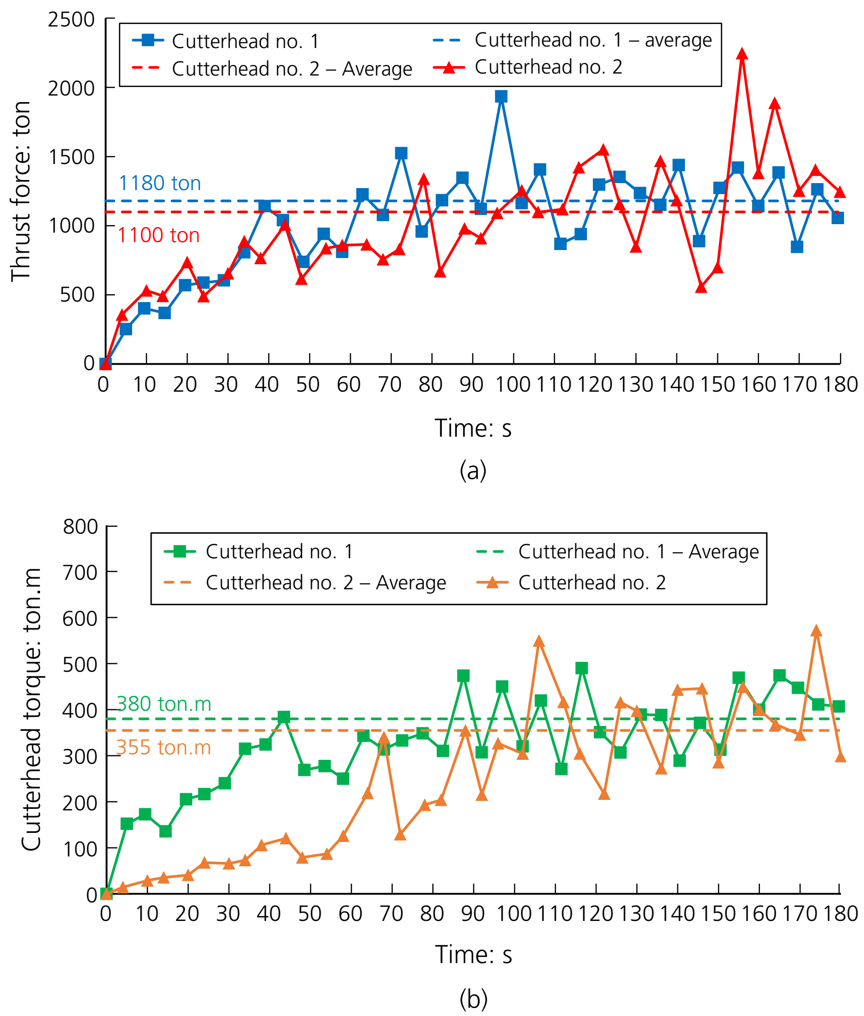


Figure 14. Comparison of numerical result for (a) thrust force magnitude and (b) cutterhead torque magnitude for non-cohesive soil and different cutterheads

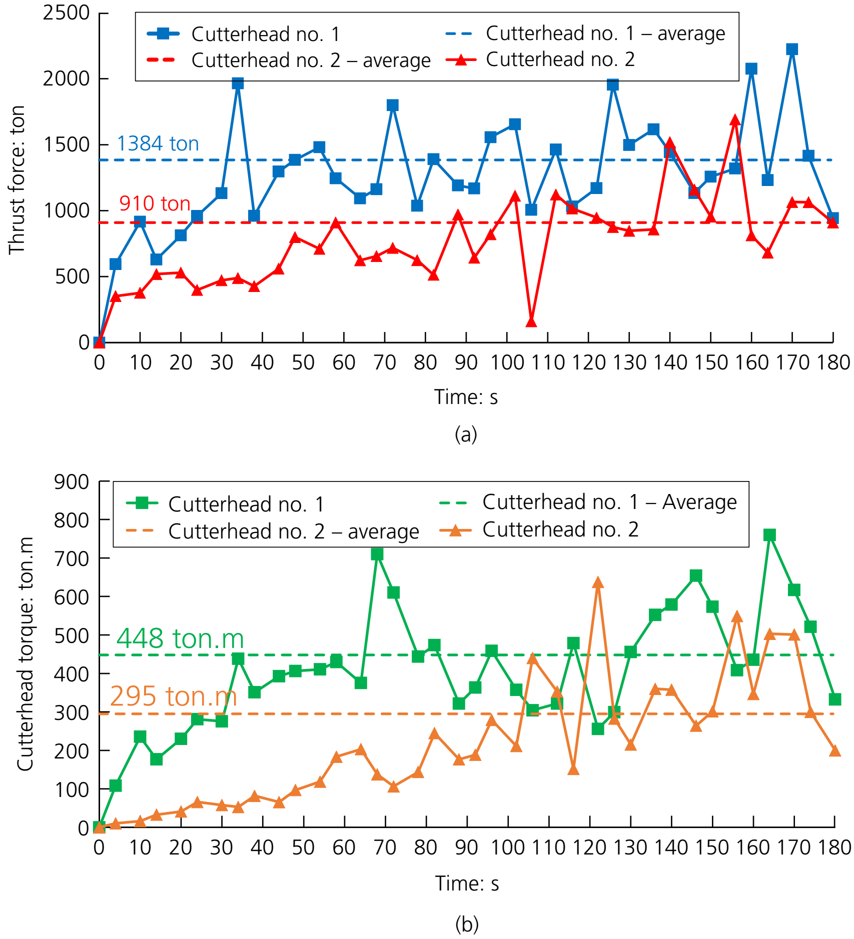


Figure 15. Comparison of numerical result for (a) thrust force magnitude and (b) cutterhead torque magnitude for cohesive soil and different cutterheads

Table 9. Operational parameters of cutterhead with different opening in non-cohesive and cohesive soils from numerical modelling

	Non-cohesive soil		Cohesive soil	
	Cutterhead no. 1	Cutterhead no. 2	Cutterhead no. 1	Cutterhead no. 2
Average thrust force: t	1180	1100 (–6.8%)	1384	910 (–34.2%)
Average cutterhead torque: t m	380	355 (–6.6%)	448	295 (–34.2%)

Thrust force and cutterhead torque were monitored based on the same geotechnical parameters, above groundwater table, the same tunnel overburden and similar soil conditioning parameters (e.g. FER, FIR and C_f), speed of rotation, penetration rate and chamber pressure. As can be seen, at the same geotechnical, mechanical and operational conditions, each machine maintained different thrust force and cutterhead torque. According to the studies of Shi *et al.* (2011), the opening ratio and the shape of the cutterhead have a considerable effect on the cutterhead performance. As can be seen in Table 10, the cutterhead torque during excavation in cutterhead no. 1 and no. 2 in the same condition maintained 340 and 230 t m (32.4% reduction in cutterhead torque), respectively. Also, the thrust force of cutterhead no. 1 and no. 2 is 1920 and 1508 t (21.4% reduction in thrust force), respectively. The central opening of cutterhead no. 2 is more effective than cutterhead no. 1. It means that of the two selected cutterheads, the opening–closing distribution in cutterhead no. 2 was designed with the proper schemes. The authors found that the cutterhead opening and the shape of the cutterhead have a strong effect on machine performance. It is suggested that the cutterhead opening distribution, especially in the central area, should be designed according to Figure 2 as a design chart. For the practical aspects with further application in the TBM industry, the opening ratio in the central area should be designed as more than 50% in cohesive soil to improve the clogging potential.

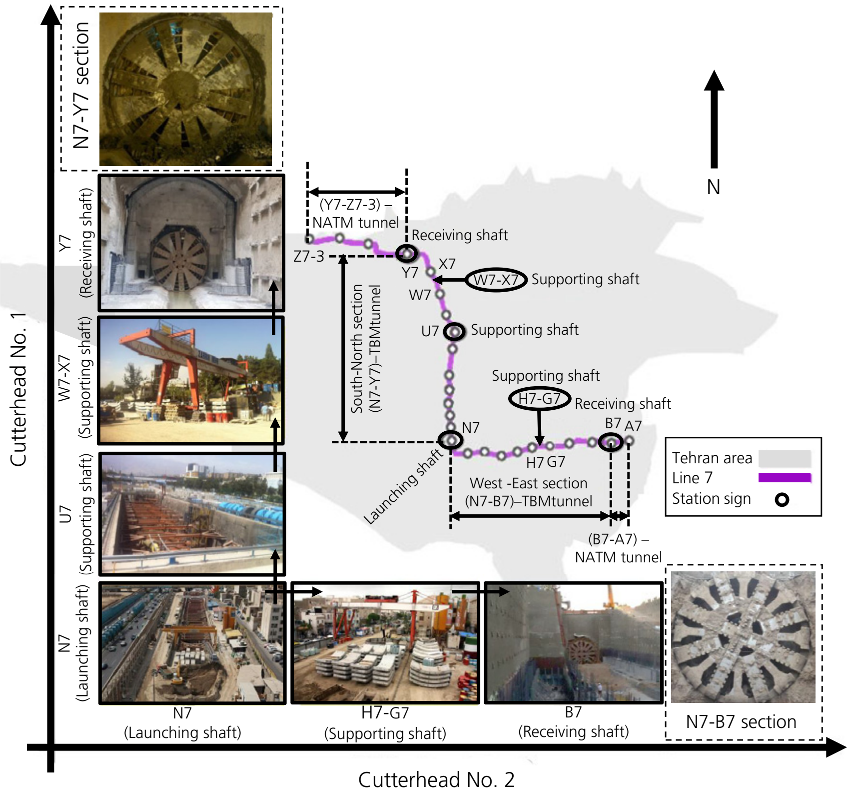


Figure 16. Mechanised tunnelling process of Tehran metro line 7 project in Iran by Lovat manufacturer; cutterhead no. 1 for south–north lot (N7 to Y7 station) and cutterhead no. 2 for west–east lot (N7 to B7 station)

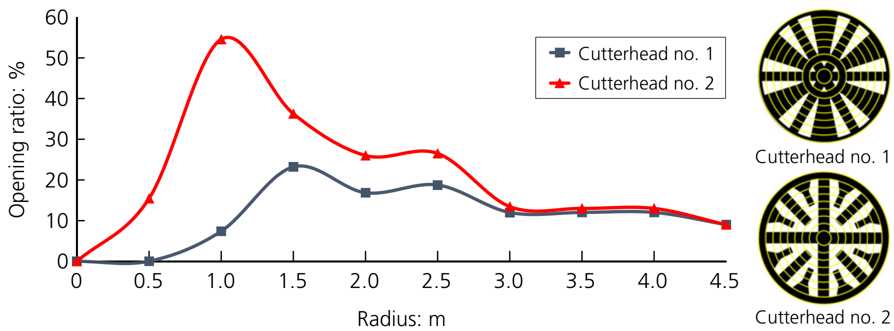


Figure 17. Opening ratio–radius curve for two EPB machines utilised in Tehran metro project line 7 by Lovat manufacturer; cutterhead no. 1 for south–north lot and cutterhead no. 2 for west–east lot based on Figure 16

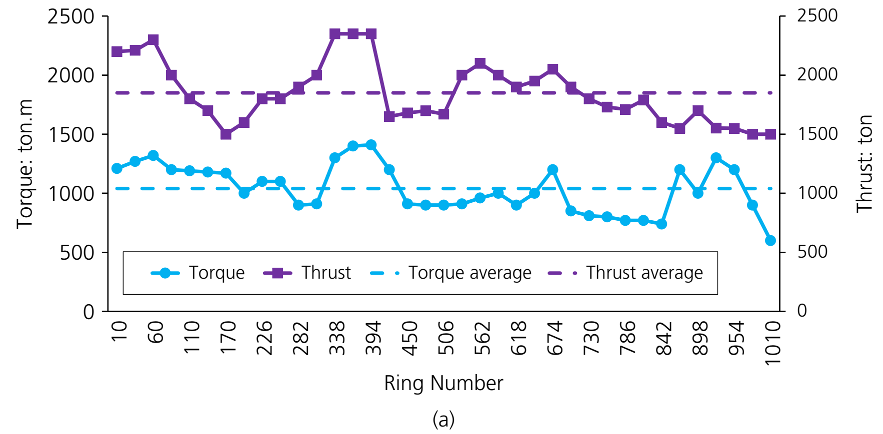
Overall, tunnel engineers and operators should be in close contact with TBM manufacturers to design the cutterhead, and especially its openings.

5. Conclusions

This paper has focused on the output parameters, including optimum opening ratio and its distribution, considering the related operational parameters of the cutterhead in various ground conditions. These parameters are obtained through a comparative study of the results of experimental and numerical models. The paper represents an attempt to confirm results obtained from field studies. The most significant results are given below.

(*a*) The liner velocity and structural considerations (e.g. rotational arms in the chamber space) are two important design factors for opening design, so the central opening ratio should be designed as more than 50% in cohesive soil to improving the clogging potential.

(*b*) A higher opening ratio in the central zone of the cutterhead than in the rest zone for cohesive soils can decrease the value of both thrust force and cutterhead torque by about



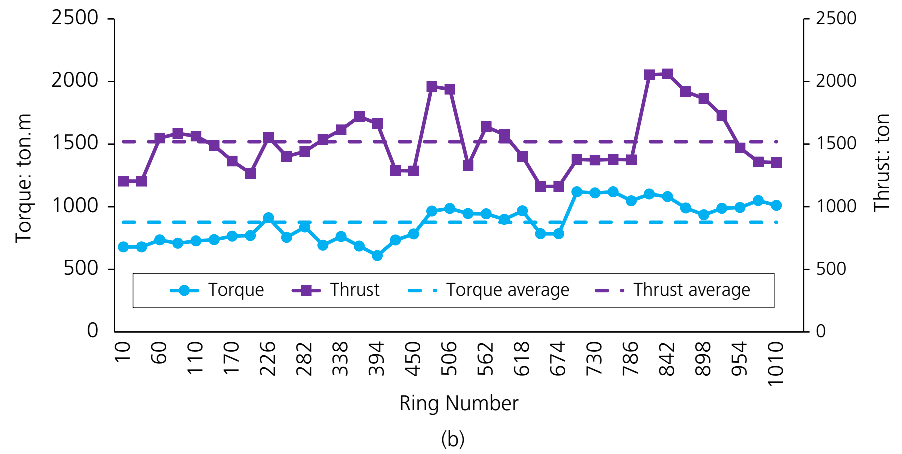


Figure 18. Comparison of field result of thrust force and cutterhead torque magnitude for (a) cutterhead no. 1 for south–north lot and (b) cutterhead no. 2 for west–east lot based on Figure 16

Table 10. Operational parameters of cutterheads utilised in line 7 of Tehran metro project as a real tunnelling practice

Cutterhead type	Average thrust force: t	Average cutterhead torque: t.m			Chamber pressure: bar	Average penetration rate: mm/min	rpm average	Soil conditioning parameters		
		Total	Mechanical	Excavation				FER	FIR: %	C_f: %
Cutterhead No. 1	1920	1040	700	340	0.55–1.00	32	1.03	2.50	50	1.2
Cutterhead No. 2	1508	880	650	230	0.60–1.00	33	1.02	2.50	50	1.2

34%; this shows that the opening design can have a direct effect on mechanical, hydraulic and electrical issues.

(*c*) A higher opening ratio in the central zone of the cutterhead than the rest zone can increase the fluidity of soil particles in this zone, especially for cohesive soil. It is suggested that the cutterhead opening distribution, especially in the central area, should be designed according to Figure 2 as a design chart.

Acknowledgements

Authors would like to dedicate their special thanks to Tunnel Saz Machine Company for their valuable efforts and cooperation to allow the authors to obtain access to software and facilities for the study. The authors also express their gratitude to Mr Erfan Rasekh for helping with the numerical modelling.

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