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RESEARCH ARTICLE

Clogging Potential of Earth-Pressure Balance Shield Driven Tunnels

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Abstract:

Background:

Nowadays, the construction of urban tunnels for rapid transportation in metropolises is necessary. Since these tunnels are excavated at low depths, they are often associated with different problems and hazards. Some of them can reduce the efficiency of the tunnel boring machines and sometimes will stop the project. Among these problems the clogging can cause problems at the cutter head, in the chamber, and in other sections where the material transference occurs.

Objective:

The main purpose of this paper is to evaluate and determine the risk of clogging in the tunneling boring machine in Line 6 of the Tehran Metro. It includes stations: Amirkabir, Shohada Square, Emam Hossein Square and Sayyadeh Shirazi. This phenomenon induces an adhesion of the shield with the soil, increasing the necessary shear forces and it can eventually leads to the project interruption.

Methods:

Due to the fact that the criterion for the behavior of fine soils against moisture is Atterberg Limits, therefore, Atterberg Limits and the water content were utilized. For this purpose, the new method proposed by Hollman and Thewes (2013) was used. In this study, in addition to the Atterberg limits, the amount of free water resulting from the machine and from the underground water inflow was included in the calculations.

Results:

It was found that the water content should be increased carefully as the soil is very sensitive to this parameter. An increase of 15% of the water content permits to reduce the risk of clogging. If the added free water amount 15%, the probability of clogging becomes high. Whereas, in case where the added free water amount reaches 20%, the risk of clogging decreases significantly.

Conclusion:

According to the performed assessments, it was found that critical areas for the clogging aspect are both the cutter head and the chamber. The sensitivity of the soil is very important to the free water amount. Therefore, due to the behavior of sticky and plastic of clay soils against increasing water, it is necessary to determine the percentage of allowable water used in mechanized excavation projects.

Keywords: Shield tunneling, Clayey soil, Clogging, Subway, Atterberg limits, Water content.

Article History	Received: February 19, 2020	Revised: May 11, 2020	Accepted: May 12, 2020

1. INTRODUCTION

Tunnel Boring Machines (TBM) permit to increase the excavation speed and decrease the ground displacement. In urban environments, these machines face challenges such as soil cohesion, soil abrasion, large rock pieces, ground settlement and instability. To identify geological hazards, it is necessary to define the different geological features, the soil parameters and the groundwater level along the tunnel route. Table **1** presents these geotechnical and engineering-geological features and parameters as well as their degree of importance to identify each geological hazard.

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Table 1. Geotechnical and geological parameters influencing the occurrence of geological hazards in urban environments [1].

Geological Hazards	The influencing geotechnical or engineering-geological parameters (high importance ■ low importance □)						
	Petrography of Grains	Soil Grading	Percentage and Type of Clay Minerals	Deformability Properties	Strength Characteristics	Water Content	Groundwater Condition
Soil Cohesion			■			■	
Soil Abrasion	■	■					
Large Rock Pieces		■					
Ground Subsidence				■	■		
Excavation Face Stability					■	■	

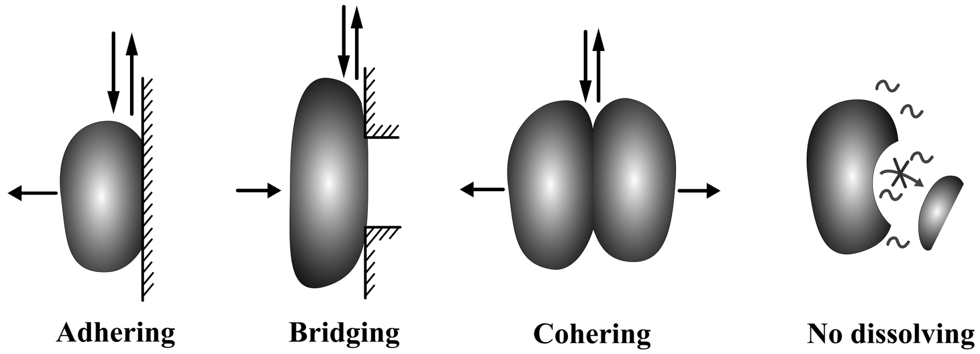

Fig. (1). Clogging potential- four effective mechanisms [2].

Some materials, especially those containing a high percentage of plastic clay, tend to stick to metal surfaces and contribute to clogging. The clogging potential of clay formations, as shown in Fig. (**1**), is defined by four effective mechanisms [2]:

- Sticking of clay particles on the components' surface,
- Bridging of clay particles on the transfer route of excavated materials,
- Adhesion and cohesion of clay particles,
- Low tendency of clay particles to be dissolved in water.

Among these four mechanisms, the sticking of clay particles to the components' surface is the most important and effective mechanism.

During a tunnel excavation by shield machines, severe clogging may occur in clay formations. This can cause problems for the excavation process and may lead to clogging in the cutter head, in the machine cutter head disks, in the chamber behind the cutter head, and in the spiral conveyors. It can also prevent shield progress due to friction. If the clogging is not successfully inhibited, it can lead to a performance decline due to reduced progression rates and time required for cleaning [3].

Recently, extensive research works were conducted on the phenomenon of clogging. Anonymous (1995), Thewes and Burger (2004), Marinos *et al*., (2008), Sass and Burbaum (2008), Hollman and Thewes (2013) are among the major investigators of this issue. Thewes and Burger (2004) presented a diagram based on the consistency index and plastic index to evaluate the sticky behavior of clay soils. Hollman and Thewes (2013) presented new diagrams to investigate the clogging potential in clay soils for all mechanized excavation machines. In addition, Thewes and Hollman (2016) proposed a new test to assess a blocked cutter head in sedimentary rocks with clay minerals.

The ability of clay to develop an adhesive behavior that leads to the clogging phenomena depends on several factors, including [4]:

- Type of soil and its grain-size distribution
- Type of clay minerals
- Plasticity of soil
- Water content of the soil and availability for free water in the area

This paper investigates the clogging potential between chainages of 7 to 11.7 km from the tunnel route of the Tehran Subway Line 6. The proposed method by Hollman and Thewes (2013) was used in this study.

2. IMPACTS OF CLOGGING ON TUNNELING

In general, the consequences of adhesive grounds are the following [5]:

- clogging makes the cutter head heavier and thus leads to machine deviations during the excavation operation.
- clogging at the cutter head leads to an increase of the torque required by the machine, in some cases where the maximum torque will not be sufficient to proceed,, the TBM will be stopped.

- clogging and blocking of the excavated materials inlet scrapers prevent the excavated materials from leaving the excavation face. This will increase the necessary driving force of the machine by maintaining a predetermined penetration rate, and can lead to a higher abrasion of the cutter head.
- As it can be seen in Fig. (**2**), the adhesion of the excavated materials results in an agglomeration. It is then difficult to transfer the material in the conveyor belt.

3. DESCRIPTION OF THE PROJECT

3.1. Tehran Subway Line 6

Line 6 of the Tehran Metro is one of its most important and longest lines, stretching from Tehran's southeast to its northeast. In its original design, line 6 extends for over 30 km and incorporates 27 stations, of which, 9 mark the intersection with other subway lines: 1, 2, 3, 4, 7, 8 and 9. Recently, with the development of the southern part of Line 6, the length and number of stations of this line have been extended to 38 km and 31 stations [6].

According to earlier studies of the profile, route plan, depth and height of the subway line, and also considering the high groundwater level, the only safe and reliable method for tunneling in the southern (first) section of the Tehran subway line 6 is the use of a TBM in terms of speed, cost and safety. As shown in Fig. (**3**), the length of the first line 6 section is approximately 11.7 km and extends to the Sayyadeh Shirazi station in which the tunneling operation has been conducted using the TBM method. The rest of the tunnel is excavated by the NATM method. Metro Line 6 starts from the shrine of Abdul Azim and after passing a south-north route, it intersects with line 4 at Shohada Square Station, with line 2 at Emam Hussein Station, line 1 at Hafteh Tir Station, and with line 3 at Valiasr Square Station, and then continues to the west and reaches the northwestern area of Tehran.

3.2. Engineering Geology

According to the existing topographic maps, the project area is approximately located at level in the range from 1085 to 1391 m above the sea level. Tehran's alluvial sediments are mainly the result of rivers and seasonal floods originating from the northern highlands, located in central Iran, which is about 650 meters above the sea level. The changes in climate and the tectonic regime have directly affected the status of the surface water inflows and their sediment transport over time. It has induced deposition of coarse-grained and fine-grained soils. More coarse-grained soils can be found in the northern parts of Tehran rather than its southern parts. The result of the feldspar alteration and weathering are clay minerals, *i.e*. Illite and Kaolinite. The crushing and erosion of quartzes mostly result in sandy elements and thus, tuffs provide fine-grained materials and alluviums [7].

The Physical soil parameters of boreholes on the route of the Tehran subway line 6 are presented in Table **2**. The depth of the identification boreholes is selected according to the type, conditions, and depth of the tunnel and station [7].

Fig. (2). Soil sticking on the conveyor belt of TBM [5].

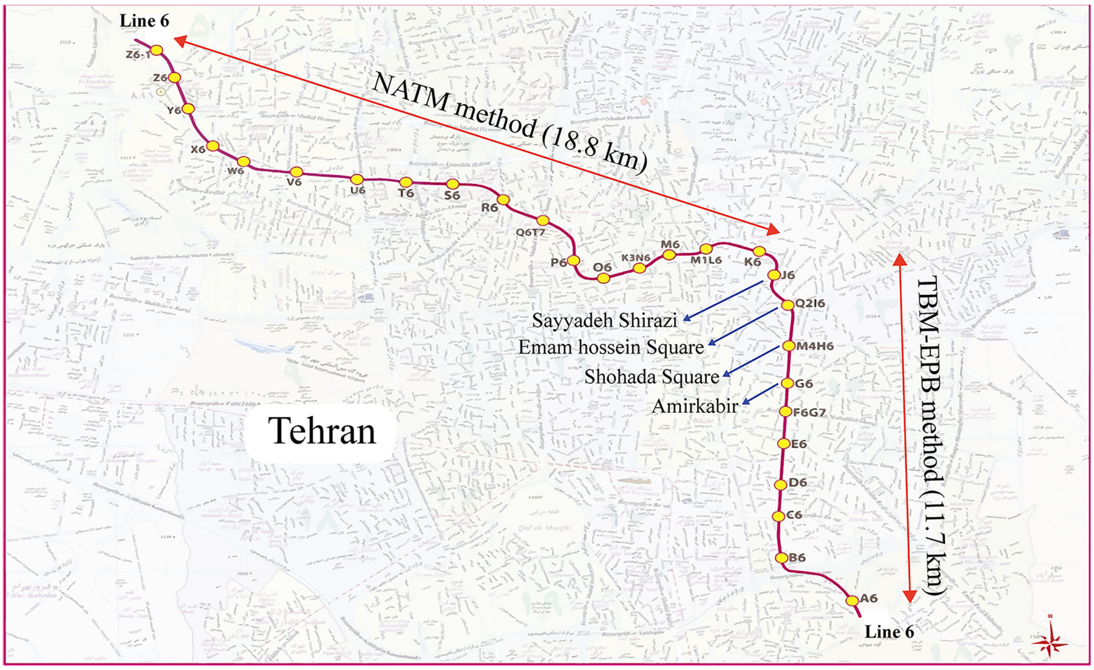

Fig. (3). The whole route of the Tehran subway line 6 [6].

Table 2. Physical properties of soil in some of the investigated boreholes [7].

Borehole	Percentage of soil passing through a sieve No. 200	Liquid limit	Percentage of water content	Plastic limit	Soil type
BH7	36-43	27 – 29	7 - 8	11 - 12	SC
BH8	14 - 19	28 – 34	16 - 18	11 - 16	GC,GM,GW-GM,GP-GM,GW
BH9	23 - 34	24 – 28	9 - 11	15 - 16	GC,GM,GW-GM,GP-GM,GW

4. METHODOLOGY

4.1. Definition of Clogging

4.1.1. Plasticity and Consistency

Fine-grained plastic soils can be defined by their water content, W_n, liquid limit W_L and plastic limit, W_p. With the increase in the water amount, the state of the soils changes from very stiff to stiff and can reach a plastic state. At the liquid limit, their consistency changes from very soft to a fluid state without significant adhesion. The plastic index (I_P) and consistency index (I_C) are defined as follows [4]:

$$I_P = W_L - W_P \quad (1)$$

$$I_C = (W_L - W_n) / I_P \quad (2)$$

The tendency of adhesive soils for clogging can be assessed using plastic and consistency indexes. To illustrate the clogging risk in tunneling with TBM, Thewes (1999) provided a diagram to estimate the degree of clogging tendency based on experimental studies [8]. According to this diagram, the soil with a plastic index of more than 20% and a high stiff consistency index has the highest potential for clogging. However, the diagram was corrected because of some site experiments suggesting that clogging can also occur in stiff clays.

4.1.2. Free Water Content

In tunneling when using a TBM, in addition to pore water, free water (groundwater inflow, machine cleaning water and ventilation water) should also be included in the calculations. Any adhesive soil with less than 10% clay has a potential for the clogging phenomenon occurrence. Its occurrence speed depends on the natural consistency and availability of additional free water. Free water inflow during the drilling operation increases the soil adhesion probability. Besides, the availability of free water depends on the soil hydrological conditions and the tunneling operating conditions. To ensure the tunnel face stability, tunneling in soft soils is often done using a slurry shield, in which water is used for maintenance. Under these conditions, the phenomenon of clogging is more likely to occur. Groundwater inflow is often associated with the machine excavation face, where the ratio of the water volume to the excavated soil depends not only on the water inflow rate but also on the inflow time (time necessary for components replacement and shift change). Finally, it can be stated that this factor is mostly dependent on the excavation diameter. After a time period, soil consistency may change [9]. Moreover, in closed-mode boring machines, water is also required, so it is important to determine the risk of the clogging phenomenon in this type of excavation.

4.2. Clogging Diagram of Thewes (1999)

The first clogging diagram (Fig. **4**) was obtained from the analysis of a large number of excavations in clayey soils. Therefore, this diagram is suitable for slurry machines. A new clogging diagram is developed in this work. It attempts to consider the changes in the materials' consistency in the drilling chamber. So, it is suitable for all types of machines [4].

4.2.1. Development of the Basic form of the Diagram

In the first step of making this diagram, the method proposed by Thewes (1999) is reviewed to find out where it can and cannot be applied to define the clogging potential diagrams for different types of machines. The principle of using the plastic index can be extended to all types of machines since this parameter is based on the plastic and liquid limits. As these parameters are intrinsic, water content change does not affect these limits. In contrast, changes in the consistency index depend on the amount of free water, which in turn depends on the type of machine system. As defined, the diagram in Fig. (**4**) can be used for slurry tunneling projects.

In open-mode machines without underground water inflow, clogging only occurs when the soil's natural consistency has already shown a tendency for adhesion. Therefore, the diagram of potential for clogging (Fig. **4**) can be modified with the consideration of the clogging material consistency (Fig. **5**). In this diagram, open-mode machines will not be exposed to clogging, whereas they are likely to be clogged based on the diagram shown in Fig. (**4**). This classification is consistent with the results of Schlick (1989), who investigated the behavior of clay clogging during ground movements without the presence of underground water inflow [10].

In the presence of groundwater inflows, the modified diagram cannot be used for open-mode machines. In these cases, the soil, with its natural non-critical consistency turns into an adhesive consistency. The intensity of the groundwater inflows considering different boundary conditions (availability of water) will create new conditions. Therefore, in these cases, it is not possible to develop a specific model for each boundary condition. If the groundwater inflow or the water from the cleaning process during tunneling is anticipated, a comparison of diagrams 4 and 5 can be used.

A new diagram with the possibility of expressing the soil consistency is required during the excavation to show potential soil changes. Therefore, an accurate estimate of how the materials are critically transferred outside the chamber can be obtained. To assess the impact of water during the excavation, the amount of water should be measured . While the water content is indirectly included in the diagram of clogging potential (Figs. **4** and **5**), changes in water content cannot be shown. According to the plastic and liquid limits, the defined consistency changes depend on the changes in the water amount.

A new diagram is presented based on the same parameters, as stated above. As previously mentioned, issues during the excavation are related to plastic or liquid consistency. Therefore, the resultant diagram is based on the difference between the liquid or plastic limit and water content (x-axis: the difference between the plastic limit and water content, y-axis: the difference between the liquid limit and water content). Very hard clay with a high plastic property and high clogging potential (Type A soil) is used as an example. The data pairs are proportionally transferred in the diagram as the water content increases (Fig. **6**). Each soil specified in Fig. (**6**) has a specific plastic index, so the line values considering different water content are related to the plastic index contours. By changing the plastic index equation, contour lines of the defined plastic index can be shown in this diagram:

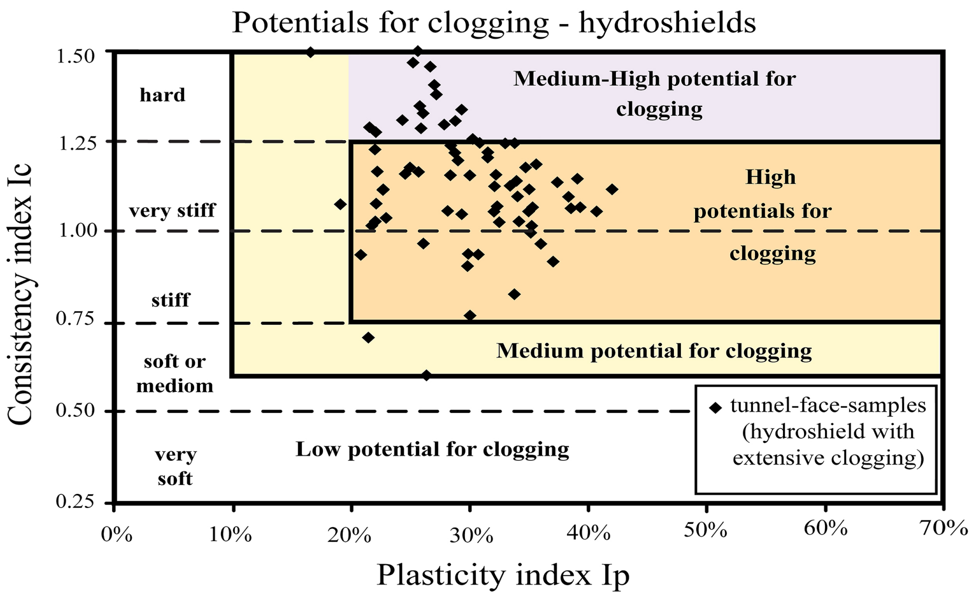

Fig. (4). Modified clogging diagram for slurry excavation machines [4].

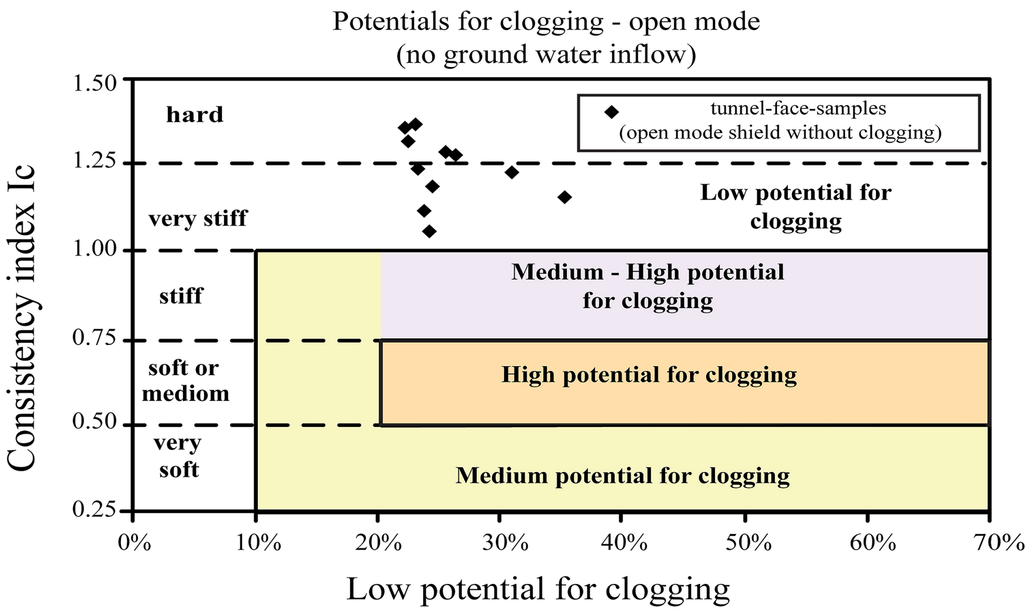

Fig. (5). Potential of clogging for open-mode machines without ground water inflow [4].

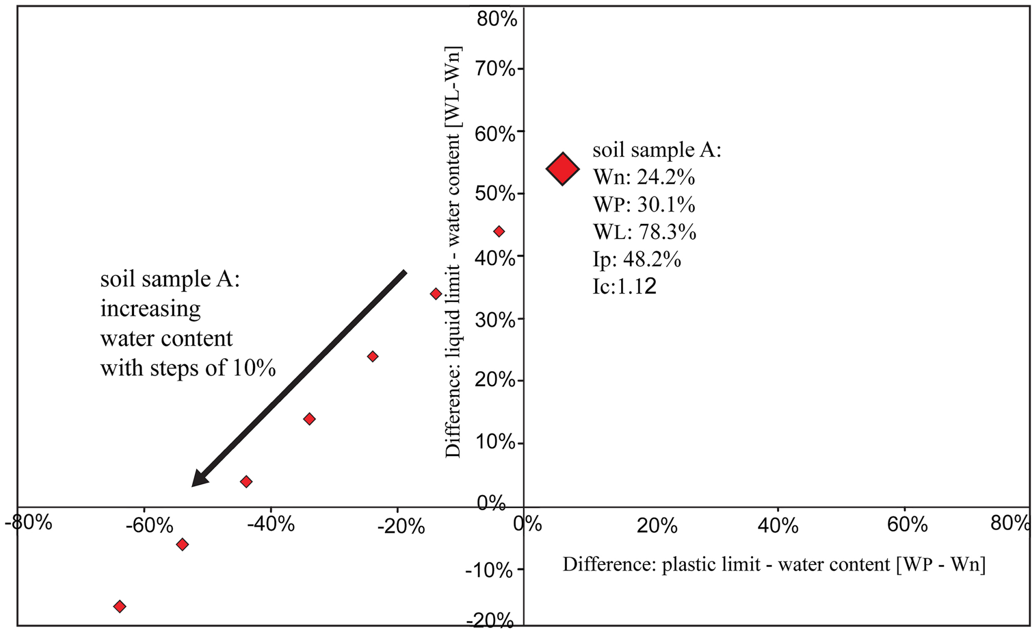

Fig. (6). Original shape of the new diagram with a soil specimen and its changes in water content [4].

$$I_P = [W_L - W_n] - [W_p - W_n] \quad (3)$$

$$[W_L - W_n] = I_P + [W_p - W_n] \quad (4)$$

The overall results can be expressed by:

$$y = x + I_P \quad (5)$$

The relationships between the values are linear, with the slope of the line being equal to unity. This line intersects the vertical axis at the plastic index value. The diagram (Fig. **7**) is stopped by the plastic index $I_p = 0$, which intersects the zero point (because the plastic index must be positive).

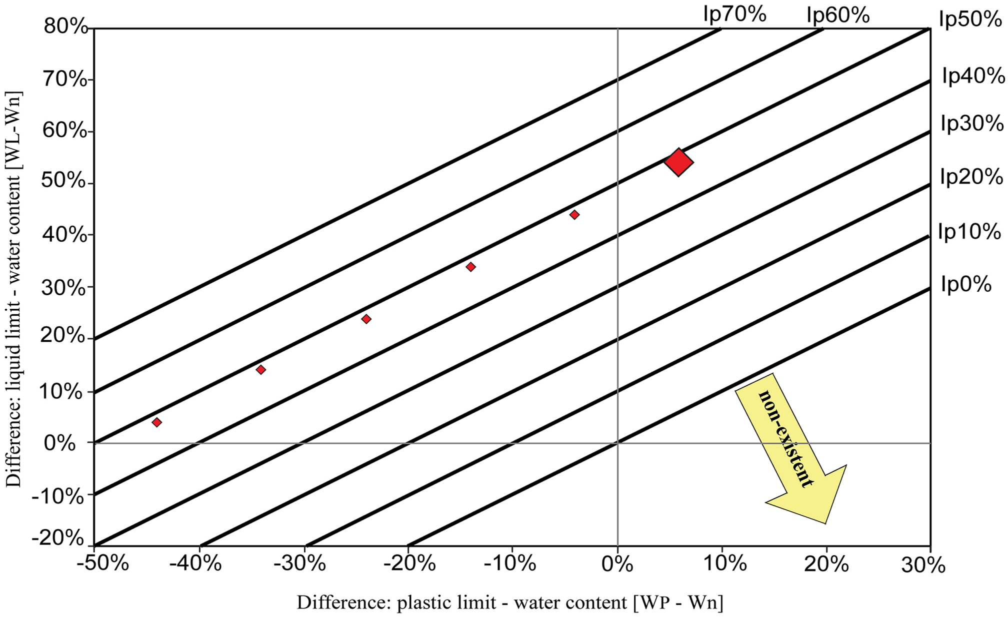

Fig. (7). The original shape of the new diagram with plastic index lines [4].

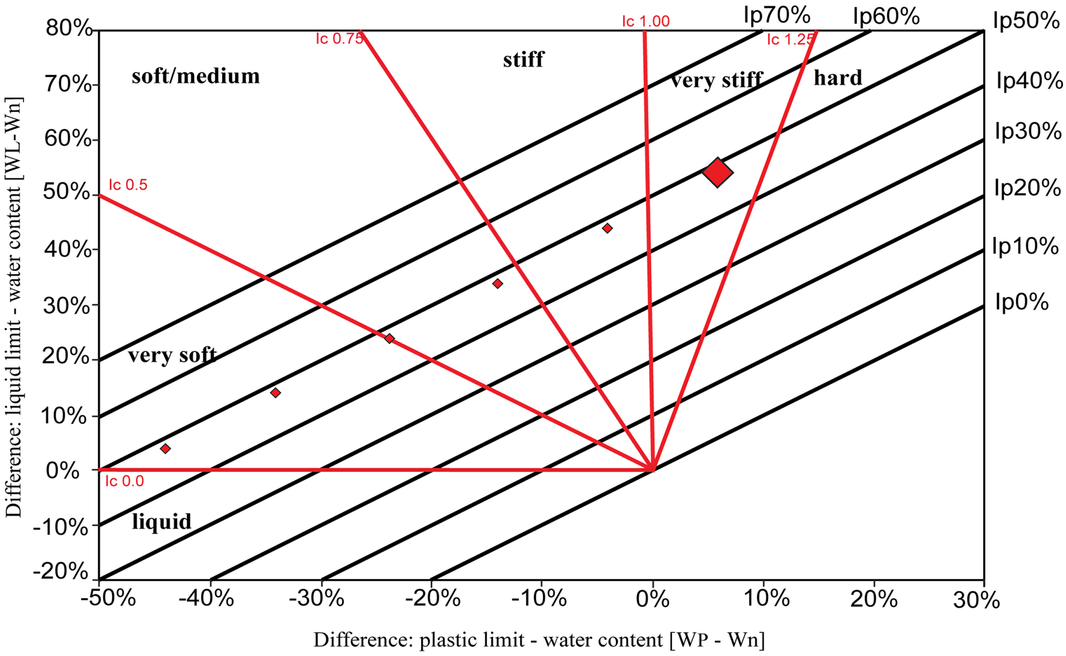

Fig. (8). Original shape of the new diagram with plastic index lines (in black) and consistency index lines (in red) [4].

According to the definitions of the axes, a soil with a water content equal to the liquid limit intersects the horizontal axes ($[W_L\text{-}W_n] = 0$) and a soil with a water content equal to the plastic limit intersects the vertical axis ($[W_P\text{-}W_n] = 0$).

Rewriting the consistency index equation (equation 2), the result is shown as follows [4]:

$$[W_L - W_n] = [W_p - W_n] * [I_C/(I_C - 1)] \quad \textbf{(6)}$$

Consistency limits can be defined as follows [4]:

$$I_C = 0.00 \longrightarrow [W_L - W_n] = 0 (\rightarrow liquid\ limit) \quad \textbf{(7)}$$

$$I_C = 0.50 \longrightarrow [W_L - W_n] = -[W_p - W_n] \quad \textbf{(8)}$$

$$I_C = 0.75 \longrightarrow [W_L - W_n] = -3 * [W_p - W_n] \quad \textbf{(9)}$$

$$I_C = 1.00 \longrightarrow [W_P - W_n] = 0 (\rightarrow Plastic\ limit) \quad \textbf{(10)}$$

$$I_C = 1.25 \longrightarrow [W_L - W_n] = 5 * [W_p - W_n] \quad \textbf{(11)}$$

By definition, it would be possible to scale the consistency on the diagram (Fig. **8**). Soils with different plastic indexes but with the same water content will not be placed in the same water content contour line. Whereas, a specific change in water content provides the same absolute value for each soil at each position on the diagram. Therefore, it is possible to define a scale for the diagram that indicates the water content changes (Fig. **9**).

The final diagram is shown in Fig. (**10**). In this diagram, each soil moves downward and to the left direction parallel to the plastic index lines as the water content increases. Whereas for coarse-grained soils, this may decrease the plastic index (*i.e.*, sand materials appear as part of the clogging). To evaluate soils with higher plastic indexes, additional lines with an index greater than 70% can also be added to the diagram (Fig. **11**).

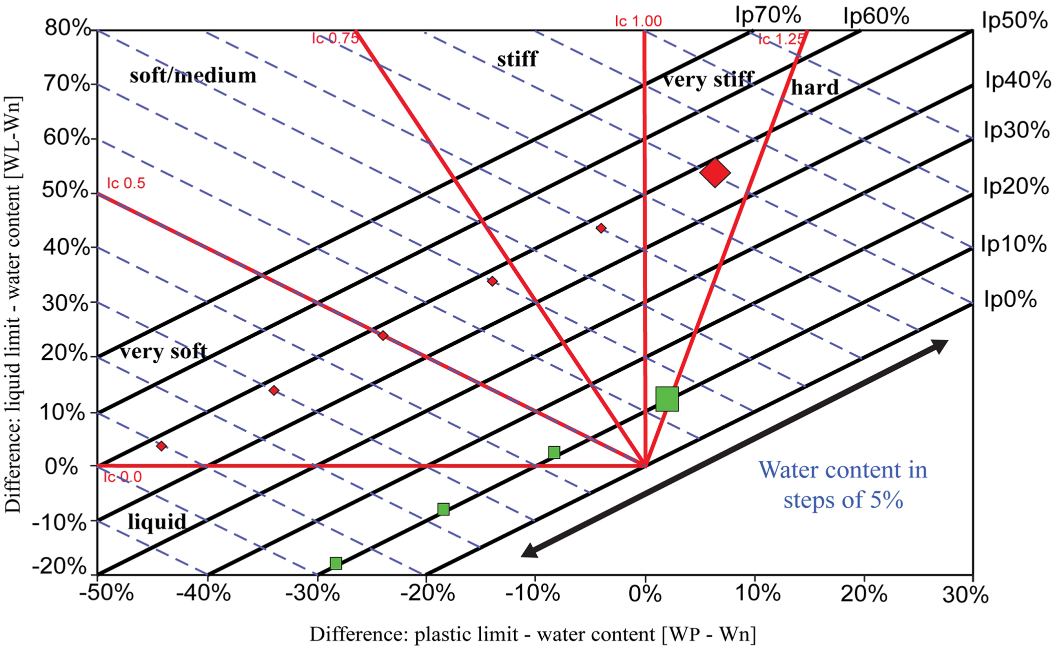

Fig. (9). Original shape of the new diagram with a scale to estimate the water content (the distancee between two blue lines illustrates 5% of difference in terms of water content) [4].

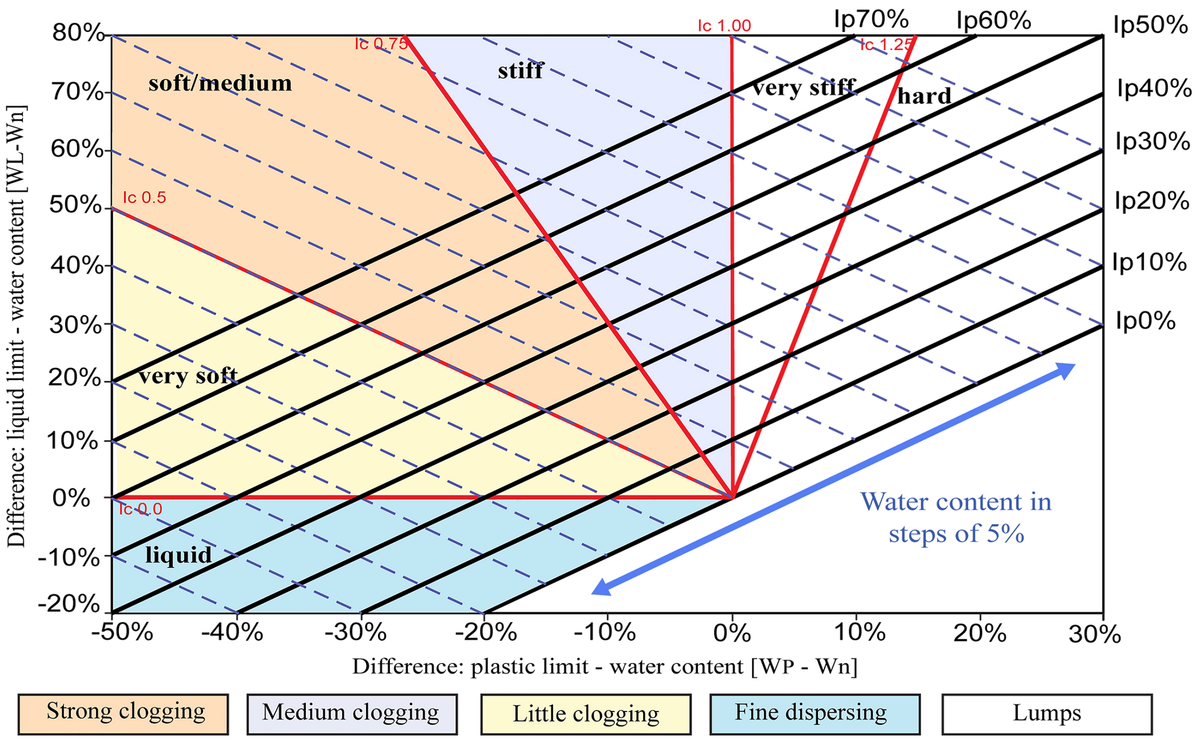

Fig. (10). General classification diagram for the critical consistency changes with respect to clogging [4].

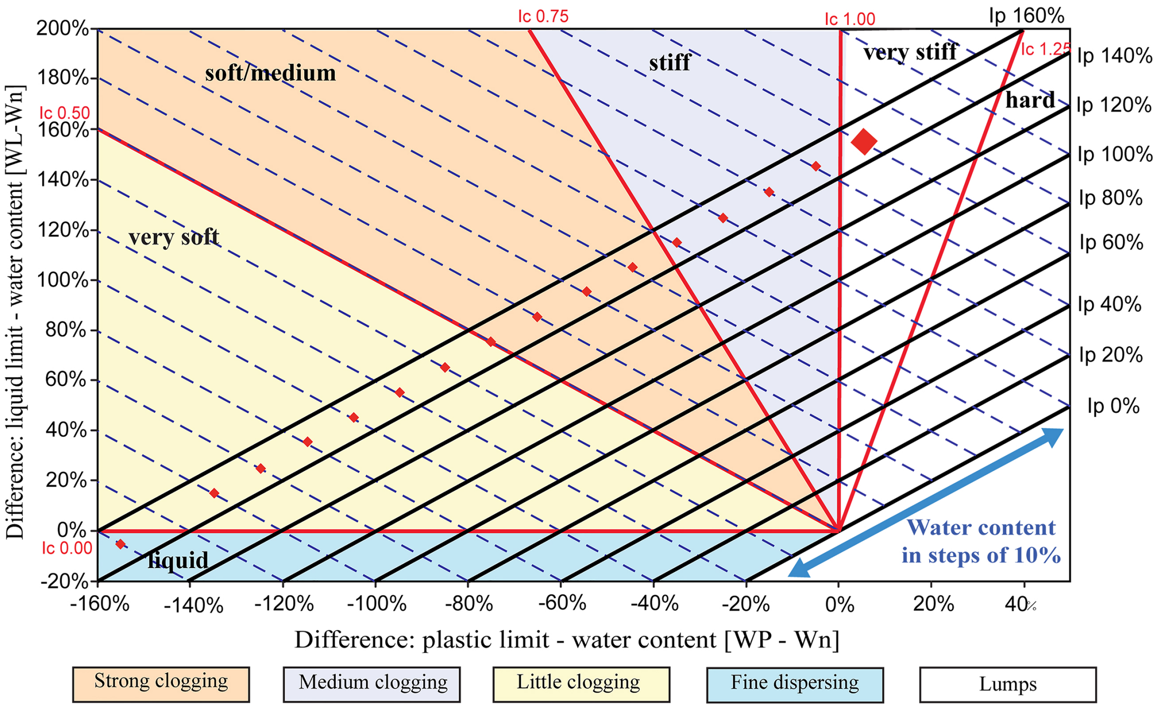

Fig. (11). Extended classification diagram for critical consistency changes for the Aalbeke clay with step increments in water content [4].

Table 3. Results of the clogging pretension for the four stations of the Tehran subway line 6.

Potential for Clogging by Adding 5% Water in Each Step	Stations			
	Amirkabir	**Shohada Square**	**Imam Hossein Square**	**Sayyadeh Shirazi**
5%	Lumps	Lumps	Lumps	Lumps
10%	Medium clogging	Medium clogging	Medium clogging	Medium clogging
15%	Strong clogging	Strong clogging	Strong clogging	Strong clogging
20%	Little clogging	Little clogging	Little clogging	Little clogging

5. DISCUSSION AND INTERPRETATION OF THE RESULTS

In this paper, the data from four stations (Amirkabir, Shohada Square, Emam Hossein Square and Sayyadeh Shirazi) are studied in terms of the risk of clogging in both the cutter head and machine chamber (Table **3**).

The plastic index, consistency index and also the difference between the plastic limit/liquid limit and the water content were used. As mentioned before, one of the optimal methods to calculate the clogging rate of a drilling machine is with the help of the diagram developed by Hollman and Thewes (2013); this diagram includes four parameters: the difference between the plastic limit and water content, the difference between the liquid limit and water content, the plastic index and the consistency index. It permits to obtain the consistency index of the soil adhesion. According to this index, the diagram is divided into various states, including very high adhesion to the liquid state.

The diagram process first requires the use of the difference between the plastic limit or the liquid limit and the water content is obtained; then, using the positioning method, the location of the soil is determined on the diagram using these parameters. Then, only the adhesion condition of the soil with its natural water content according to the value of the consistency index is determined. Subsequently, in order to express the addition of free water during excavation, a line parallel to the plastic index lines is drawn. It passes through the gravity center of the points. The difference between each blue lines on the diagram represents 5% of difference in terms of water content. In fact, in this way, the effect of free water is also included.

The diagram can be split from the top right to the bottom left, which means that at the left bottom, the soil becomes more sensitive to the amount of water and as a small amount of water is added, it can changes from the hard adhesion zone to the very soft adhesion zone, while the same amount of water in the upper right of the diagram cannot affect the consistency of the soil. In other words, the studied soils are highly sensitive to water additions and a slight difference in the amount of water can alter their consistency, so extreme caution must be taken when adding water.

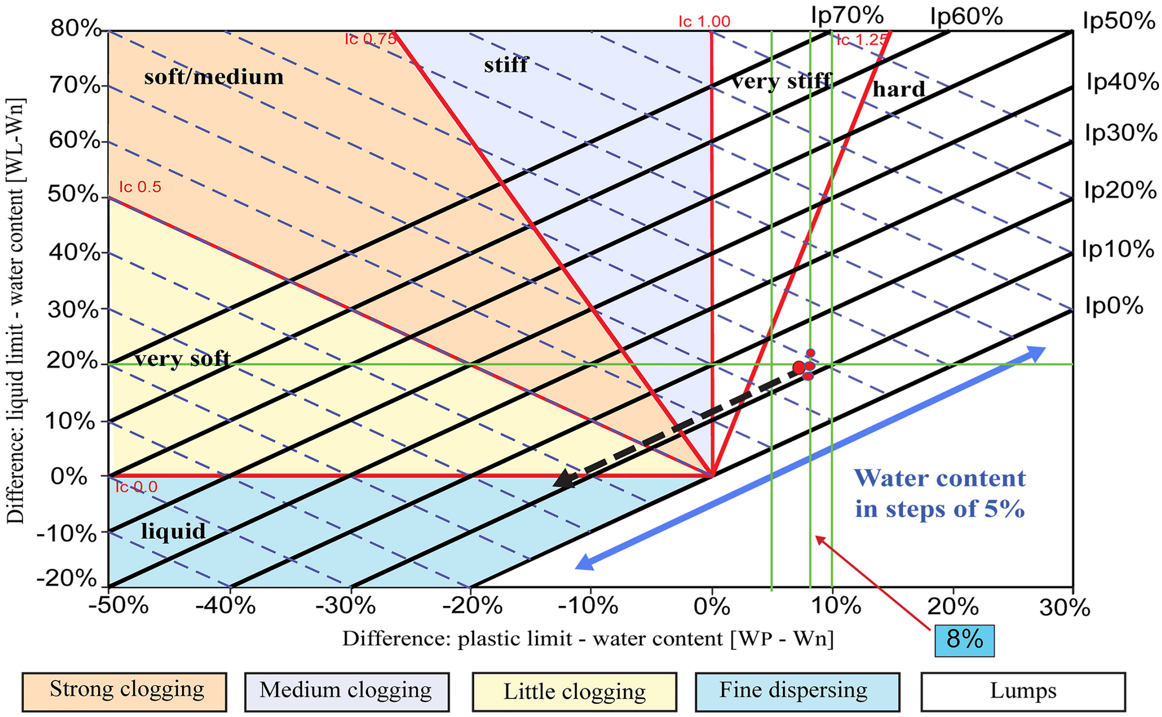

Fig. (12). Results obtained from the borehole information on the clogging determination diagram for four stations of Tehran subway line 6.

CONCLUSION

The main purpose of this paper was to evaluate and determine the risk of clogging in the tunneling boring machine in Tehran (Line 6 of the Tehran Metro) (Fig. **12**). This phenomenon induces adhesion of the shield with the soil, increasing the necessary shear forces and it can eventually lead to the project interruption. For this purpose, the new method proposed by Hollman and Thewes (2013) was used. In this study, in addition to the Atterberg limits, the amount of free water resulting from the machine and from the underground water inflow was included in the calculations. According to the performed assessments, it was found that critical areas for the clogging aspect are both the cutter head and the chamber. The sensitivity of the soil is very important with respect to the free water amount. If the added free water amount is 15%, the probability of clogging becomes high. Whereas, in case where the added free water amount reaches 20%, the risk of clogging decreases significantly. Therefore, extreme caution should be taken to add the free water amount.

CONSENT FOR PUBLICATION

Not applicable.

AVAILABILITY OF DATA AND MATERIALS

None.

FUNDING

None.

CONFLICT OF INTEREST

The author declares no conflict of interest, financial or otherwise.

ACKNOWLEDGEMENTS

Declared none.

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