Journal of Mining and Environment (JME) Vol. 16, No. 1, 2025, 321-351

Shahrood University of Technology

Journal of Mining and Environment (JME)

Journal homepage: www.jme.shahroodut.ac.ir

Iranian Society of Mining Engineering (IRSME)

# Cutting Wheel Opening Configuration in Soft Ground Shield Tunneling by Considering Field and Numerical Studies

Dariush Mohammadi, Kourosh Shahriar*, Parviz Moarefvand, and Ebrahim Farrokh

*Department of Mining Engineering, Amirkabir University of Technology, Tehran, Iran*

***Article Info***

*Received 17 March 2024*
*Received in Revised form 6 July 2024*
*Accepted 9 August 2024*
*Published online 9 August 2024*

*DOI: 10.22044/jme.2024.14323.2678*

*Keywords*

*Cutterhead design*
*Radial opening ratio*
*DEM*
*TBM manufacturers*

## *Abstract*

The correct design of the cutterhead of a tunnel boring machine (TBM) plays a vital role in the efficient operation of the machine, as the cutterhead structure remains unchanged during the tunneling project. This paper aims to elucidate the fundamental principles in the design of the cutterhead opening in soft ground based on data obtained from TBM manufacturers. Initially, a comprehensive database of soft ground cutterheads from different TBM manufacturers across various projects and ground conditions was compiled. The most frequently used cutterhead configurations with diameters exceeding 5 meters were categorized into 36 distinct opening configurations based on a radial opening ratio curve and opening patterns per sector. Next, the performance parameters and particle flow characteristics of three Herrenknecht cutterhead designs featuring varying opening configurations in the central and circumference areas were analyzed using the Discrete Element Method (DEM) by considering material parameters for machine and soil and contact parameters between soil particles and soil particles-machine structures. Hertz–Mindlin model was assigned as the contact model for these elements. Additionally, three different cutterheads employed in Tehran metro projects in Iran were identified by monitoring the cutterhead torque and thrust force under same geotechnical conditions and operational parameters. Generally, a higher opening percentage in the central area of the cutterhead indicates good performance during excavation in cohesive soils. However, the higher opening percentage in circumferential areas is a better choice for effective excavated material removal around the cutterhead and tunnel in non-cohesive soils, weathered rocks, mixed and heterogeneous conditions.

## 1. Introduction

The design process of TBM cutterheads for soft ground conditions is a complex task that involves balancing various factors to ensure efficient excavation [1]. Manufacturers have evolved cutterheads with different configurations through experience over various tunneling projects worldwide and industry rules of thumb (e.g. Nishitake in Mitsubishi Heavy Industries Ltd., Japan [2], Burger in Herrenknecht Corp., Germany [3], Mongillo and Alsaleh in Caterpillar Tunneling Corp., Canada [4], Grothen in Robbins Corp., USA [5]). Manufacturers have also developed proprietary algorithms for their designs [6]. Comparisons will be made between the varying schools of thought in terms of cutterhead opening design among European, North American and Japanese manufacturers [5]. In many cases, the philosophies of these manufacturers were found to be quite different [5, 7, 8]. For example, the Channel Tunnel Rail Link (CTRL) in UK is a highlighted project in soft ground cutterhead design (Figure 1). In CTRL project, 8 closed-face soft ground TBMs were used to excavate a total 40 km (20 rout km) of 8 m outer diameter twin running tunnel. Given that the geology was almost the same (e.g. sand, soft clay and chalk) in the entire length of the tunnel, but based on Figure 1, four different red, blue, yellow and green cutterheads were manufactured with different types, opening-closing distribution and cutting

---

Corresponding author: k.shahriar@aut.ac.ir (K. Shahriar)

tools layout by Kawasaki Co. in Japan, Wirth Co. in Germany, Lovat Co. in Canada and Herrenknecht Co. in Germany, respectively [9].

When designing a cutterhead for soft ground conditions, there is a key question which method and design philosophy for soft ground cutterheads, employed by global tunnel boring machine manufacturers, is best suited for specific geotechnical conditions. The selection of the most appropriate approach for a particular project can significantly impact the performance and success of the tunneling operation. Key factors to consider in this decision include the structural parameters of the cutterhead like opening, configuration, geotechnical characteristics of the ground, and operational requirements. By carefully evaluating these factors and aligning the cutterhead design with the specific characteristics of the project ground, engineers can enhance the efficiency and effectiveness of the tunneling process, ultimately contributing to the overall success of the project. Collaboration between tunnel engineers and mechanical engineers is essential to ensure a comprehensive understanding of the design principles and operational considerations that influence the performance of the cutterhead in soft ground conditions.

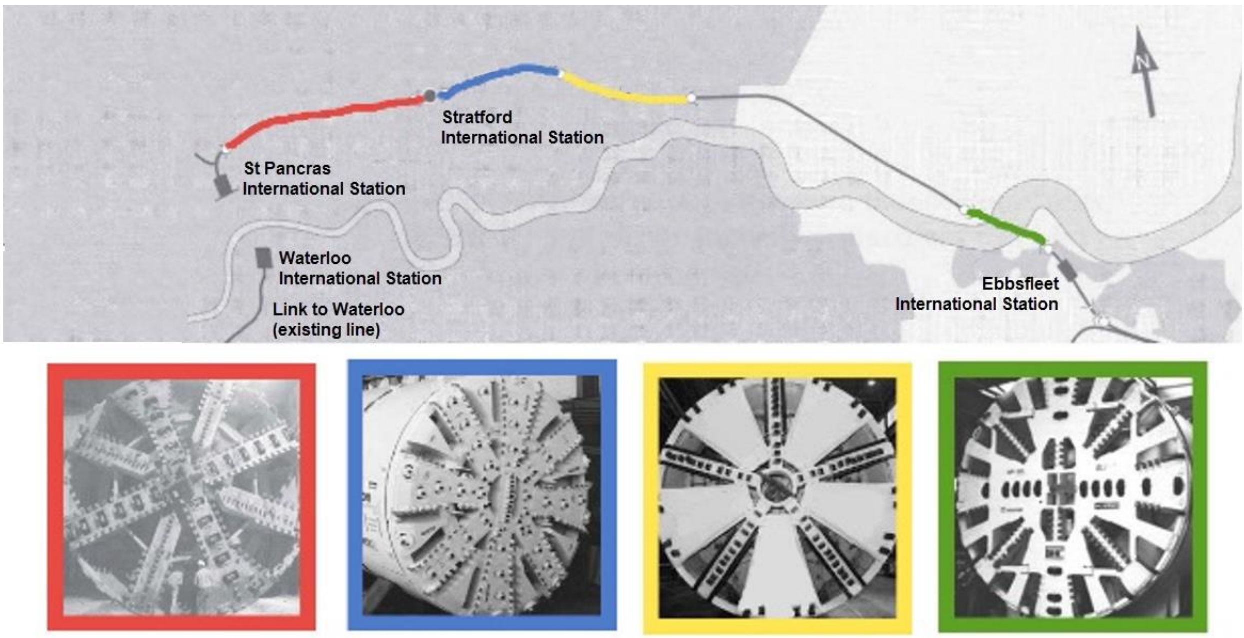


**Figure 1. CTRL project cutterheads [9].**

The research on soft ground cutterhead opening design and its configurations has been extensive, with various researchers and manufacturers contributing valuable insights. Yang et al. [10] conducted model tests to analyze thrust force, cutterhead torque, and soil pressure in chamber for two different cutterhead opening rates (30% and 70%). Burger [3] introduced design principles for soft ground cutterhead openings for slurry pressure balance machines (SPBMs) and earth pressure balance machines (EPBMs) based on experiences from tunneling projects. Ocak and Bilgin [11] compared the performance of two EPB machines with different cutterhead types and opening configurations in the Istanbul metro project. Mongillo and Alsaleh [4] examined the application of discrete element analysis to cutterhead performance optimization with different total opening ratios and opening distributions.

Shi et al. and Wang et al. determined the cutterhead torque and thrust force for EPB shield tunneling machines by considering the total opening ratio, respectively [12, 13]. Guo et al. studied the performance of different schemes of cutterhead opening ratios and shapes using a computational fluid dynamics (CFD) model [14]. Godinez et al. determined the cutterhead torque for an EPB machine by considering the total opening ratio with a mathematical model and real data from the Seattle metro in the USA [15].

Grothen as well as Sandell and Stypulkowski introduced the design principles of soft ground cutterhead openings for different types of machines [5, 16]. Cheng et al. and Li et al. introduced a comparative study on the suitability of EPB machines with different cutterhead configurations in typical sandy cobble ground and coarse-grain soils in China, respectively [17, 18]. Yang et al. considered the radial opening ratio of EPB TBM cutterheads for cutterhead modification [19]. Ebrahimy et al. presented a comparison between the performances of two cutterhead configurations in Isfahan metro project in Iran [20]. Mohammadi et al. assessed the performance of two Herrenknecht's cutterheads with different opening ratios in the central area for cohesive and non-cohesive soils using DEM [1]. Chen et al. studied the influence of cutterhead opening ratios on soil arching effect and face stability during tunneling through non-uniform soils using a finite element model (FEM) [21].

This paper is intended to outline some fundamental principles for designing cutterhead openings in soft ground based on insights gleaned from TBM manufacturers' experiences in various tunneling projects. Recommendations regarding the opening ratio and configuration of cutterheads for different ground conditions will be proposed utilizing data from TBM manufacturer databases. The study will review the current state-of-the-art design practices employed by TBM manufacturers for cutterhead openings in soft ground. Additionally, the performance parameters and particle flow characteristics of cutterheads with distinct opening configurations in the central and circumferential areas will be analyzed using the Discrete Element Method (DEM). Ultimately, the study aims to evaluate the performance of three different cutterhead designs featuring varied opening configurations in the real tunneling projects. The significant innovations presented in this manuscript can be outlined as follows: (1) Compilation of a database comprising machine manufacturing factories from the cutterheads of 50 tunnelling projects worldwide, (2) Implementation of cutterhead zoning to facilitate the design of individual cutterhead part openings in diverse ground conditions, (3) Analysis of the impact of varying cutterhead openings in each zone through the utilization of discrete element numerical modeling and field experiences from real tunneling projects on machine operational and performance parameters, and (4) Enhancement and elaboration of the radial opening ratio diagram in the cutterhead design process, along with the introduction of a design graph utilizing the machine manufacturers' database.

## 2. A brief overview of the soft ground cutterhead opening design

### 2.1. Performance parameters and cutterhead opening

The correct design of a tunnel boring machine is crucial for the success of a tunneling project, and this is reflected in the machine's performance parameters. As shown in Figure 2, the performance of a soft ground machine is influenced by ground, structural, and operational parameters that interact in a complex manner. The cutterhead of the TBMs, as a structural parameter, plays a vital role in the machine design. Among the various elements of soft ground cutterheads, the design of the cutterhead openings is considered the most crucial, as it impacts the design of other cutterhead elements such as cutting tools and the screw conveyor. The cutterhead opening refers to the open space on the TBM's rotating cutterhead through which the excavated material is transported away from the tunnel face. The soft ground cutterhead opening significantly affects the machine's performance and efficiency in several ways, including excavated material removal efficiency, wear patterns on cutting tools, precise control over earth pressure, thrust and torque requirements, advance rate, and TBM's progress.

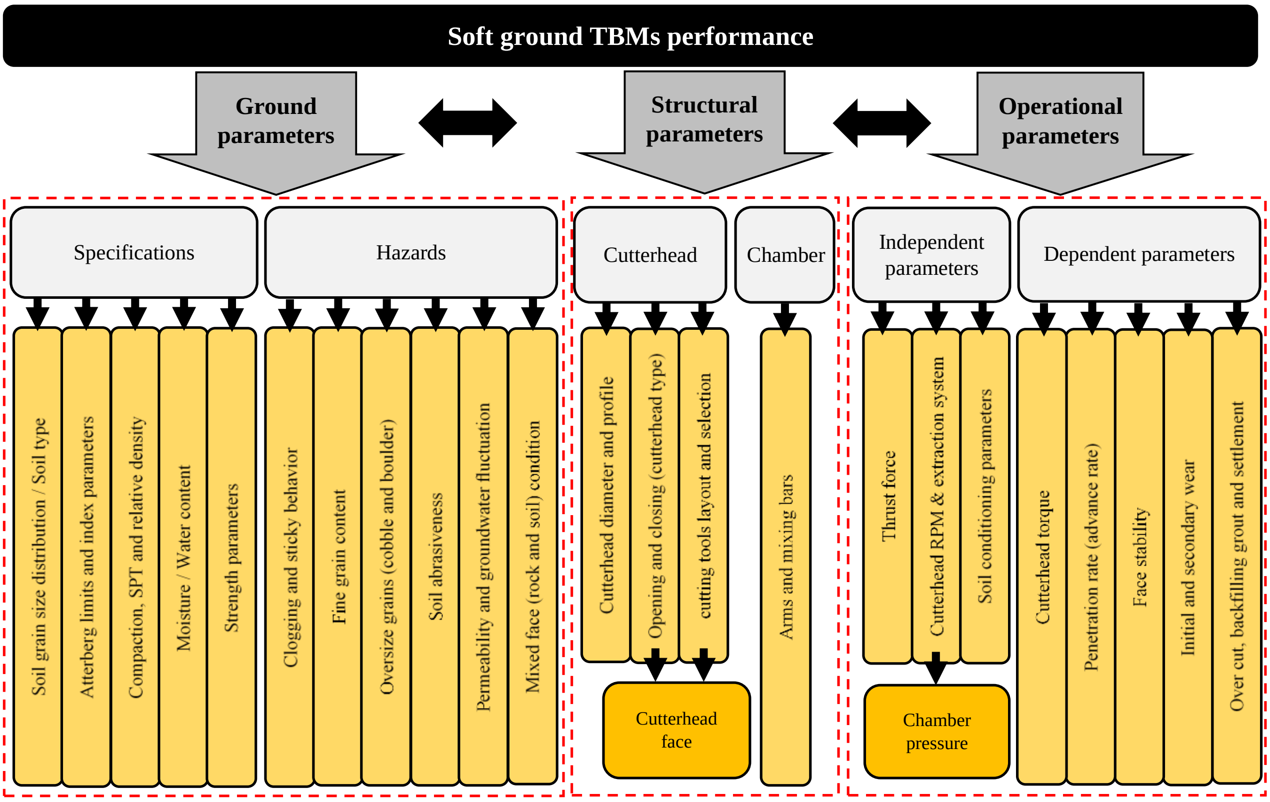
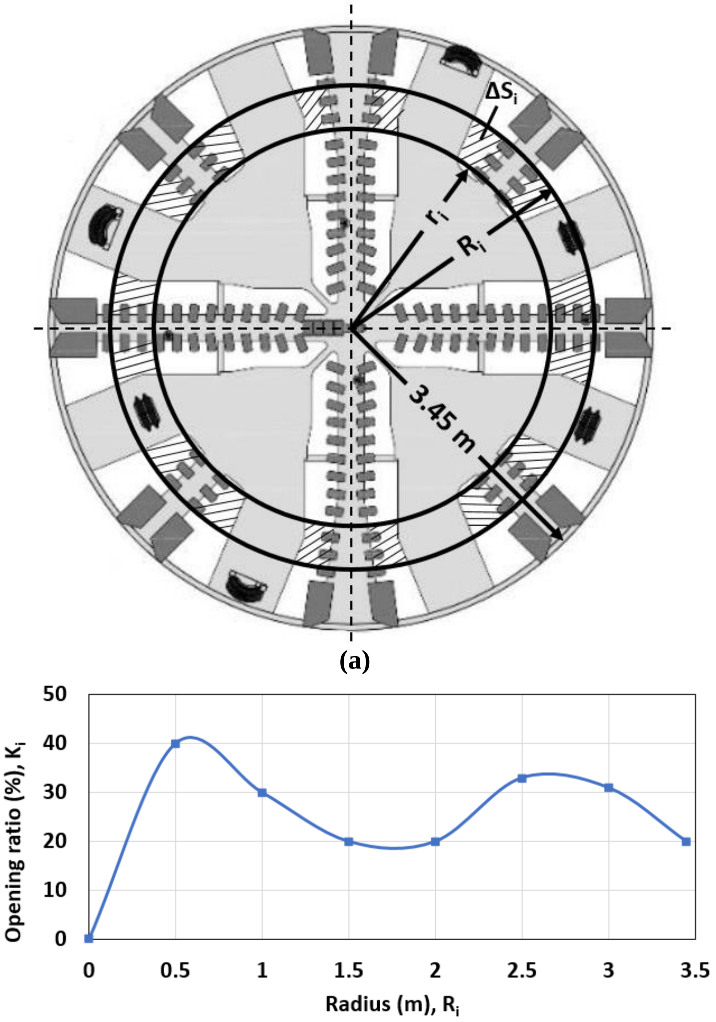


**Figure 2. Soft ground TBMs performance parameters.**

## 2.2. General characteristics of the cutterhead openings

The structure of the soft ground cutterhead includes opening and closing areas that define the cutterhead type itself. The opening areas (light sections) and closing areas (dark sections) on the cutterhead are illustrated in Figure 3. The total opening ratio of cutterheads, which represents the area ratio of the cutterhead openings to the entire cutterhead, is an important index for cutterhead design depending on geological conditions. Here is a general overview of opening percentages for different TBMs as follows [3, 4, 17, 18]: EPB cutterheads (25% to 40% or more), SPB cutterheads (10% to 25%), and mixed shield TBMs (15% to 30%).

However, the total opening ratio of the cutterheads alone cannot fully illustrate the opening configuration. To address this limitation, Burger from Herrenknecht Corp. proposed the concept of radial opening ratio [3]. The radial opening ratio curve provides a visual representation of the opening value of each area of the cutterhead along the radial direction of the cutterhead, which can well reflect the distribution of the openings in each area of the cutterhead (Figure 3). In order to draw the following curve, the cutterhead is divided into several annular areas with equal annular distances ($\Delta R_i = R_i - r_i$) as shown in Figure 3a. The annular total area is $S_i = \pi (R_i^2 - r_i^2)$ and the annular opening area is $\Delta S_i$. The annular opening ratio of each annular area ($K_i = \Delta S_i / S_i$) is measured. In other words, the opening ratio is calculated by dividing the opening area by the annular area between two concentric circles, and then the radial opening ratio characteristic curve is made with the cutterhead radius $R_i$ as the horizontal axis and the annular opening ratio $K_i$ as the vertical axis (Figure 3b). Figure 3b is the radial opening ratio characteristic curve of the cutterhead of line 1 of Isfahan metro in Iran shown in Figure 3a under the annular distance $\Delta R_i = 0.5$ m.



(a)

(b)

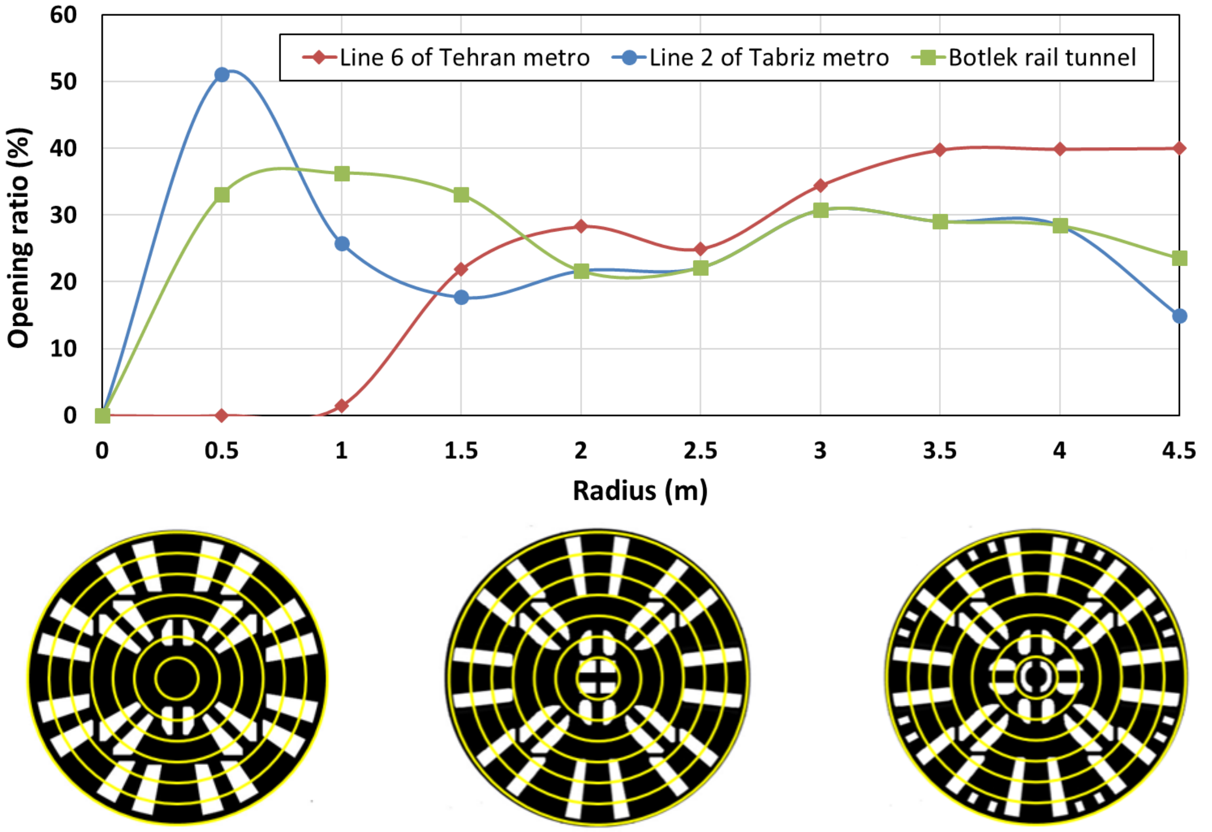
**Figure 3. (a) Schematic diagram of radial opening ratio of cutterhead, and (b) characteristic curve of radial opening ratio.**

A comparison between total opening ratio and radial opening ratio can help to understand the issue. Based on Figure 4, the opening percentage of the Tabriz metro and Tehran metro cutterhead varies from 50% (central zone) to (20-30) % (the rest of the zones) and from 0% (central zone) to (30-40) % (the rest of the zones), respectively. However, the total opening percentage on the Tabriz metro and Tehran metro cutterhead face is approximately 24.2% and 33.4%, respectively.

## 3. Opening ratio and cutterhead configuration

### 3.1. TBM manufacturers' database

Different manufacturers have unique cutterhead opening configurations optimized for specific geological conditions. Regular updates and improvements to cutterhead design are also informed by lessons learned from previous projects. Thus, the products of TBM manufacturers can serve as a valuable handbook for the design of cutterhead openings for future projects. In this study, an analysis was conducted on products, which manufactured by the top 10 TBM manufacturers as shown in Table 1 in various projects from sources across the webs, with the aim of categorizing different configurations of cutterhead opening in diverse ground conditions. This comprehensive analysis provides insights into the variety designs of cutterhead opening employed by leading TBM manufacturers, offering valuable information for the design and selection of cutterhead configuration based on specific geological conditions.



Line 6 of Tehran metro, Iran Line 2 of Tabriz metro, Iran Botlek rail tunnel, Netherlands

**Figure 4. Radial opening ratio curve for three different Herrenknecht cutterheads [1, 3].**

**Table 1. Information of top 10 TBM manufacturers worldwide.**

| Manufacturer | Country | Established year |
|---|---|---|
| Herrenknecht Corp. | Germany | 1975 |
| Robbin Corp. | USA | 1951 |
| Kawasaki Heavy Industries Ltd. | Japan | 1987 |
| Mitsubishi Heavy Industries Ltd. | Japan | 2009 |
| Wirth-CREG (China Rail tunneling Equipment Group Co.) | Germany (China) | 1965 |
| NFM Technologies-NHI | France (China) | 1988 |
| Lovat (LNSS-Lovsuns) | Canada (China) | 1972 |
| Hitachi Zosen Corp. | Japan | 1967 |
| CRCHI (China Railway Construction Heavy industry Co) | China | 2007 |
| Terratec | Australia | 1990 |

A comprehensive database was compiled from various companies, encompassing important information such as cutterhead opening configuration, machine type, geotechnical conditions of the project, machine diameter, and machine manufacturer. In Appendix A of this article, a schematic summary of cutterhead analyses is provided. Based on this information, cutterhead designs can be categorized by dividing them into sectors of a circle, allowing the complete shape of a cutterhead to be formed by assembling these sectors together. The majority of cutterhead designs are associated with 45-degree, 60-degree, and 90-degree sector designs as shown in Figure 5. In general, smaller sectors (e.g. 45-degree) are used to make machines with larger diameters (e.g. diameter greater than 8 m), and on the contrary, larger sectors (e.g. 90 degree) are used for smaller diameters (e.g. diameter smaller than 8 m) based on database (Figure 5).

As indicated in Appendix A, many TBM manufacturers prefer spoke-type cutterheads for soft ground condition. It is characterized by having a central hub with a number of spoke-like arms extending outward from the center. Each arm contains cutting tools, which are used to excavate the ground as the TBM progresses. In this case, the openings are located between the spokes, which the opening size can be reduced by means of elements such as sub-spokes or face panel (spoke-panel type). The number of spokes varies from 8 to 3 based on the TBM diameter

(Figure 5), with larger machines having a greater number of spokes. For the purposes of this study, it was decided to use same spoke cross-section and width in all cutterhead configuration with radius "R". By applying a constant spoke cross-section to all cutterheads, the resulting outputs, would then be directly compared as to the effectiveness of one cutterhead design over the other. Herrenknecht Corp. in Germany, as one of the largest and well-known TBM manufactures globally, offers a wide range of soft ground cutterhead with panel type. The panel cutterhead consists of rectangular or trapezoidal openings arranged in a grid pattern on the face of the cutterhead.

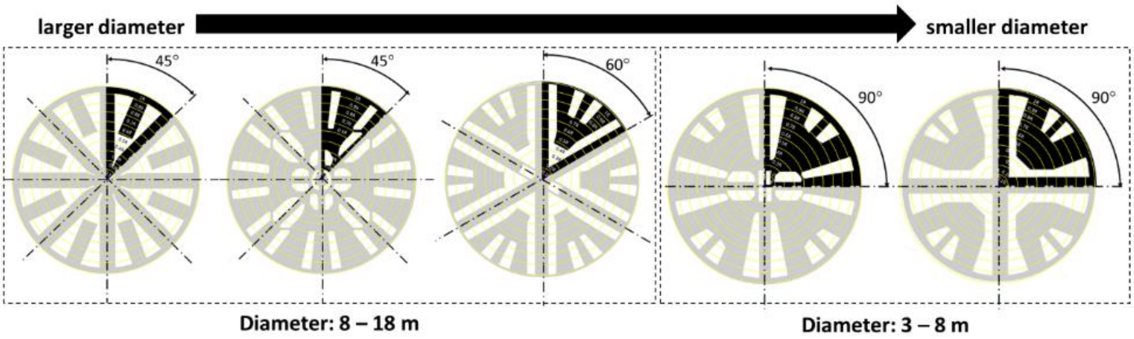


**Figure 5. Relationship between cutterhead diameter and circular sector.**

Based on database, 8-spoke, 4-spoke and panel cutterhead types are placed in the 45-degree sector design as shown in Figure 6. The cutterheads with 6-spoke are designed based on 60-degree sector design as depicted in Figure 7. As seen in Figures 8, 4-spoke and panel design of cutterhead are placed in the 90-degree sector design. As seen in Figures 6-8, the soft ground cutterheads were practically divided into 36 different opening configurations using radial opening ratio. Based on the trend of the radial opening ratio curves in Figure 6-8, it is easy to understand that the opening area should be divided into two parts for the design of cutterhead openings. In fact, the rotational arms divide the space in the chamber into two zones, as shown in Figure 9. 'Zone 1' refers to the area between the central point of the cutterhead and rotational arms, while 'zone 2' encompasses the remaining areas between the rotational arms and the circumference.

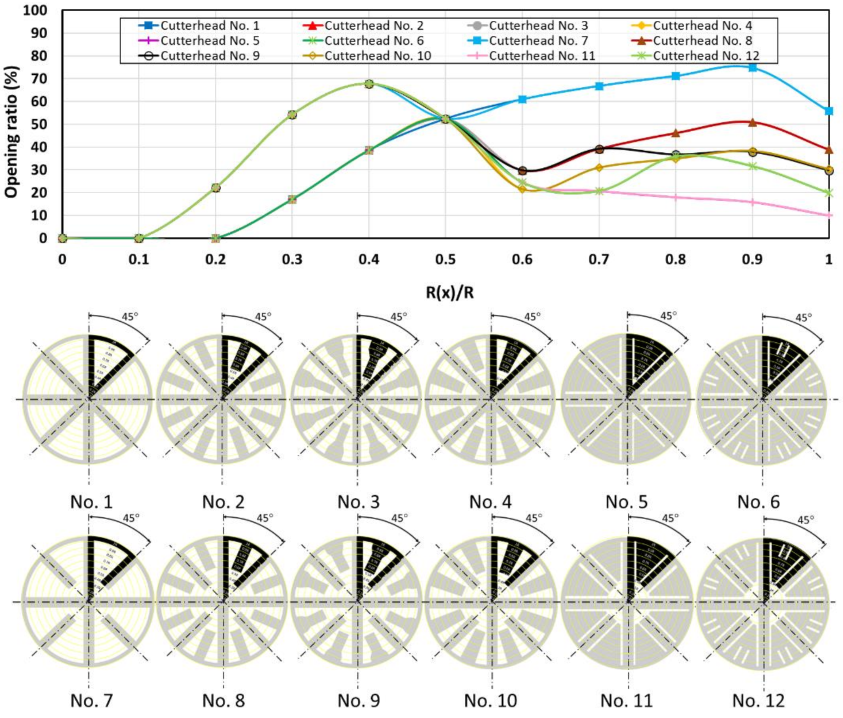


**Figure 6. Radial opening ratio curve for cutterhead configuration based on 45-degree sector.**

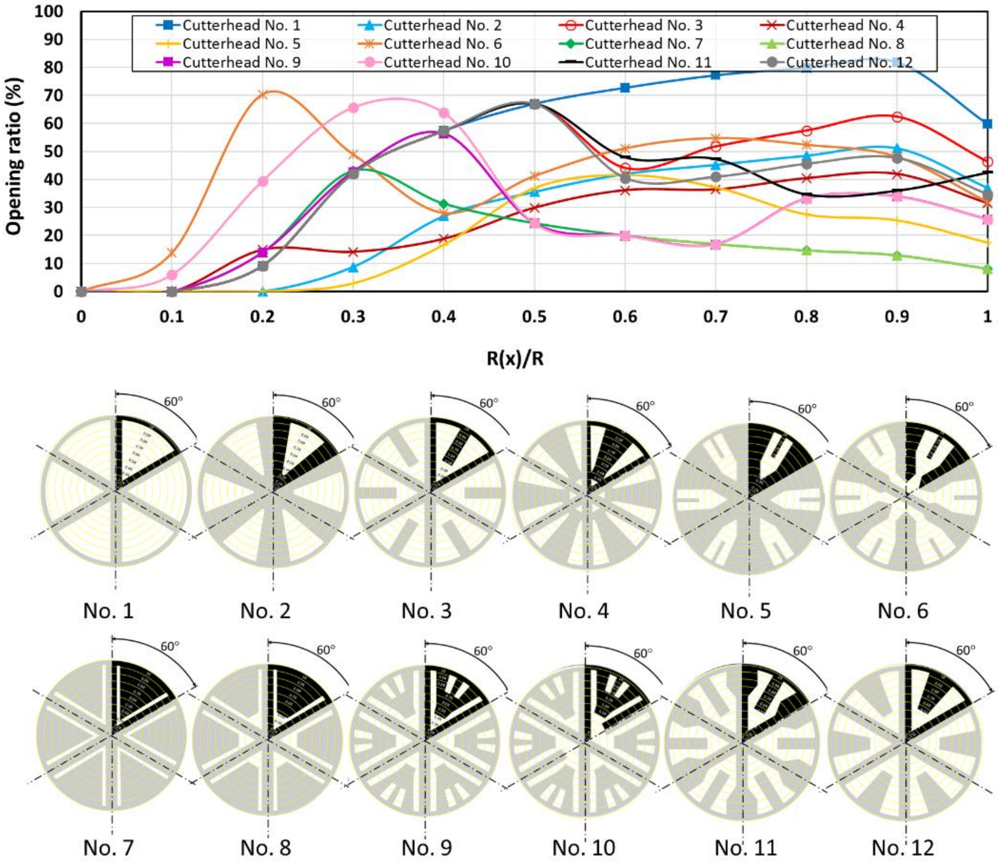


**Figure 7. Radial opening ratio curve for cutterhead configuration based on 60-degree sector.**

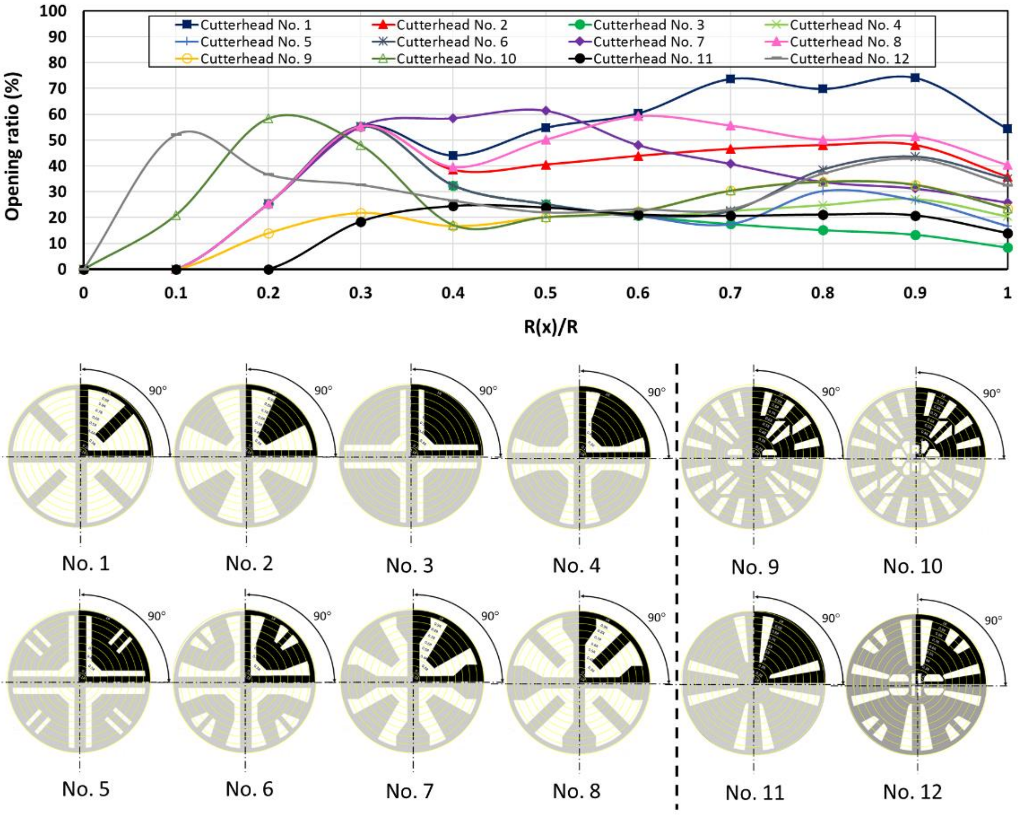
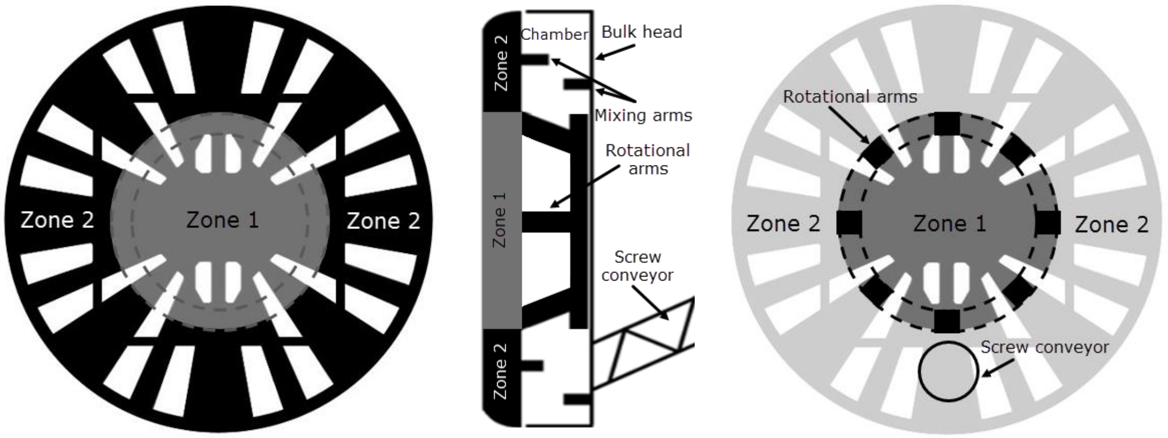


**Figure 8. Radial opening ratio curve for cutterhead configuration based on 90-degree sector.**



Front view Side view Rear view

**Figure 9. Defining "zone 1" and "zone 2" for the cutterhead design purposes.**

Opening size (opening percentage) and the opening geometry-location (opening distribution with respect to radius from the center) on a cutterhead in zone 1 and 2 (Figure 9) are two different aspects in opening design. When designing the cutterhead, attention should be given to the geometry of the openings in each area, which determines the trend of the radial opening curve, as well as the percentage of openings, which indicates the value of the openings. There may be two cutterheads with the same opening geometry (same trend of the radial opening curve) but different percentages of the total cutterhead area occupied by opening.

By comparing the Figures 6-8, we can identify three different types of trends in radial opening ratio curves for soft grounds. The first type starts at zero and gradually increases, as seen in Figure 10 – configuration 2 (e.g. cutterhead No. 1 in Figure 6, cutterhead No. 1, 2, 4 and 5 in Figure 7 and cutterhead No. 1, 9 and 11 in Figure 8). The second type reaches a maximum value and then gradually decreases, as shown in Figure 10 – configuration 1 and 4 (e.g. cutterhead No. 3, 5, 9 and 11 in Figure 6, cutterhead No. 6, 7, 8, 11 and 12 in Figure 7 and cutterhead No. 2, 3, 4, 7, 10 and 12 in Figure 8). The last type has two peaks, as depicted in Figure 10 – configuration 3 (e.g. cutterhead No. 2, 4, 6, 7, 8, 10 and 12 in Figure 6, cutterhead No. 3, 9 and 10 in Figure 7 and cutterhead No. 5, 6 and 8 in Figure 8). Figure 10 illustrates an idealized trend with a consistent pattern and no significant changes throughout the chart, as well as the percentage range of each configuration based on the database.

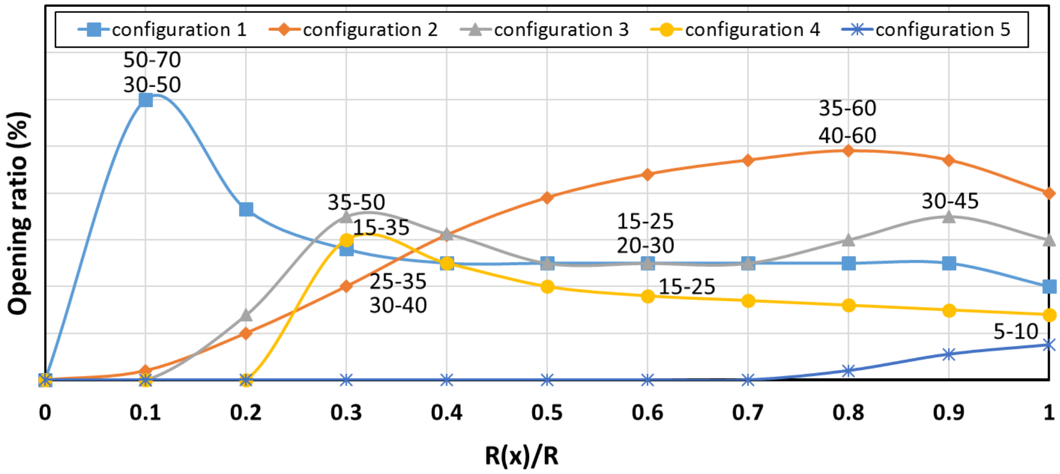


**Figure 10. Idealized radial opening type based on database.**

Table 2 shows the cutterhead opening configuration and percentage (Figures 6-8 and 10) based on TBM manufacturer's database by considering ground condition. Based on database, in cohesive soils, a higher percentage of openings is recommended in zone 1 than in zone 2, whereas the opposite is true for non-cohesive soils, rocks and mixed grounds.

**Table 2 Cutterhead opening configuration based on database by considering ground condition.**

| Ground condition | Opening percentage with respect to radius | | Cutterhead configuration type | Idealized radial opening type based on Figure 10 | Machine type suggestion |
|---|---|---|---|---|---|
| | zone 1 | zone 2 | | | |
| Soft grounds (sand, silt, clay) / Alluvium | 30-50 | 20-30 | Spoke-panel and panel | Configuration 1 | EPB |
| Cohesive soils (clay) / Chalk, marl and gypsum | 50-70 | 20-30 | Panel | Configuration 1 | EPB |
| Non-cohesive soils (sand and gravel) | 25-35 | 40-60 | Spoke and spoke-panel | Configuration 2 | SPB / Multi-mode |
| Mixed-face conditions and heterogeneous formations (soft ground to rock) | 15-35 | 15-25 | Spoke-panel and panel | Configuration 4 | Multi-mode |
| Mixed-face conditions and heterogeneous formations (cohesive soil to non-cohesive soil) | 35-50 | 30-45 | Spoke and spoke-panel | Configuration 3 | EPB |
| Boulder and cobble ground conditions | 30-40 | 35-60 | Spoke and spoke-panel | Configuration 2 | EPB / Multi-mode |
| Sedimentary ground conditions (sandstone, mudstone, marlstone, limestone, siltstone, conglomerate and shale) | 30-50 | 15-25 | Spoke-panel and panel | Configuration 1 | EPB / Multi-mode |
| High water pressure (underwater) / pressurized conditions | 15-35 | 15-25 | Spoke-panel and panel | Configuration 4 | SPB / Multi-mode |
| Hard rocks to weathered rocks (Heterogeneous formations) | 0-30 | 20-45 | Panel | Configuration 2 | Multi-mode |
| Hard rocks (Gneiss, granite, basalt, andesite, breccia, syenite, diorite and tuff) | 0 | 5-10 | Panel | Configuration 5 | Hard rock / Multi-mode |

## 3.2. Opening configuration analysis based on database

### 3.2.1. Opening configuration in zone 1

The central area of cutterheads is the most critical area for plugging and clogging in SPB and even more so in EPB machines. These geohazards depend on soil conditioning parameters (e.g. FER, FIR, Cf, and position of flushing nozzles) and cutterhead design (e.g. opening and cutting tools condition). Clogging can be likened to cancer cells spreading from the center to the circumference, as shown in Figure 11, and can lead to an increase in the requirement for torque and yield less efficient excavated material flow into the chamber.

Certainly, the openings close to the center are of considerably greater importance than the ones at the outer face area, especially for cohesive soil, where low material velocities and linear velocity exist, resulting in less mixing, high density, and poor fluidity of excavated material. In cohesive ground conditions, such as clay, chalk, marl, and gypsum, the soil tends to stick together and can create a suction effect around the cutterhead of a tunnel boring machine. This suction effect can make it difficult for the cutterhead to effectively break through the soil and can slow down the tunneling process. By increasing the size of the cutterhead opening in the central area, more soil can be removed at once, reducing the suction effect and allowing the tunnel boring machine to progress more smoothly through the ground.

**(a) Line 16 of Grand Paris Express Project** **(b) Line 3 of Tehran Metro Project** **(c) Line 1 of Ahvaz Metro Project**

**Figure 11. Diffuse configuration of clogging centrally to peripherally (Cancer cells-like).**

The most commonly used range for the central openings is shown in Figure 12. In cohesive grounds, a larger cutterhead opening may be required to prevent clogging in the central area, such as configuration No. 1 in Figure 10. These points tend to central enlarged opening type in spoke and panel type cutterheads with a large opening ratio in zone 1, allowing for better excavated material removal in sticky grounds. Due to the structure of spoked cutterheads, a lower opening percentage can be considered in the central area compared to panel cutterheads.

Central openings in spoked cutterheads are typically in the range of 0.3R to 0.4R of the cutterhead, while in panel type, they can be considered in the range of 0 to 0.2R, as shown in Figures 8 and 10. It is evident that fewer spokes make the greater opening percentage in the central area, and this design can shift the central openings closer to the center of the cutterhead. In practice, TBM manufacturers increase the central opening percentage of spoke-type in sticky grounds by implementing such as triangulation, thinning the ends of the spokes in the central area, or using sub-spokes as shown in Figure 12.

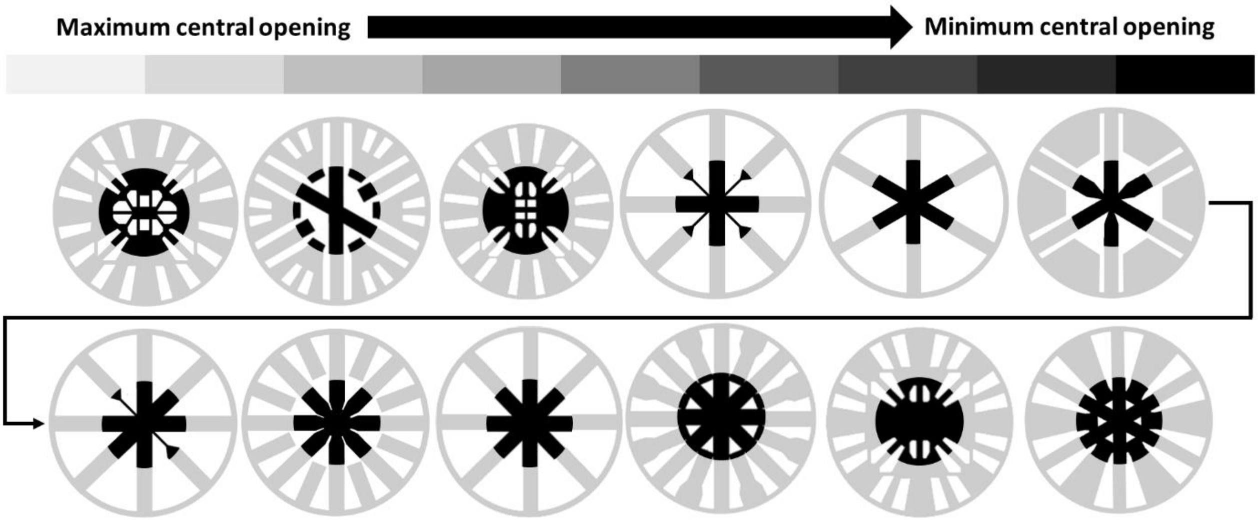


Figure 12. Opening pattern for central area (zone 1 of the cutterhead).

### 3.2.2. Opening configuration in zone 2

The opening pattern in each sector is closely aligned with the face panel, such as sub-spoke and face plate elements, in a spoke and panel type cutterhead, as depicted in Figure 13. Different patterns have varying opening ratios ranging from maximum to minimum opening configurations. The rectangular, triangular, and trapezoidal openings are three shapes used in the design of cutterhead openings (Figure 13). When designing the opening pattern per sector, the designer should consider the principles of circular motion and linear velocity. Circular motion refers to the movement of an object along the circumference of a circle or rotation along a circular path, while linear velocity is the measure of the rate of change of displacement with respect to time when the object moves in the circular direction. The linear velocity value increases from the center to the circumference of the cutterhead (see the amount of blur and clarity in Figure 14).

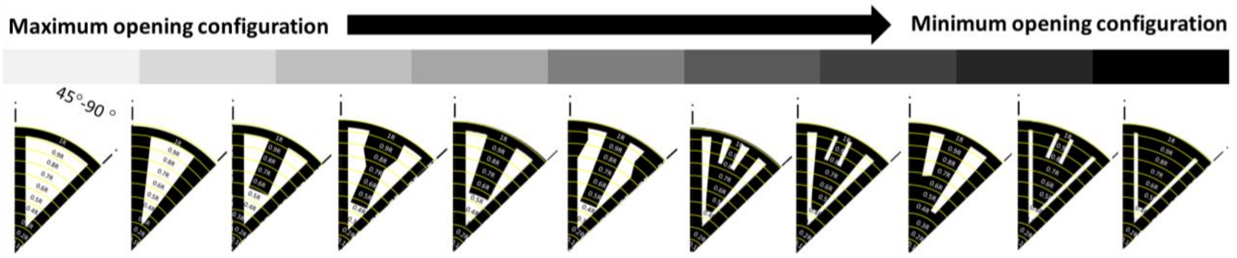


Figure 13. Opening pattern per sector for 45-, 60- and 90- degree sector.

**Figure 14. Schematic representation of linear velocity on cutterhead face.**

Based on these principles, the volume of excavated material at each point of the cutterhead is different. Therefore, the cutterhead opening configuration should be designed to ensure the uniform and smooth transfer of excavated materials from the tunnel face to the chamber space, which can prevent any blind zones on the cutterhead. In fact, as we move towards the circumference area of the cutterhead, the amount of opening area should increase. In other words, the opening percentage along all points of zone 2 should be the same. These points tend to support triangular and trapezoidal openings as a better choice to promote a more balanced opening ratio with respect to the radius on the face. Figure 15 shows practical example of different opening designs in zone 2. In practice, the same percentage of the opening relative to the radius on the entire zone 2 is recommended, as seen in zone 2 of cutterhead No. 2 in Figure 15. The decreased trend in zone 2 (e.g. cutterhead No. 1 in Figure 15) is not recommended.

In certain bolder ground conditions, the shape of the opening may allow for irregularly shaped boulders to enter the chamber and slow down TBM operations [4]. In these cases, rectangular or trapezoidal openings provide better protection from these occurrences, and additional rectangular or trapezoidal openings may be used to increase the percentage opening, as shown in zone 2.2 of cutterhead No. 3 and 4 in Figure 15. Grizzly-bars are used in the opening design to limit the size and shape of material entering the mixing chamber in some cases.

The high opening ratio in zone 2.2 (e.g. cutterhead No. 3 and 4 in Figure 15) is a better choice in sandy gravel soils with boulders and mixed-ground conditions (soil ground to rock) for effective excavated material removal, such as rock fragmentation and granular soils, and for preventing obstructions around the cutterhead. Additional rectangular or trapezoidal openings in zone 2.2 may include additional opening edge cutting tools on the same circular excavation path (cutterhead No. 3 and 4 in Figure 15). This is generally expected to reduce the wear on any one opening edge cutting tools by allowing the cutting action to be shared equally by all the tools on the same path.

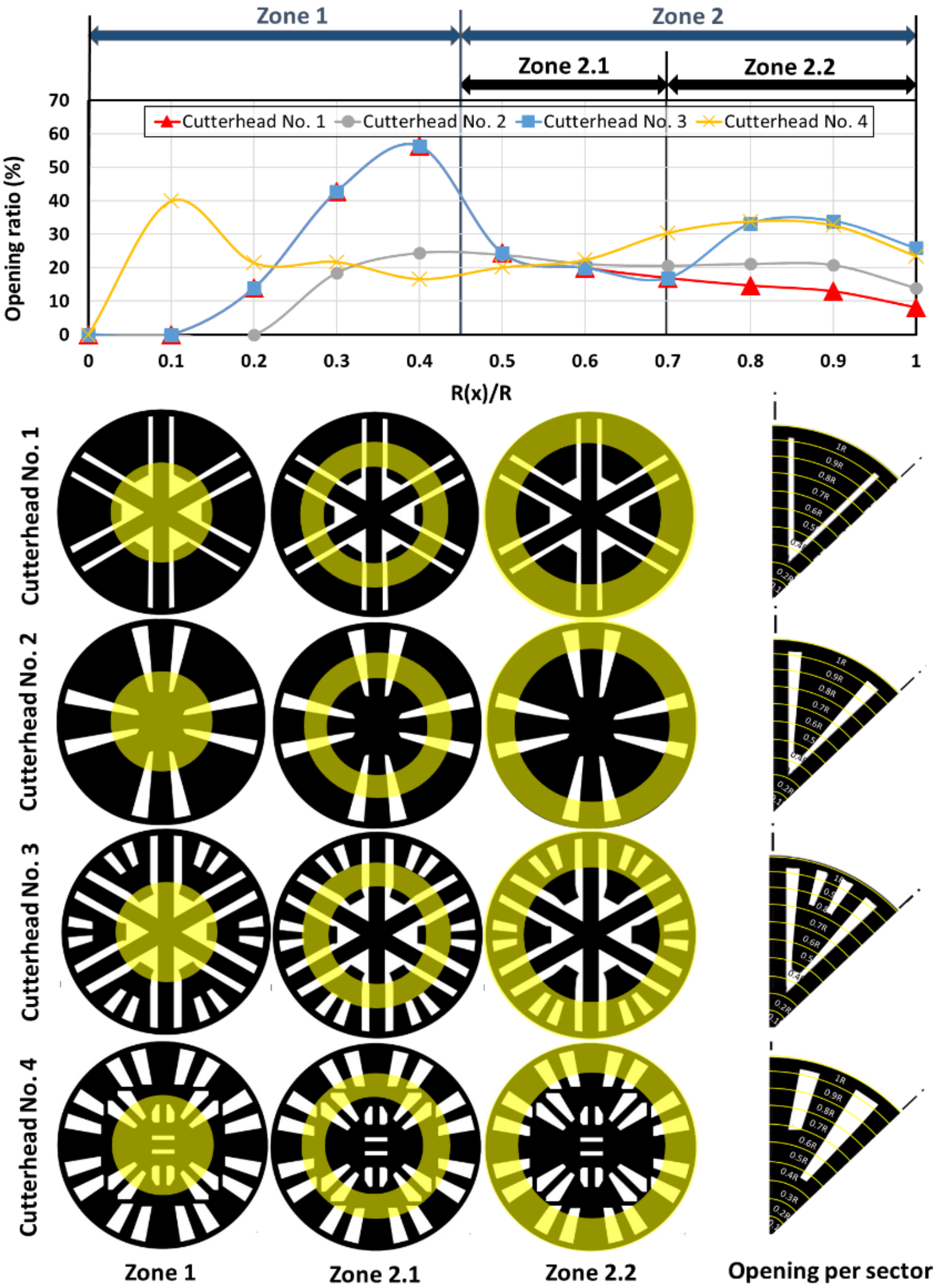


**Figure 15. Practical example of different opening design in zone 2.**

## 4. Discrete-element model for evaluation of cutterhead opening configuration in EPBMs

Discrete Element Method (DEM) analysis is a numerical modeling technique used in tunneling and underground excavation projects to simulate the behavior of soil or rock masses subjected to various loading conditions [22, 23]. DEM is particularly useful for analyzing the interaction between individual particles or blocks within a granular material, providing insights into the complex mechanisms of deformation, failure, and stability [24, 25]. By using DEM analysis in soft ground and hard rock TBM tunneling projects, engineers and tunneling contractors can better understand the complex interactions between the tunneling process and the geological conditions, leading to safer, more efficient, and cost-effective tunnel construction [26]. In the numerical modeling phase of the current study, a partial flow code as a distinct element framework will be employed to assess the cutterhead opening configuration in central and circumference areas. The discrete element method, also known as the distinct element method, is a numerical method used to compute the motion and interactions of a large number of small particles, making it suitable for analyzing large deformation problems [27]. The DEM is a numerical model that can handle particles of any shape and was developed by Cundall [28].

### 4.1. Statement of problem

Based on the database of various TBMs through soft ground, it is suggested that a larger cutterhead opening in the central area may be required to prevent clogging in cohesive grounds. However, a high opening ratio in the circumference area is a better choice in sandy gravel soils and mixed-ground conditions (soil ground to rock) for preventing obstructions around the cutterhead. To assess these principles, a comparative study using numerical models should be conducted. For this purpose, three different Herrenknecht cutterheads with different radial opening ratio in “zone 1 and 2” will be adopted for the numerical modeling to excavate in both non-cohesive and cohesive of Tehran alluvium for Tehran Metro Projects in Iran (Figure 16). The diameter of the machines considered for numerical simulation is about 9 m. The problem statement involves optimizing EPBM performance parameters by considering cutterhead opening configuration when excavating in different grounds. The best opening configuration for different grounds is determined when thrust force, cutterhead torque, and geo-hazards are minimized, and advance rate is maximized.

### 4.2. Structural element model (cutterhead and EPB system model)

In Figure 17, a three-dimensional model of the cutterhead, soil chamber, shield, and screw conveyor system for an EPB system was constructed at a full-scale ratio of 1:1. The cutterhead has a diameter of 9330 mm and a width of 550 mm. The chamber structure is cylindrical with a height of 1036 mm and external and internal diameters of 9330 mm and 9210 mm, respectively. The soil chamber includes four fixed mixing arms on the bulkhead and four rotational mixing arms behind the cutterhead, as well as eight rotational arms with a diameter of 508 mm. The screw conveyor, shown in the side view of Figure 17, has an installation angle of 23 degrees and consists of a shaft, screw blades, and conveyor housing. The screw blades have a pitch of 630 mm and a diameter of 1000 mm. Various cutting tools are arranged on the cutterhead face, which is consistent for three cutterheads based on Figure 16.

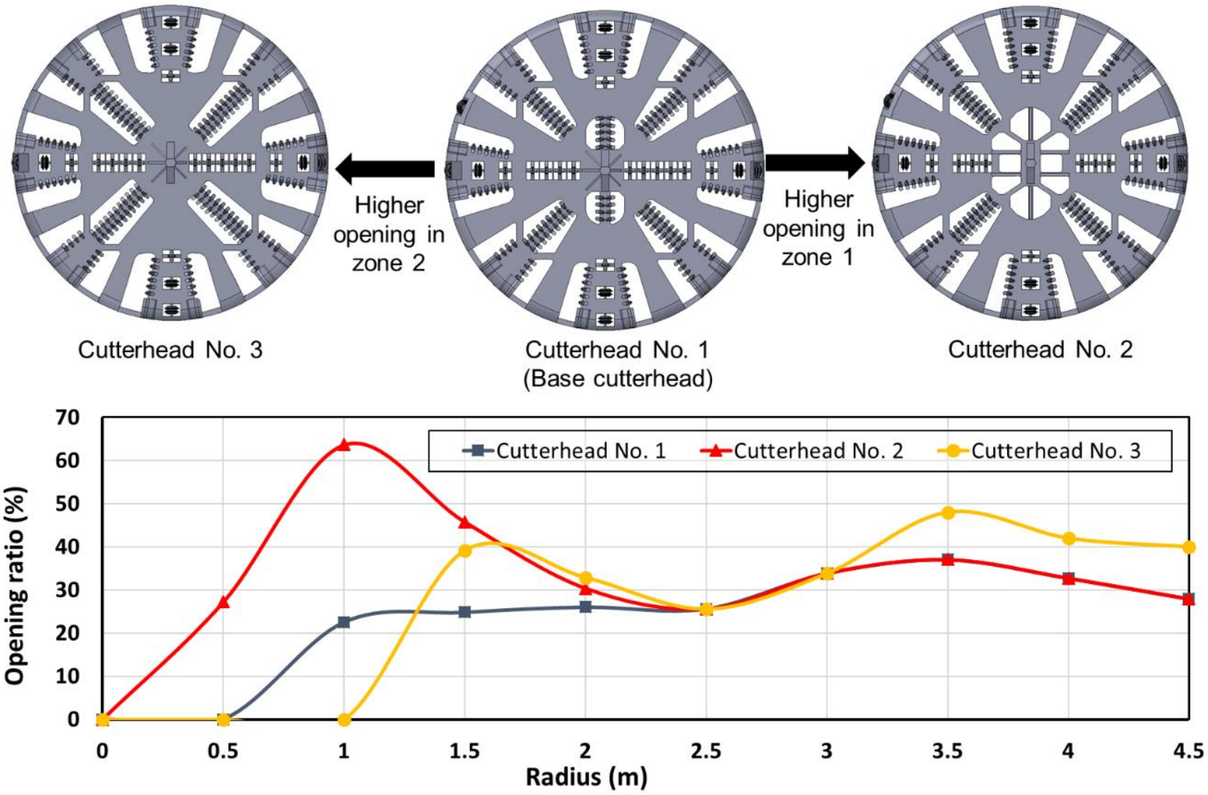


Figure 16. Radial opening ratio curve for cutterheads No. 1, 2 and 3 using numerical model.

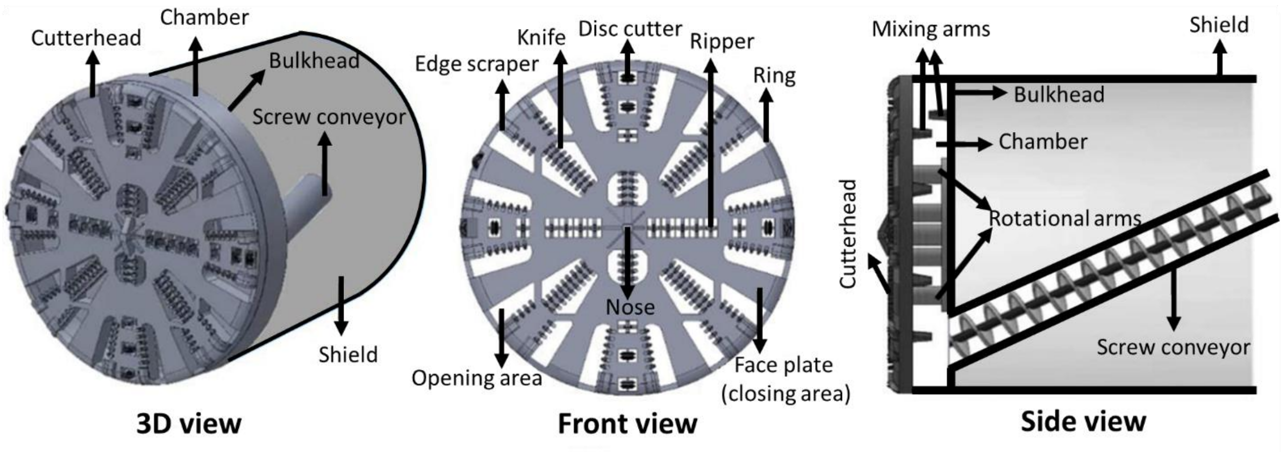


**Figure 17. Three-dimensional, front and side views of EPB system in numerical model.**

The steel material and Hertz–Mindlin model were assigned as the contact model for the soil particle-TBM components, including the cutterhead, cutting tools, chamber structure, screw conveyor, and shield (Table 3). The Hertz–Mindlin model is a soft-sphere model utilized for calculating particle-particle or particle-wall contact interactions. In this model, the normal force component is determined based on the Hertzian contact theory. The restitution coefficient, static friction coefficient, and rolling friction coefficient serve as input parameters for the model to compute the tangential force, normal force, and damping.

**Table 3. Material parameters for TBM structure and contact parameters of soil particle-TBM structure.**

| Material parameters | | | Contact parameters of particle-TBM structure | | | |
|---|---|---|---|---|---|---|
| Density, $\rho_s$ (kg/m$^3$) | G, shear modulus (Mpa) | Poisson's ratio, $\nu_s$ | Contact model* | e, restitution coefficient** | $\mu_s$, static friction coefficient** | $\mu_r$, rolling friction coefficient** |
| 7800 | 7*10$^4$ | 0.3 | Hertz–Mindlin | 0.25 | 0.7 | 0.001 |

* The contact model of soil particle-TBM structure adopts Hertz-Mindlin [29].

** The contact parameters of soil particle-TBM structure are derived from literature [30].

### 4.3. Particle element model (soils model)

In DEM simulations, the selection of a reliable DEM model for the soils is crucial. Directly defining input particle parameters for the DEM model was not feasible. Therefore, these parameters were estimated through back analysis of direct shear test results [31]. Two typical non-cohesive and cohesive soils from Tehran alluvium in Tehran metro projects were chosen for the DEM simulation, as shown in Table 4. Three-dimensional direct shear tests (based on ASTM D3080 [32]) were conducted to characterize the soil particle parameters and their interactions in the DEM model to validate the geotechnical parameters. The direct shear test was simulated using soil particles and box geometries, as depicted in Figure 18a. The servo control system regulated the shear displacement rate and shear strain under three different normal loads. The shear force and corresponding shear displacement were monitored in the test box through shear direction in the simulation to calculate the shear stress (Figures 18b and 18c). The contact parameters of the particle material were calibrated based on Table 5. With these parameters in place, the results of the direct shear test conducted through DEM simulation aligned with the laboratory test results based on the Mohr–Coulomb failure criteria and linear regression analysis (Figure 19). Hertz-Mindlin with JKR (Johnson-Kendall-Roberts) is a contact model that allows users to represent the cohesive nature of fine and moist materials.

**Table 4. The particle parameters of Tehran alluvium along Tehran metro tunnel projects [33].**

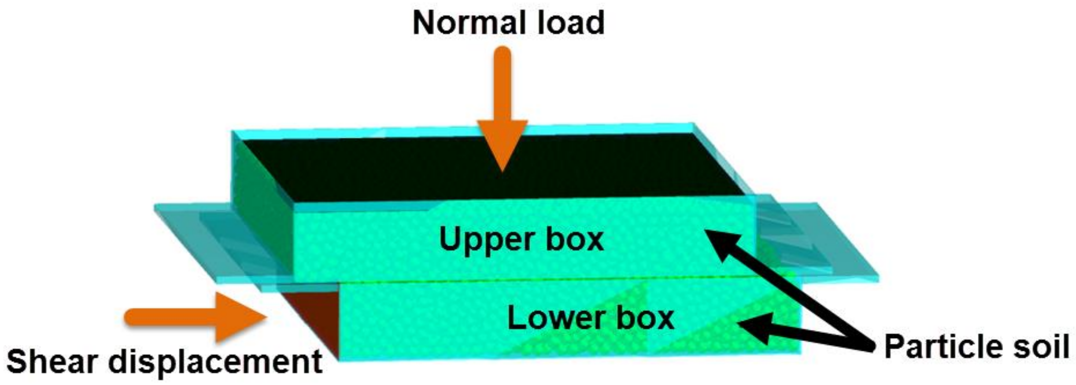
| Soil type | Soil type according to USCS standard | Material behavior | Elastic Modulus (MPa) | Cohesion (kPa) | Friction angle (deg.) | G, shear modulus (MPa) | Poisson's ratio | Unit weight (KN/m3) |
|---|---|---|---|---|---|---|---|---|
| ET-1 | GW and SW | non-cohesive | 80 | 5 | 35 | 30 | 0.35 | 21 |
| ET-5 | ML and CL | cohesive | 35 | 40 | 26 | 13 | 0.35 | 21 |

The cohesion and internal friction angle determined from the numerical model were approximately 4.8 kPa and 35.5° for the ET-1 soil type and 42 kPa and 25° for the ET-5 soil type, respectively (as compared to Table 4). This demonstrates the consistency and accuracy of the DEM simulation in capturing the behavior of different soil types under varying conditions.

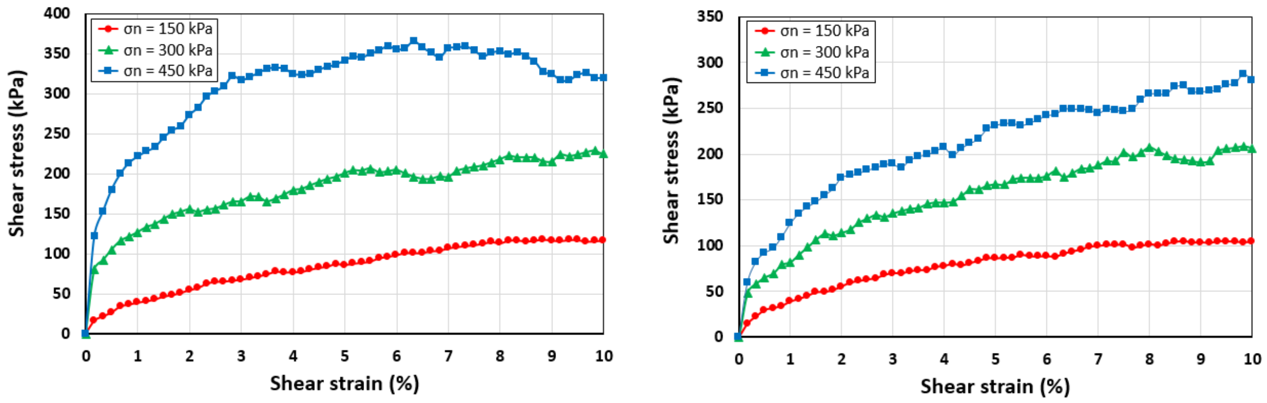
**Table 5. The calibrated contact parameters of Tehran alluvium along Tehran metro tunnel projects.**

| Soil type | Particle shape | Contact model | e, restitution coefficient | $\mu_s$, static friction coefficient | $\mu_r$, rolling friction coefficient | k, surface energy 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 |

Due to the substantial number of soil particles and TBM elements utilized in the DEM models, along with the dynamic interactions between these elements, computational cost and runtime were significant concerns in this academic study. To enhance computational performance, the particle sizes in the DEM simulation were increased by a factor of 8. The magnification factor was determined considering the cutterhead and screw conveyor capacities. Based on Figure 20, the sphere soil particles with diameters of 168 mm, 232 mm, and 312 mm accounted for 60.50%, 30.80%, and 8.70% of the total mass, respectively in the case of ET-1 soil. For ET-5 soil, particles with diameters of 8 mm, 2 mm, and 1 mm constituted 91.90%, 4.55%, and 3.55% of the total mass, arranged randomly. This approach allowed for efficient representation of the soil particles and structural elements in the DEM simulation, optimizing computational performance without altering the overall grading.



(a)



(b) (c)

**Figure 18. (a) Modeled direct shear test by DEM, (b) Shear test numerical results for ET-1 soil under three normal stress values and (c) Shear test numerical results for ET-5 soil under three normal stress values.**

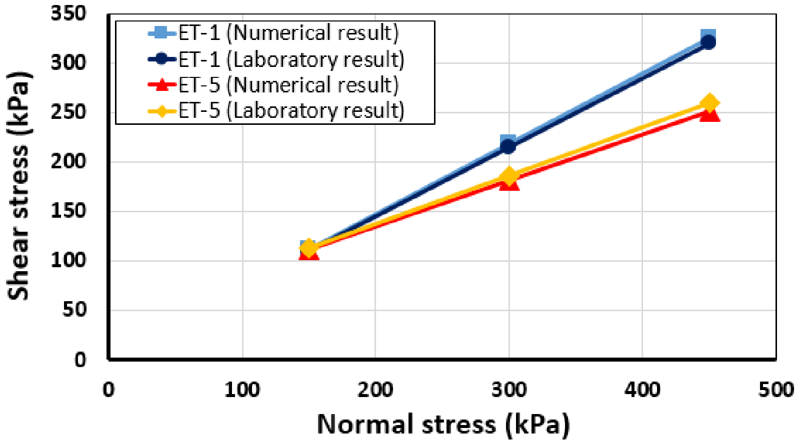


**Figure 19. Comparison of laboratory and numerical simulation results based on the Mohr–Coulomb failure criteria.**

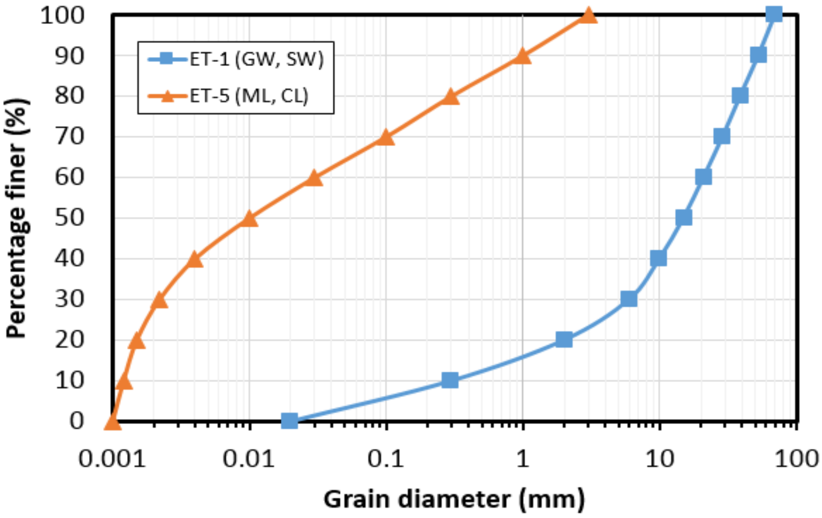


**Figure 20. Particle size distribution curves for non-cohesive and cohesive soil particles.**

In order to define the parameters of conditioned soil in the chamber system and screw conveyor in the Discrete Element Model (DEM), a series of slump tests were conducted to evaluate its flow behavior. Field studies indicated that the foam expansion ratio (FER), foam injection ratio (FIR), and foam concentration (Cf) were approximately 2.5, 50%, and 1.2%, respectively. The slump cone test was scaled up by a factor of 8, with a top diameter of 800 mm, bottom diameter of 1600 mm, and height of 2400 mm. The measured slump magnitude based on Tehran metro project was approximately 180 mm, as shown in Figure 21. The preferred slump range for EPB is between 10 cm and 20 cm, as specified in DIN EN 12350-2:2019 [34].

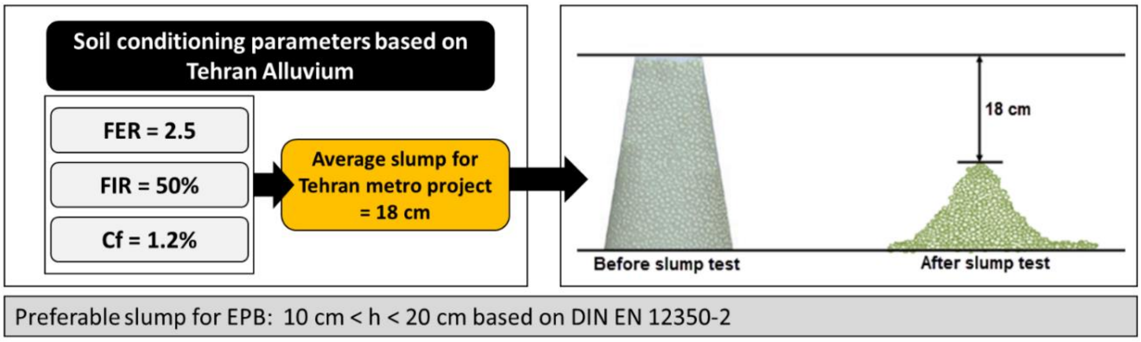


**Figure 21. Simulated slump test for conditioned soil to define the soil conditioned parameters.**

### 4.4. Assembly modeling, validation and collaboration

The simulation model of DEM is assembled with a structural element model (cutterhead and EPB system model) and a particle element model (soil model) based on Figure 22. 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, with wall-related parameters defined with soil particle parameters. The bottom, rear, and front sides of the soil box in DEM are constrained with rigid walls, which do not allow soil particles to escape from the soil box. However, periodic boundary conditions are assigned to the left and right boundaries of the soil box, meaning the boundary conditions are effectively infinite in the transverse direction, equivalent to removing the boundaries. This allows escaped soil particles to re-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 22, 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 for soil excavation at a specific speed, and the cutterhead and screw conveyor were rotated at specific speeds. The operational parameters are considered in Table 6. Excavation was simulated for 180 s.

**Table 6. The operation parameters of TBM for running in DEM [35].**

| Advance speed (mm/min) | Cutterhead Rpm (r/min) | Screw conveyor Rpm (r/min) | Chamber pressure (bar) |
|---|---|---|---|
| 33 | 1.1 | 4.5 | 0.9 |

In order to validate and calibrate the assembly modeling of soil particles (in-situ soil and conditioned soil in chamber) and TBM structure, the thrust force and cutterhead torque are monitored in the numerical model and on-site. Figure 23 shows the variations of on-site and numerically measured thrust force and cutterhead torque when tunneling under the same conditions. As seen in Figure 23, the thrust force for the numerical model and on-site remained at an average level of 1180 tons and 1150 tons, respectively. Additionally, the cutterhead torque was recorded at an average level of 380 ton.m and 370 ton.m, respectively. These results indicate good agreement, confirming the validity of the model and paving the way for the application of the numerical model for analysis.

### 4.5. Adaptability evaluation

#### 4.5.1. Particles flow characteristics

The performance of the EPB system is influenced by the flow conditions of soil particles within the chamber, with the goal of achieving higher operational efficiency, reducing clogging risks, and enhancing excavated material transport. The flow characteristics of the particles interact with the cutterhead structure, particularly its openings, as well as the chamber structure, including the rotational arms and mixing bars. The optimal cutterhead opening configurations for both central and circumference zones, considering non-cohesive and cohesive soils, will be determined through DEM simulation to analyze the flow dynamics within the chamber. Figures 24 and 25 illustrate the cross-sectional view of the velocity distribution of non-cohesive soil particles (ET-1) and cohesive soil particles (ET-5) for various cutterhead openings (Figure 16) within the chamber space.

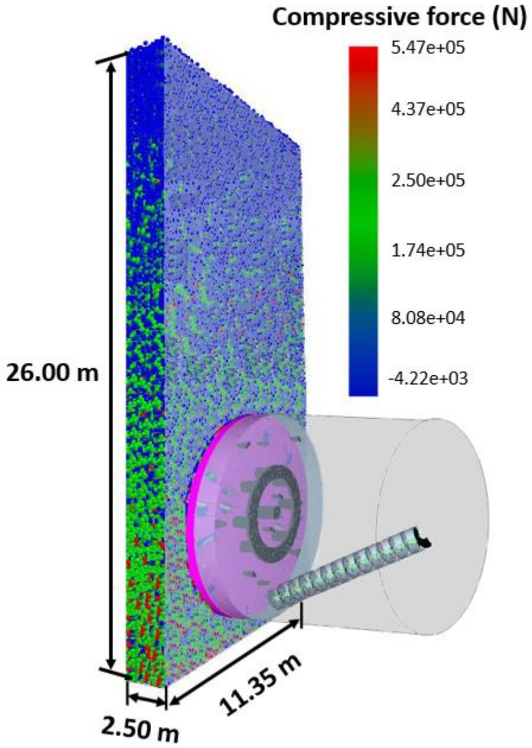
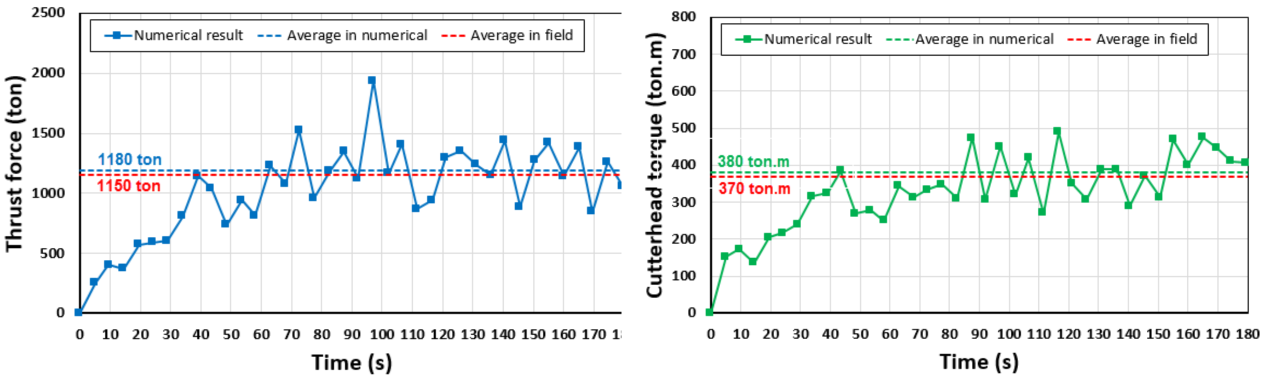
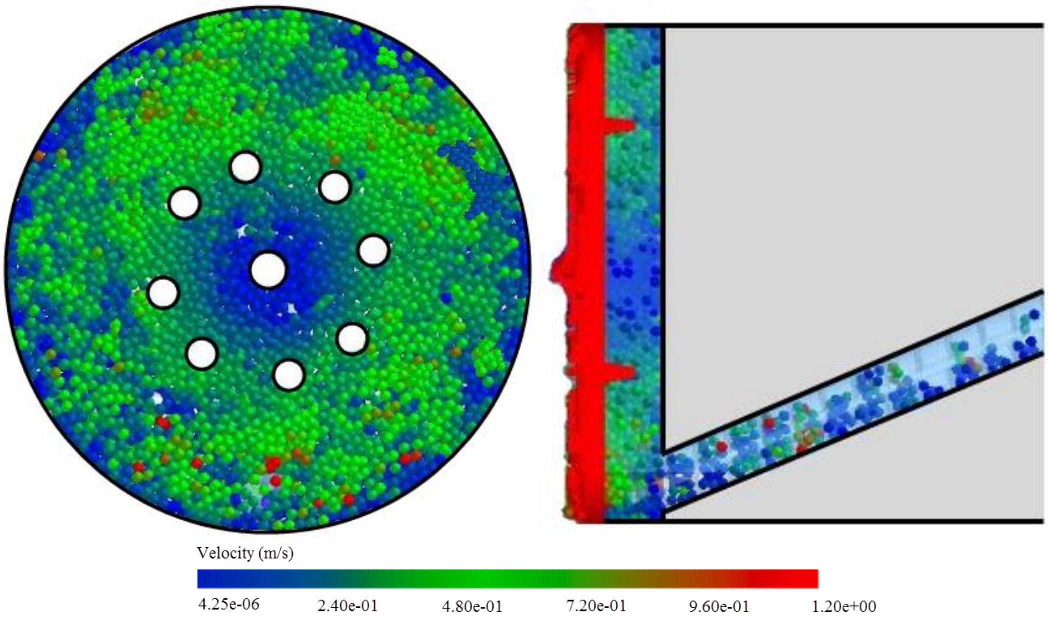


Figure 22. Assembled 3D DEM.

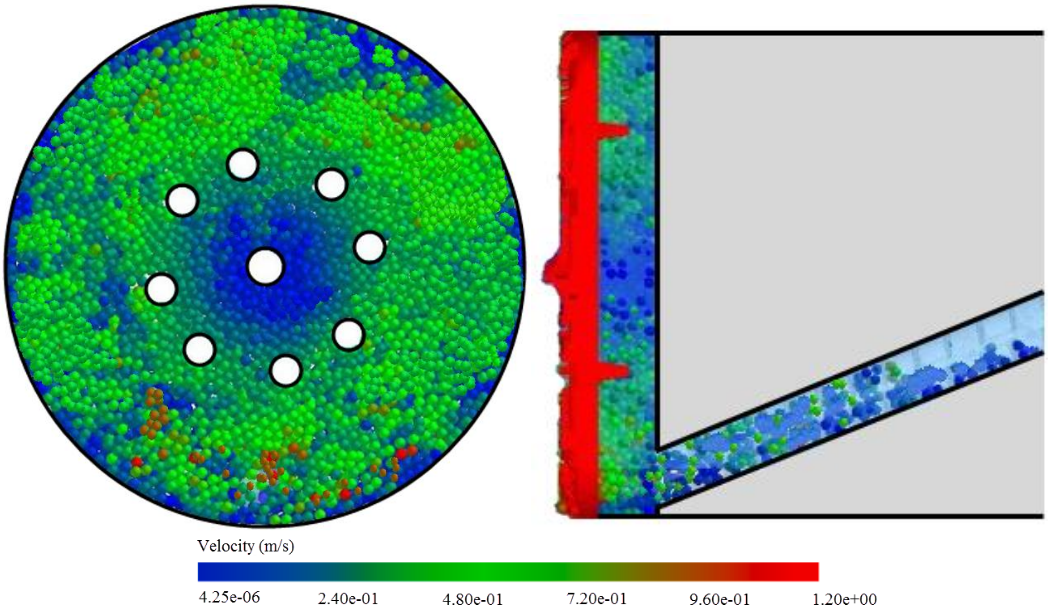


(a) (b)

**Figure 23. Comparison of the on-site and numerical result for (a) thrust force and (b) cutterhead torque.**

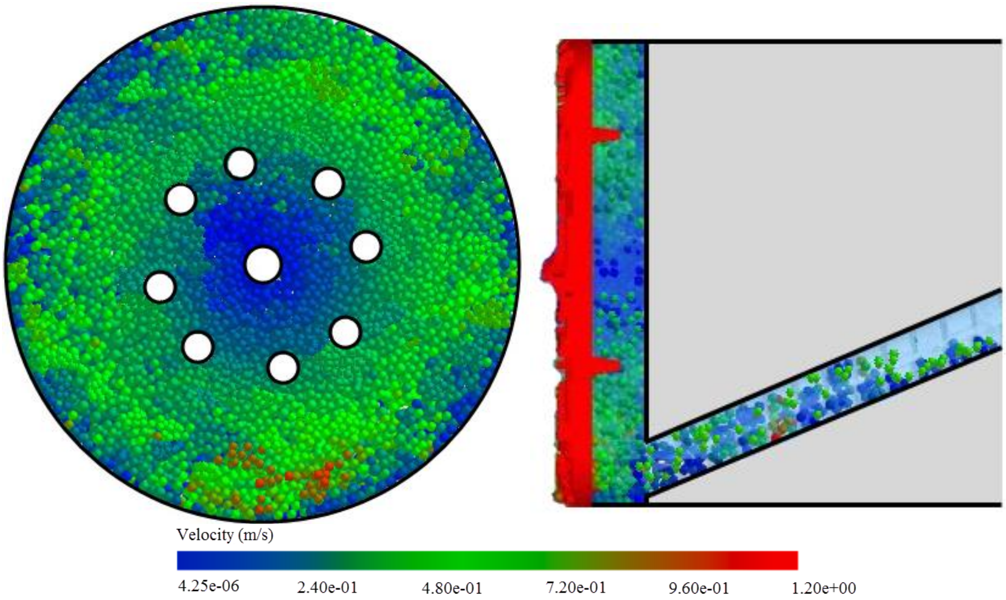


**(a) transverse and longitudinal sections along the chamber for cutterhead No. 1**

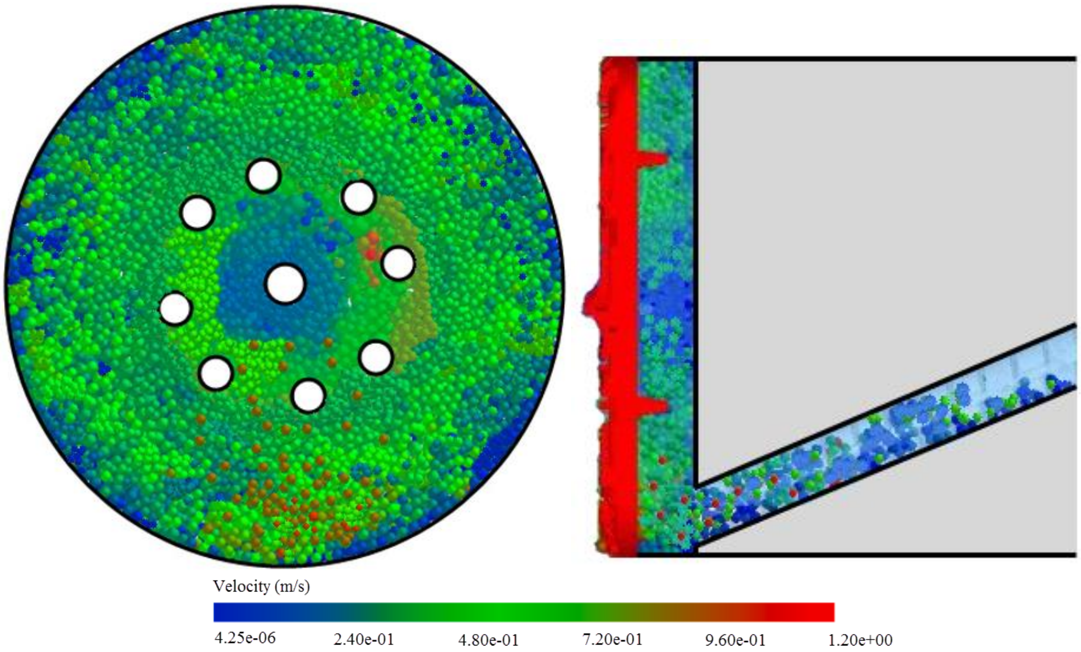


**(b) transverse and longitudinal sections along the chamber for cutterhead No. 3**

**Figure 24. The velocity distribution of soil particles in chamber for non-cohesive soils (ET-1).**



**(a) transverse and longitudinal sections along the chamber for cutterhead No. 1**



**(b) transverse and longitudinal sections along the chamber for cutterhead No. 2**

**Figure 25. The velocity distribution of soil particles in chamber for cohesive soils (ET-5).**

In Figures 24 and 25, the rotational arms create distinct zones within the chamber, with high fluidity observed in the areas outside the central zone enclosed by the arms (referred to as zone 1 in Fig 9). A comparison between Figure 24a and Figure 24b, focusing on non-cohesive soil, reveals that a higher circumference ratio of the cutterhead (cutterhead No. 3 in Fig 16) enhances the fluidity of soil particles, particularly in sandy gravel soils with boulders and mixed-ground conditions (transitioning from soil to rock). This configuration facilitates effective excavated material removal, including rock fragmentation and handling granular soils, while also preventing obstructions around the cutterhead. As observed, the particle movement speed within the chamber environment is higher in cutterhead No. 3 compared to cutterhead No. 1.

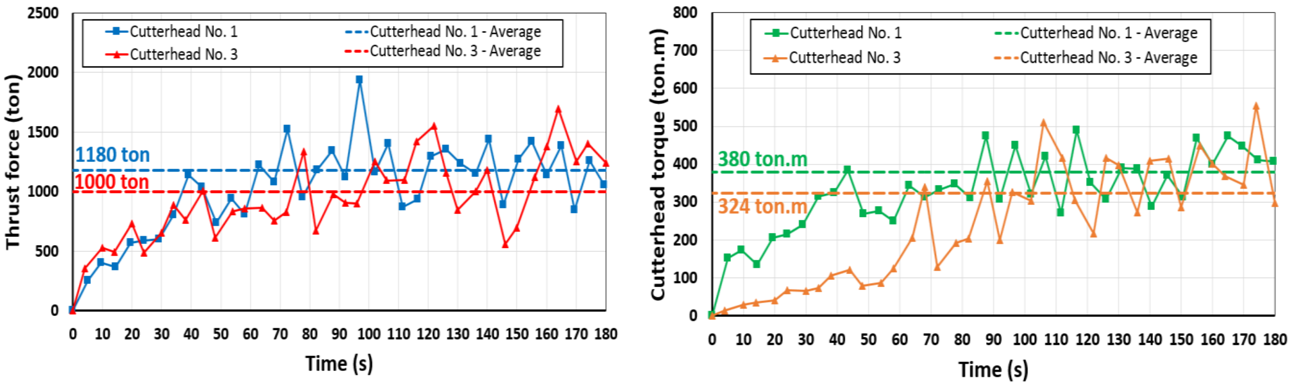
Similarly, comparing Figure 25a and Figure 25b for cohesive soil, a high opening ratio in the central zone of the cutterhead (cutterhead No. 2) enhances the fluidity of soil particles in this region, especially for cohesive soils. This design choice reduces the clogging risk, minimizes the standing time of particles, improves consolidation conditions in this area, and helps regulate the cutterhead temperature and energy consumption during the tunneling process. This comparison highlights the effectiveness of central cutterhead openings in enhancing fluidity and operational efficiency.

### 4.5.2. Cutterhead torque and thrust force

The cutterhead torque is the rotational force applied by the cutterhead to break and remove the soil as the TBM advances. In cohesive soils such as clay or silt, the soil particles tend to stick together, making it harder for the cutterhead to cut through and extract the soil. To effectively excavate cohesive soil, the cutterhead torque magnitude needs to be carefully calibrated to overcome the resistance offered by the soil. If the torque is too low, the cutterhead may struggle to break through the soil, leading to slower progress and potential machine downtime. On the other hand, if the torque is too high, it can put excessive stress on the cutterhead components and the tunnel boring machine as a whole, leading to increased wear and potential damage.

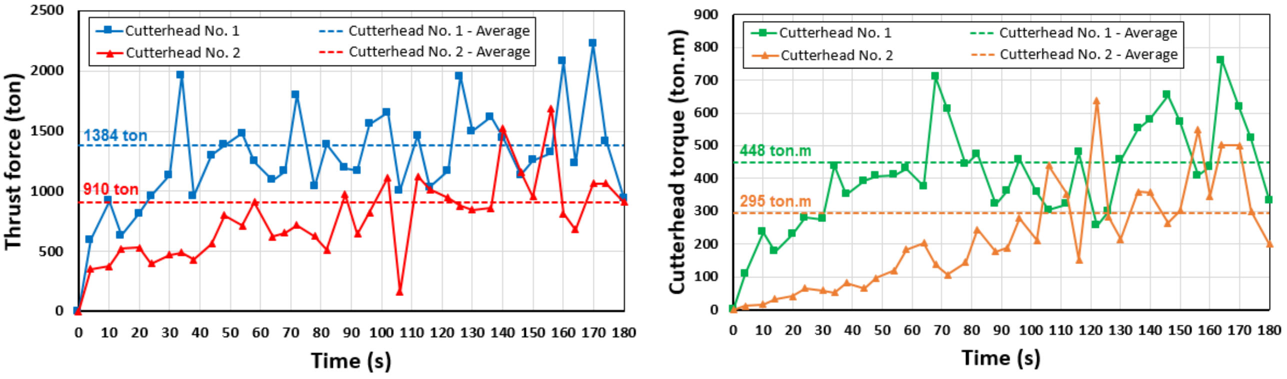
The thrust force magnitude for a TBM is influenced by several factors, including the type and strength of the soil, the diameter and length of the tunnel being excavated, the speed and power of the TBM, and the presence of any obstructions or obstacles in the soil. In cohesive soils, which are typically composed of fine particles, the soil has a tendency to stick together and form a cohesive mass. This can create a significant amount of resistance to the movement of the TBM, resulting in a higher thrust force requirement compared to non-cohesive soils.

To select the optimal cutterhead opening configuration, operational parameters such as thrust force and cutterhead torque values are analyzed. Comparing Figures 26a and 26b, and referring to Figures 27a and 27b, it is evident that both the thrust force and cutterhead torque decrease by approximately 15% and 34% when utilizing cutterhead No. 3 for non-cohesive soils and cutterhead No. 2 for cohesive soils in numerical simulations, in contrast to cutterhead No. 1. This reduction in operational forces signifies the improved efficiency and performance of the selected cutterhead configurations.



(a) (b)

**Figure 26. Comparison of numerical result for (a) thrust force magnitude and (b) cutterhead torque magnitude for non-cohesive soil and different cutterheads.**



(a) (b)

**Figure 27. Comparison of numerical result for (a) thrust force magnitude and (b) cutterhead torque magnitude for cohesive soil and different cutterheads.**

According to the data presented in Table 7, cutterhead No. 2 is identified as more suitable for cohesive soils, while cutterhead No. 3 is preferable for non-cohesive soils. These findings align with the results obtained from the numerical modeling studies, confirming the effectiveness of the selected cutterhead designs for their respective soil types.

**Table 7. Operational parameters of cutterhead with different opening in non-cohesive and cohesive soils from numerical modeling.**

| | **Non-cohesive soil** | | **Cohesive soil** | |
|---|---|---|---|---|
| | **Cutterhead No. 1** | **Cutterhead No. 3** | **Cutterhead No. 1** | **Cutterhead No. 2** |
| Average thrust force (ton) | 1180 | 1000 (-15.3%) | 1384 | 910 (-34.2%) |
| Average cutterhead torque (ton.m) | 380 | 324 (-14.7%) | 448 | 295 -34.2%) |

## 5. Field study for evaluation of cutterhead opening configuration in EPBMs

The Tehran metro project in Iran serves as a case study for comparative analysis of cutterhead opening design. Tehran metro lines 6 and 7 were excavated by four EPBMs and NATM method with the length of about 41.4 km and 29.6 km, respectively. Two Herrenknecht and two Lovat TBMs had excavated approximately 18.5 km in line 6 and 22.6 km in line 7 with an excavated diameter of 9.13 m, respectively, Figure 28.

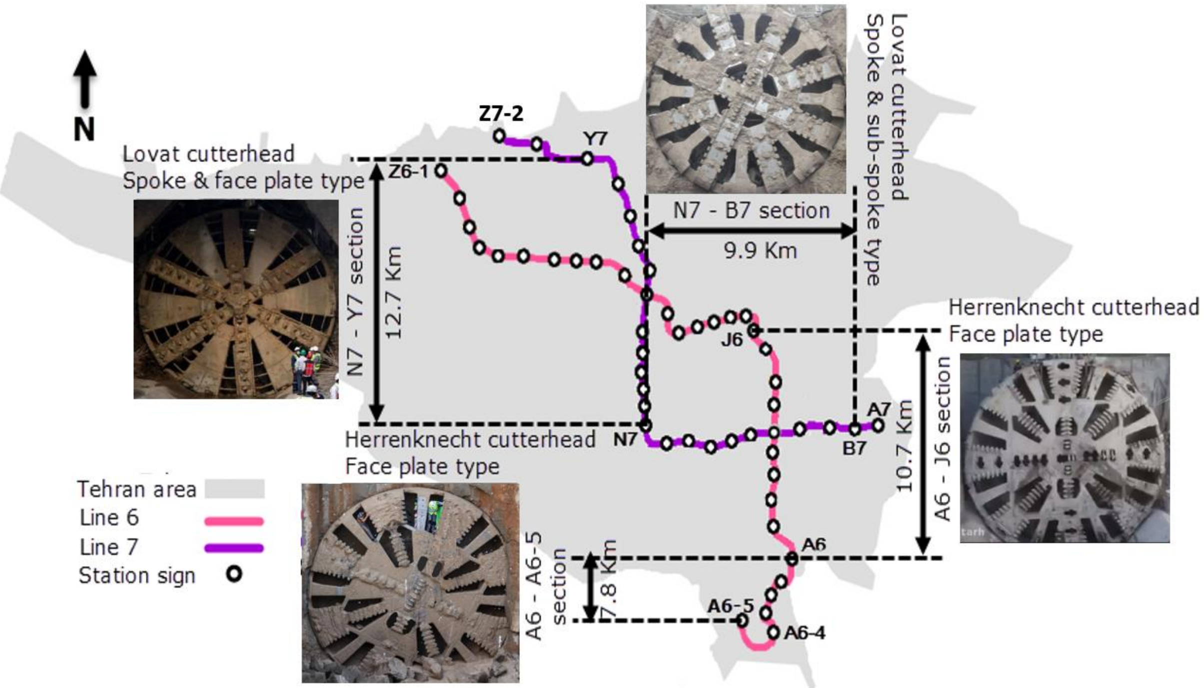


**Figure 28. Different cutterhead types for lines 6 and 7 of Tehran metro project.**

The radial opening ratio curve for the three different cutterhead configurations used in these projects is shown in Figure 29. Cutterhead No. 1, designed as a spoke-panel type, has an opening ratio of (6-24) % in zone 1 and (30-45) % in zone 2. Cutterhead No. 2, also a spoke-panel type, has an opening ratio of (0-47) % in zone 1 and (30-45) % in zone 2. Cutterhead No. 3, designed as a panel type, has an opening ratio of (0-30) % in zone 1 and (25-40) % in zone 2.

The geological conditions encountered during tunneling in these projects, as well as the properties of the machines and the variation of EPB machine operational parameters and performance parameters for 1010 selected rings that were subjected to the same geotechnical conditions and overburden, are shown in Appendix B. These parameters are summarized in Table 8. Thrust force and cutterhead torque were monitored based on the same geotechnical parameters (ET-2 and ET-3 units from Tehran Alluvium), above the groundwater table, the same tunnel overburden, similar soil conditioning parameters, rpm, penetration rate (advance rate), and chamber pressure. All three cutterheads had the same cutting tools and chamber structure.

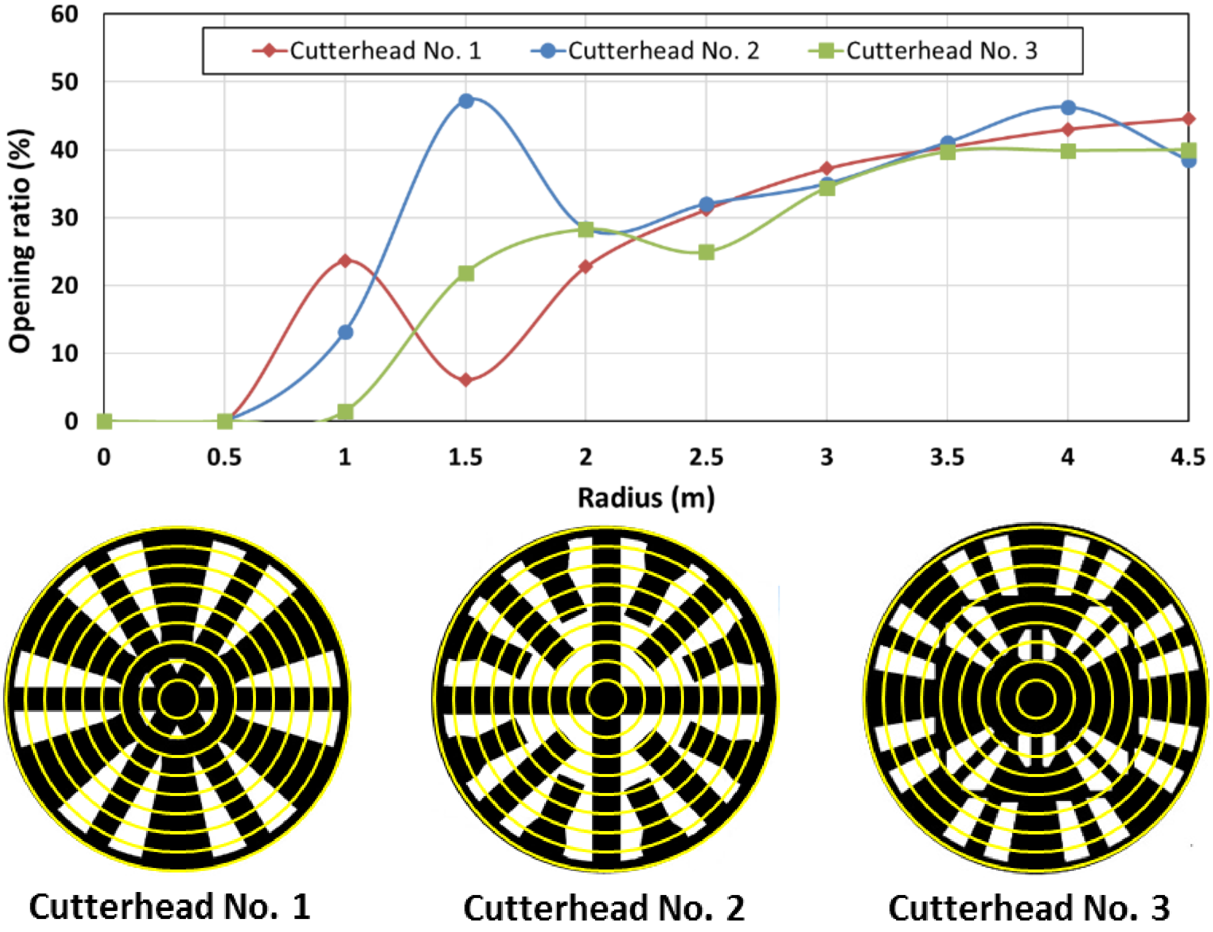


**Figure 29. Radial opening ratio curve of cutterheads in lines 6 and 7 of Tehran metro project.**

**Table 8 Operational and performance parameters of EPB machines in 1010 selected rings for Tehran metro project.**

| Cutterhead No. | Average thrust force (ton) | Average cutterhead torque (ton.m) | | | Chamber pressure (bar) | Average penetration rate (mm/min) | rpm average | Soil conditioning parameters | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Total | Mechanical | Excavation | | | | FER | FIR (%) | $C_f$ (%) |
| Cutterhead No. 1 | 1850 | 1040 | 700 | 340 | 0.55 – 1.00 | 32 | 1.03 | 2.50 | 50 | 1.2 |
| Cutterhead No. 2 | 1520 | 880 | 650 | 230 | 0.60 – 1.00 | 33 | 1.02 | 2.50 | 50 | 1.2 |
| Cutterhead No. 3 | 1153 | 370 | 150 | 220 | 0.65 – 1.00 | 33 | 1.08 | 2.50 | 50 | 1.2 |

It's interesting to note the impact of cutterhead opening configuration on machine performance. The findings from Shi et al.'s studies further emphasize the significance of this factor [12]. The variation in thrust force and cutterhead torque despite the same geotechnical and operational conditions suggests that the cutterhead opening configuration indeed plays a crucial role in the performance of EPB machines. This insight could be valuable for optimizing machine design and operational parameters to enhance tunneling efficiency and effectiveness.

Based on the data in Table 8, it is evident that cutterhead No. 2 and cutterhead No. 3 demonstrated strong adaptability in Tehran Alluvium (ET-2 and ET-3 units) due to their average excavation torque (approximately 230 ton.m and 220 ton.m, respectively) and average total thrust (around 1520 ton and 1153 ton, respectively). This indicates that the opening-closing configuration of these two cutterheads was well-designed for effective performance in these geological conditions. Furthermore, the central opening in cutterhead No. 2 proved to be more effective than cutterhead No. 3 in cohesive soil (ET-5 unit). This suggests that the specific design of the central opening in cutterhead No. 2 was particularly well-suited for excavation in this type of soil. On the other hand, cutterhead No. 1 displayed an excavation torque value approximately 50% higher than the other cutterheads, indicating relatively poor performance compared to cutterhead No. 2 and No. 3.

In summary, based on the data provided in Table 8, it can be concluded that cutterhead No. 1 exhibited the worst performance, while cutterhead No. 2 and No. 3 demonstrated strong adaptability and effective performance in the specified geological conditions. It's interesting to note that the optimal opening cutterhead design for excavation in Tehran Alluvium typically requires a certain distribution of opening percentages in the zone 1 and 2. The range of 30% to 50% in the zone 1 and 30% to 40% in zone 2 for excavation in all types of Tehran Alluvium suggests a specific design requirement for cutterheads to achieve optimal performance in this geological context. Furthermore, the statement regarding the suitability of both spoke and panel type cutterheads for Tehran Alluvium emphasizes the adaptability of these designs to the geological conditions encountered in the Tehran metro tunneling projects.

## 6. Conclusions

The research reviewed the current state-of-the-art design of TBM manufacturers for the opening configuration of soft ground cutterheads. The following study underscores the importance of well-designed cutterheads in addressing the challenges posed by various ground types. A comprehensive analysis was conducted on different cutterhead opening configurations using TBM manufacturers' databases. Furthermore, the study involved analyzing the performance parameters and particle flow characteristics of cutterheads with distinct opening configurations in both the central and circumferential areas of the cutterhead using Discrete Element Method (DEM). Finally, the research examined the performance of different EPB cutterhead designs under the same geotechnical and operational parameters in the real tunneling projects in Iran. The key findings are as follows:

1. According to the trend of the radial opening ratio curves based on the database, the cutterhead opening area should be divided into two main parts (e.g. zone 1: the area between the central point of the cutterhead and rotational arms and zone 2: the remaining areas between the rotational arms and the circumference) for the design aspects.
2. As we move towards the circumference area of the cutterhead, the amount of opening area should increase. In other words, the opening percentage along all points of zone 2 should be the same. The cutterhead opening configuration should be designed to ensure the uniform and smooth transfer of excavated materials from the tunnel face to the chamber space, which can prevent any blind zones on the cutterhead.
3. Generally, the opening area in “zone 1” increases from hard rock to cohesive grounds due to low linear velocity, clogging potential, less mixing, high density, and poor fluidity of excavated material in this zone.
4. Generally, the opening area in “zone 2” decreases from hard rock to cohesive grounds due to quick transport of the excavated material around the cutterhead. The high opening ratio in zone 2.2 is a better choice for effective excavated material removal and for preventing obstructions around the cutterhead in sandy gravel soils with boulders and mixed-ground conditions (soil grounds to rock).
5. The suggestion derived from the analysis of TBM manufacturers' databases, numerical results, and field studies indicates that for cohesive ground conditions, a larger cutterhead opening in the central area may be necessary. Conversely, in non-cohesive ground conditions, opting for a higher opening ratio in the circumference area is recommended.
6. The optimal cutterhead opening design requires, on average, 30% to 50% in zone 1 and approximately 30% to 40% in zone 2 for excavation in all types of Tehran Alluvium in Iran.

## References

[1]. Mohammadi, D., Shahriar, K., Moarefvand, P., & Farrokh, E. (2023). Discussion of cutterhead opening design for earth pressure balance machines (EPBMs) in soft grounds. *Proceedings of the Institution of Civil Engineers (ICE) - Geotechnical Engineering.*

[2]. Nishitake, S. (1987). Earth pressure balanced shield machine to cope with boulders. *Rapid Excavation and Tunneling Conference*, pp. 552–572.

[3]. Burger, W. (2007). Design Principles for Soft Ground Cutterheads, *Rapid Excavation and Tunneling Conference*, pp. 13–22.

[4]. Mongillo, G., & Alsaleh, M. (2011). Discrete element method to predict soft ground cutterhead performance, *Society for Mining, Metallurgy, and Exploration*, pp. 1058–1067.

[5]. Grothen, B. (2015). Optimizing Soft Ground Excavation: Development and Design of EPB and Slurry Cutterheads, *ITA WTC.*

[6]. Herrenknecht, M., Thewes, M., & Budach, C. (2011). The development of earth pressure shields: from the beginning to the present, *Geomechanics and Tunnelling (4)*, pp. 11-35.

[7]. Rostami, J., & Chang, S. (2017). A closer look at the Design of Cutterheads for Hard rock Tunnel-Boring Machines, *Engineering (3)*, pp. 892–904.

[8]. Wu, L., Guan, T., & Lei, L., (2013). Discrete element model for performance analysis of cutterhead excavation system of EPB machine, *Tunnelling and Underground Space Technology (37)*, pp. 37–44.

[9]. British Tunnelling Society (BTS) (2005). Closed-face tunnelling machines and ground stability, *ICE publisher*.

[10]. Yang, H.J., Fu, D.M., & Ge, X.R. (2006). Experimental study and numerical simulation of earth pressure around shield machine. *Yanshilixue Yu Gongcheng Xuebao 25*, 1652–1657.

[11]. Ocak, I., & Bilgin, N. (2009). The performance of Two EPB machines in Istanbul Metro tunnel drives in soft and shallow ground, *a Chapter in ResearchGate*.

[12]. Shi, H., Yang, H., Gong, G., & Wang, L. (2011). Determination of the cutterhead torque for EPB shield tunneling machine, *Automation in construction (20)*, pp. 1087-1095.

[13]. Wang, L., Gong, G., Shi, H., & Yang, H. (2012). Modeling and analysis of thrust force for EPB shield tunneling machine, *Automation in construction (27)*, pp. 138-146.

[14]. Guo, W., Hu, J., & Liu, J. (2014). The scheme design for the earth pressure balance shield cutterhead structure, *Engineering Mechanics*, pp. 4589-4599.

[15]. Godinez, R., Yu, H., Mooney, M., Alavi-Gharahbagh, E., & Frank, G. (2015). Earth Pressure Balance Machine Cutterhead Torque Modeling: Learning from Machine Data, *Colorado School of Mines.*

[16]. Sandell, T.D., & Stypulkowski, J. (2015). Dual mode “crossover” type tunnel boring machines: a unique solution for mixed ground in the middle east, *robbinstbm.com.*

[17]. Cheng, C., Liao, S., Chen, L., & Zhou, Z. (2016). Comparative Study on Suitability of EPB Machine in Typical Sandy Cobble Ground in China, *Transportation Research Congress*, pp. 590-603.

[18]. Li, X., Yuan, D., & Huang, Q. (2017). Cutterhead and Cutting Tools Configurations in Coarse Grain Soils, *The Open Construction and Building Technology Journal* (11), pp. 182-199.

[19]. Yang, Z.H., Jiang, Y.S., & Zhang, J.X. (2018). Radial opening ratio of EPB TBM cutterheads. *Chinese Journal of Geotechnical Engineering*, Vol. 40, No. 12.

[20]. Ebrahimy, B., Khosravi, A.A., Lees, D., & Koohsari, A. (2022). Effect of cutterhead on performance of EPBM in mixed face condition, *WTC2022, Copenhagen, Denmark*.

[21]. Chen, X.J., Fang, P.P., Chen, Q.N., Hu, J., Yao, K., & Liu, Y. (2023). Influence of cutterhead opening ratio on soil arching effect and face stability during tunnelling through non-uniform soils, *underground space journal.*

[22]. Sarfarazi, V., Haeri, H., Fatehi Marji, M., & Saeedi, G. (2024). On the 2D discrete element analyses of the transversely isotropic elastic geo-materials; insight to scale effects and loading rate, *Journal of Mining and Environment 15 (3)*, 1051-1070.

[23]. Sarfarazi, V., Haeri, H., Bagheri, F., Zarrin Ghalam, E., & Fatehi Marji, M. (2022). PFC simulation of Brazilian tensile strength test in geomaterials’ specimens with T-shaped non-persistent joints, *Journal of Mining and Environment 13 (4)*, 1189-1209.

[24]. Fu, J., Safaei M.R., Haeri, H., Sarfarazi, V., Fatehi Marji, M., Xu, L., & Arefnia, A. (2022). Experimental investigation on deformation behavior of circular underground opening in hard soil using a 3D physical model, *Journal of Mining and Environment 13 (3)*, 727-749.

[25]. Sarfarazi, V., & Asgari, K. (2022). Influence of Single Tunnel and Twin Tunnel on Collapse Pattern and Maximum Ground Movement, *Journal of Mining and Environment 13 (1)*, 117-128

[26]. Sarfarazi, V., Haeri H., Shemirani, A.B., Hedayat, A., & Hosseini, S.S. (2017). Investigation of ratio of TBM disc spacing to penetration depth in rocks with different tensile strengths using PFC2D, *Computers and Concrete, An International Journal 20 (4)*, 429-437.

[28]. Cundall, P.A., & Strack, O.D.L. (1979). A discrete numerical method for granular assemblies. *Geotechnique 29 (1)*, 47–65.

[27]. DEM Solutions Ltd. (2022). *EDEM user guide. Edinburgh, United Kingdom.*

[29]. Hu, G.M. (2010). Analysis and simulation of granular system by discrete element method. *Wuhan University of Technology Press, Wuhan* (in Chinese).

[30]. Ma, T. (2016). Study on particle flow and ground settlement control of earth pressure balance shield tunneling in sandy pebble stratum based on the DEM. Master thesis. *Jiaotong University, Beijing*, pp. 46 (in Chinese).

[31]. EFNARC A. (2005). Specifications and Guidelines for the use of specialist products for mechanized tunnelling (TBM) in soft ground and hard rock. *Recomm Eur Fed Prod Contract Spec Prod Struct 1*:18–30.

[32]. ASTM D 3080 (2011). Standard test methods for direct shear test of soils under consolidated drained conditions. ASTM International, *West Conshohocken, PA, USA*.

[33]. P.O.R. Consulting Co. (2009). Geotechnical Investigations & Foundation Report for Tunnel and Station, *Tehran Metro Line 6 and 7 Project., Tehran, Iran (in Persian)*.

[34]. DIN EN 12350-2 (2019). Testing fresh concrete - Part 2: Slump test; *German version EN 12350-2*. Prüfung von Frischbeton - Teil 2: Setzmaß; *Deutsche Fassung EN 12350-2*.

[35]. SELI Co. (2015). Earth Pressure Balance Machine Specification and the Operational Parameters and Performance Analysis. *Report for Tehran Metro Project-Line 6 and 7 North–South Section, Tehran, Iran*.

## Appendix A

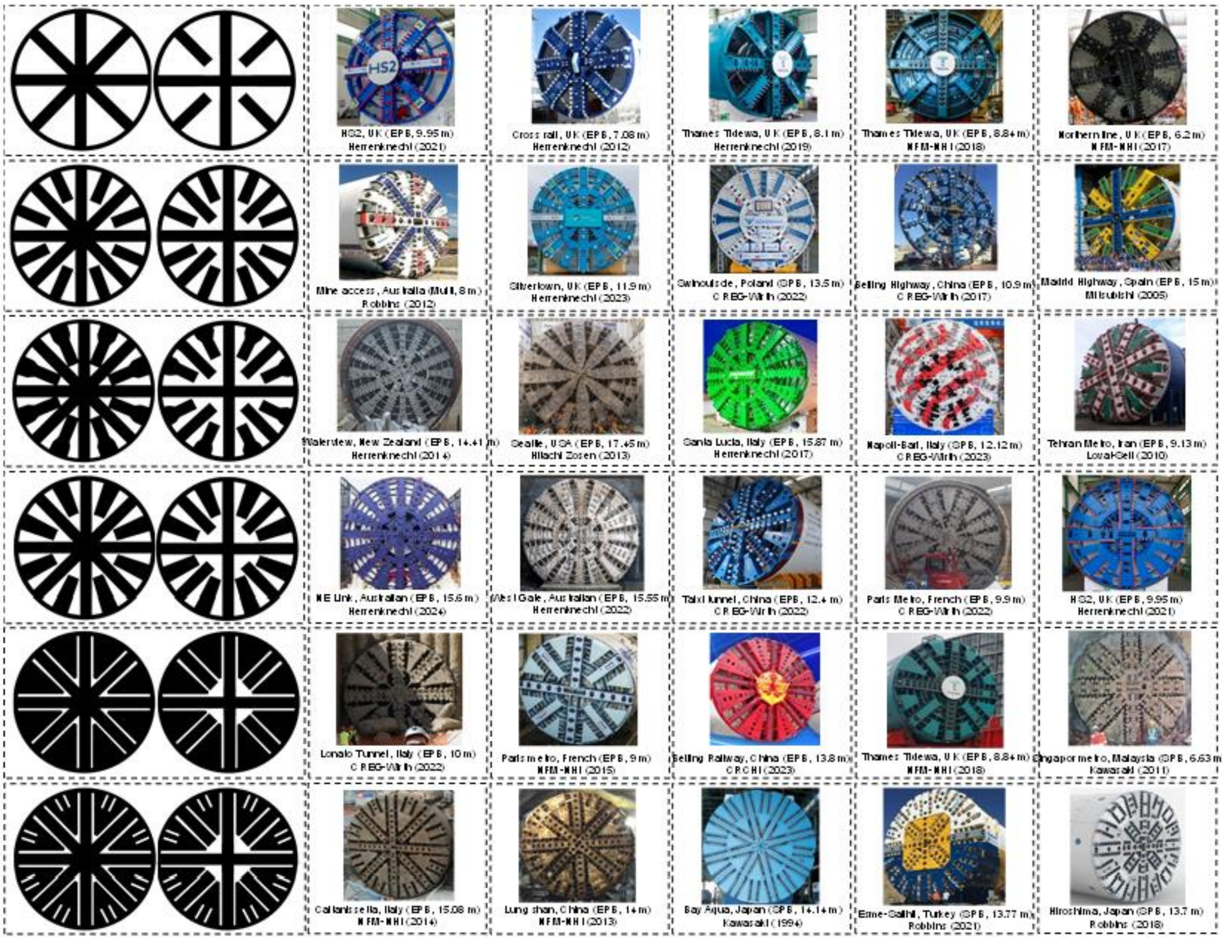


Figure A1 shows schematic summary of database from different soft ground cutterheads.

**Figure A1. Different cutterhead configurations based on database for soft ground conditions**

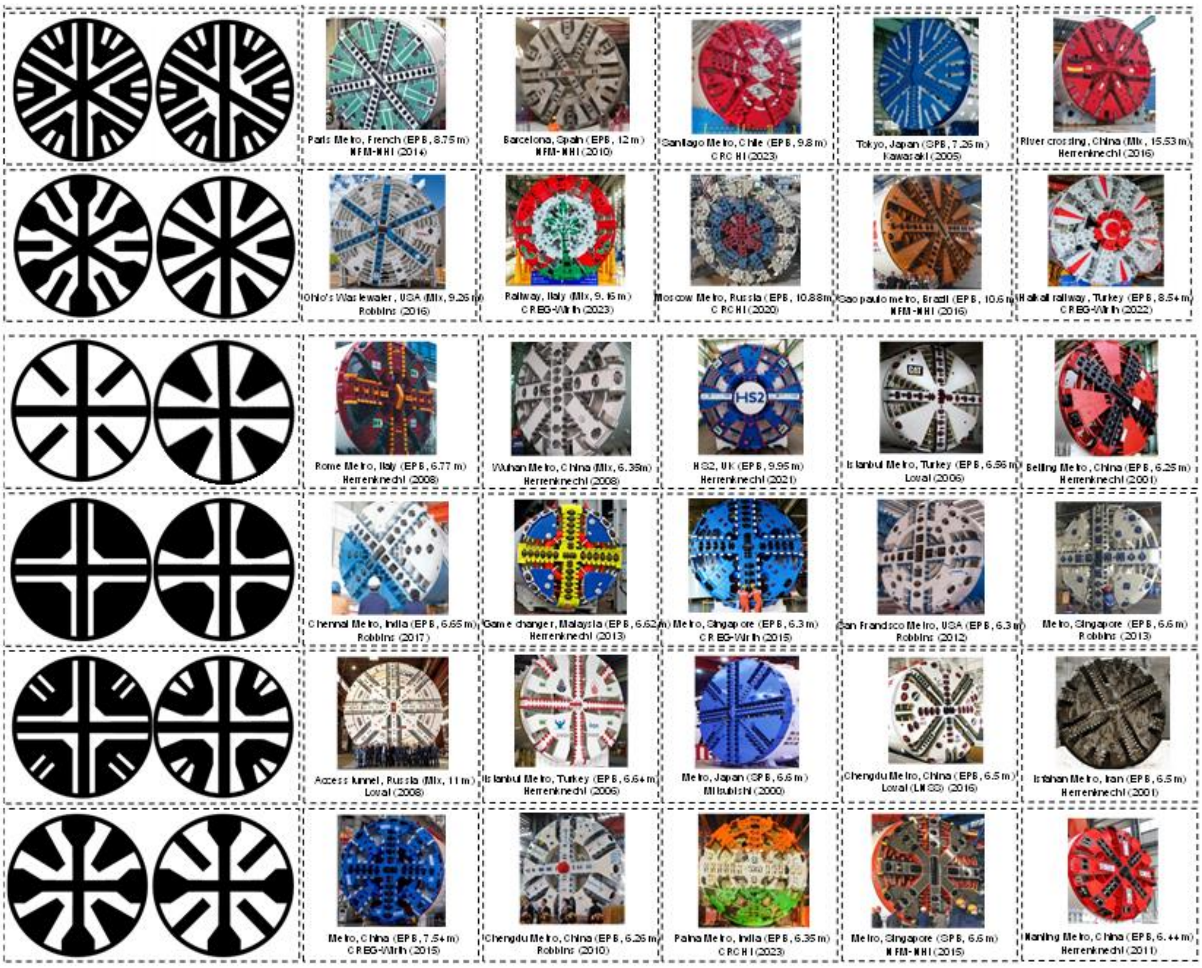


**Figure A1. Different cutterhead configurations based on database for soft ground conditions.**

## Appendix B

General range of values for the specifications of engineering geological units along lines 6 and 7 of Tehran metro tunnel and their TBM properties were illustrated in Table B1 and Table B2, respectively.

**Table B1 Specifications of engineering geological units along Tehran metro tunnel [33].**

| Engineering-type (ET) specification | ET-1 | ET-2 | ET-3 | ET-4 | ET-5 | ET-6 |
|---|---|---|---|---|---|---|
| Soil description | sandy GRAVEL & gravely SAND | gravely SAND with silt and clay | silty clayey SAND with gravel, sandy CLAY (or SILT) with gravel | clayey silty SAND with GRAVEL | clayey SILT and silty CLAY with sand, sandy CLAY (or SILT) | clayey SILT and silty CLAY with sand, sandy CLAY (or SILT) |
| Passing sieve no. 200 | 3-12% | 12-30% | 30-60% | 22-34% | 60% < | 60% < |
| Soil type according to USCS standard | GW, GW-GM, GP-GC, SW and SP | GC, SC-SM and SC | ML, CL, SC, SM and GC | SC, SM, CL and ML | ML and CL | ML and CL |
| Cohesion (kPa) | 5-12 | 11-19 | 24-36 | 21-25 | 27-40 | 0-2 |
| Friction angle (deg.) | 33-35 | 32-34 | 28-38 | 31-36 | 26-31 | 25-29 |

**Table B2 General properties of lines 6 and 7 Tehran metro TBMs.**

| TBM properties | No. 1 | No. 2 | No. 3 |
|---|---|---|---|
| Manufacturer | LOVAT - Canada | LOVAT - Canada | Herrenknecht - Germany |
| Diameter (m) | 9.16 | 9.16 | 9.33 |
| Type of drive | Hydraulical | Hydraulical | Hydraulical |
| Main drive diameter (mm) | 4200 | 4163 | 5000 |
| Hydro-motor number | 11 | 10 | 18 |
| Hydro-pump number | 7 | 7 | 8 |
| Cutterhead speed (rpm) | 0 - 2 | 0 - 2 | 0 – 2.8 |
| Breakaway torque (kN.m) | 25079 | 26000 | 24997 |
| Nominal torque (kN.m) | 20063 | 20900 | 20533 |
| Cutterhead power (kw) | 2100 | 2100 | 3200 |
| Main thrust cylinders number | 2 × 19 | 2 × 19 | 2 × 13 |
| Maximum thrust force (kN) | 65000 | 65400 | 87824 |

Figures B1-B3 show operational and performance parameters of three different TBMs utilized in Tehran metro lines 6 and 7.

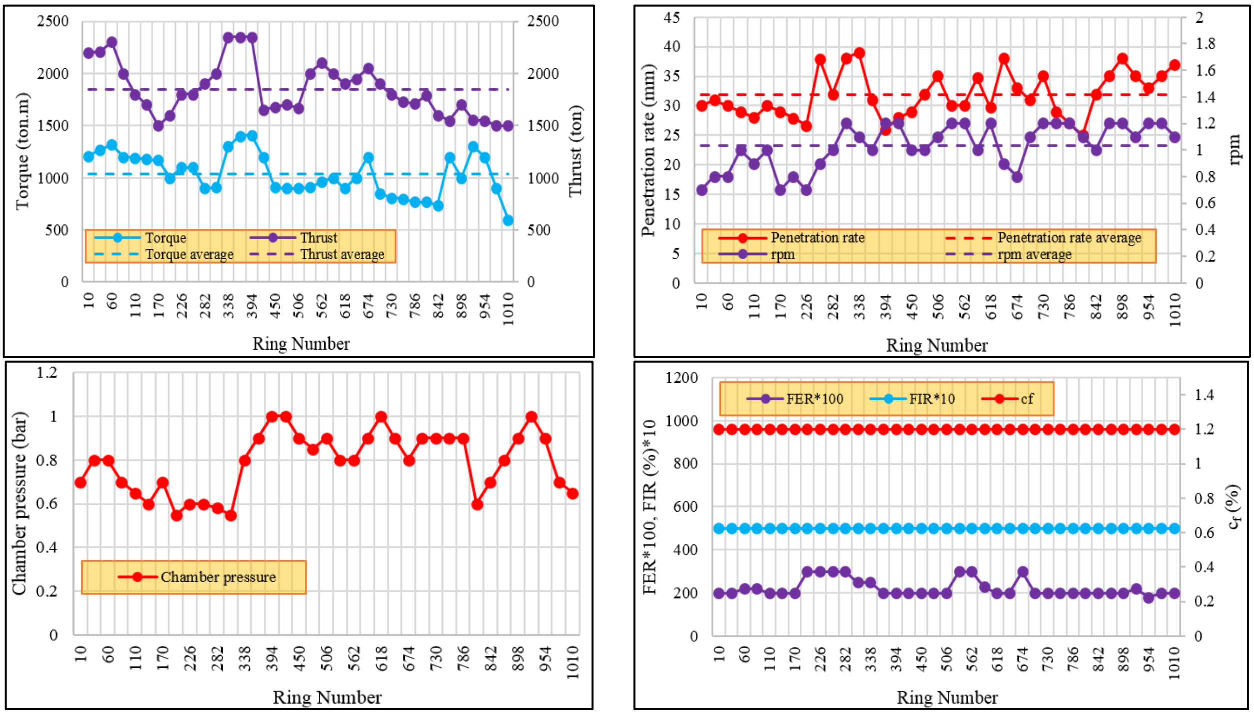


**Figure B1. Variation of operational and performance parameters of cutterhead No. 1.**

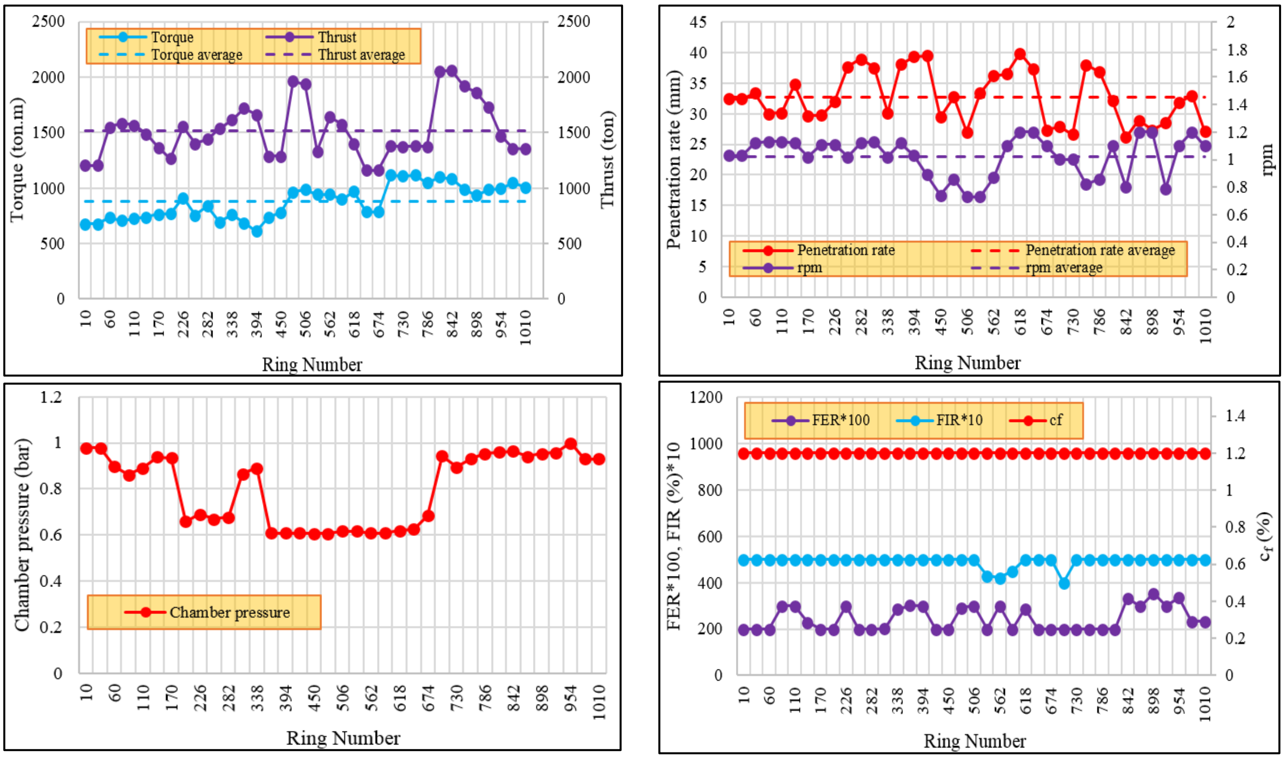


**Figure B2. Variation of operational and performance parameters of cutterhead No. 2.**

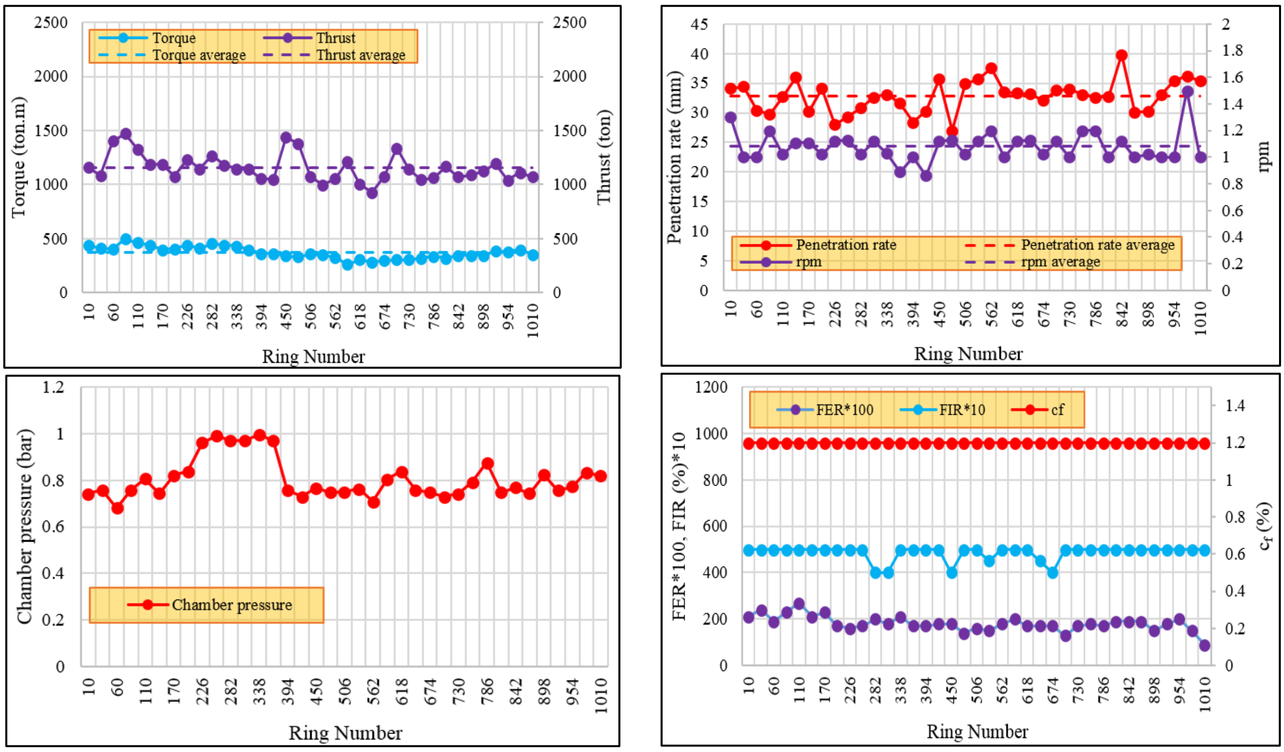


**Figure B3. Variation of operational and performance parameters of cutterhead No. 3.**

# پیکربندی بازشوهای کله‌حفار ماشین‌های حفار تمام مقطع تونل در زمین نرم با در نظرگیری مطالعات میدانی و عددی

**داریوش محمدی، کوروش شهریار*، پرویز معارف‌وند، و ابراهیم فرخ**

**دانشکده مهندسی معدن، دانشگاه صنعتی امیرکبیر، تهران، ایران**

ارسال ۲۰۲۴/۰۳/۱۷، پذیرش ۲۰۲۴/۰۸/۰۹

* نویسنده مسئول مکاتبات: k.shahriar@aut.ac.ir

## چکیده:

طراحی صحیح کله‌حفار ماشین‌های حفار مکانیزه تمام مقطع تونل (TBM) نقش بسیار مهمی در بهره‌وری و عملکرد این ماشین‌ها دارد؛ زیرا سازه‌ی کله‌حفار در طول فرآیند حفاری و ساخت تونل بدون تغییر باقی بماند. هدف از این مقاله بیان اصول اساسی در طراحی بازشوهای کله‌حفار در زمین‌های نرم بر اساس داده‌های به دست آمده از سازندگان ماشین‌های حفار است. در ابتدا، یک پایگاه داده جامع از کله‌حفارهای زمین نرم از تولیدکنندگان مختلف TBM در پروژه‌های گوناگون در شرایط زمین‌شناسی مختلف جمع‌آوری شد و پرکاربردترین پیکربندی کله‌حفار با قطر بیش از ۵ متر بر اساس منحنی نسبت بازشوی شعاعی و الگوهای بازشوهای آن به ۳۶ مورد مجزا طبقه‌بندی شدند. سپس، پارامترهای عملکرد و ویژگی‌های جریان ذرات در سه طرح کله‌حفار شرکت هرنکنشت آلمان با پیکربندی‌های مختلف بازشوها در نواحی مرکزی و محیطی با استفاده از روش المان مجزا (DEM) با در نظرگیری پارامترهای مواد برای ماشین و خاک و پارامترهای تماس بین ذرات خاک-خاک تجزیه و تحلیل شدند. مدل هرتز-میندلین به عنوان مدل تماس برای ذرات خاک-سازه‌ی ماشین انتخاب شده است. علاوه بر این، سه کله‌حفار مختلف به کار رفته در پروژه‌های متروی تهران در ایران با پایش گشتاور پیچشی کله‌حفار و نیروی رانش تحت شرایط ژئوتکنیکی و پارامترهای عملیاتی یکسان مورد بررسی قرار گرفتند. به طور کلی، حفاری با ماشین‌هایی با درصد بازشوی بیشتر در ناحیه مرکزی کله‌حفار در خاک‌های چسبنده عملکرد بهتری را نشان می‌دهد. با این حال، درصد بازشوی بالاتر در نواحی محیطی، انتخاب بهتری برای انتقال مواد حفاری شده در اطراف کله‌حفار در خاک‌های غیر چسبنده، سنگ‌های هوازده، زمین‌شناسی مخلوط و ناهمگن است.

**کلمات کلیدی:** طراحی کله‌حفار، نسبت بازشوی شعاعی، مدل المان مجزا، سازندگان ماشین حفار.