Effect of Joint Spacing on the Earth Pressure Against the Support System in a Jointed Rock Mass

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ABSTRACT: This study examined the magnitude and distribution of earth pressure on the support system in a jointed rock mass due to the different joint spacing as well as varying the rock type and joint condition (joint shear strength and joint inclination angle). Based on a physical model test and its numerical simulation, a series of numerical parametric analyses were conducted using a discrete element method. The results showed that the magnitude and distribution of earth pressure were strongly affected by the different joint spacing as well as the rock type and joint condition. In addition, the study results were compared with Peck’s earth pressure for soil ground, which indicated that the earth pressure in a jointed rock mass could be considerably different from that in soil ground. The study suggests that the joint spacing as well as the rock type and joint condition are important factors affecting the earth pressure in a jointed rock mass and they should be considered when designing a support system in a jointed rock mass.

Keywords: Rock excavation, Support system, Earth pressure, Joint spacing, Rock type, Joint condition

1. Introduction

Braced excavations are used extensively in the construction of high-rise structures and underground facilities in congested urban areas. On the other hand, the impact of these excavation works on the surrounding environment has become a major concern. In particular, a miscalculation of the earth pressure on the excavation walls can cause collapse of the support systems in open cuts that eventually leads to substantial time loss, financial damage, work stoppages, legal action, and compensation. Therefore, it is important to ensure the safety of the support system in urban underground structures and minimize the related problems (both social and economic ones). In addition, it is also necessary to clearly understand the behavioral characteristics of the ground and excavation walls and have a clear understanding of the ground-wall interactions.

Many studies have examined the earth pressure on the retaining walls caused by ground excavation works through experimental, analytical and numerical assessments (Peck, 1969; Tschebotarioff, 1973; Lambe & Whitman, 1978; Potts & Fourie, 1986; Liao & Neff, 1990; Wong et al., 1997; Hashash & Whittle, 2002; Worden & Achmus, 2013). Most of these studies focused mainly on the soil ground (sand and clay). Fig. 1 shows the apparent earth pressure envelopes suggested by Peck (1969) and Tschebotarioff (1973), which are used widely as the support systems in soil ground. Other related studies measured the earth pressure on the excavation walls in multi-layered ground including soil and rocks (Chae & Moon, 1994; Jeong...
These studies simply compared the measured earth pressures with Peck’s empirical earth pressure and did not consider the effects of the rock and joint conditions.

In other words, few studies have examined the earth pressure in rock strata by considering the rock and joint characteristics as well as the ground-wall interactions, even though they are important factors affecting the magnitude and distribution of earth pressure. This may be due to the general aspect that the rock strata represent a better condition than the soil ground. Recently, Son (2013), and Son & Park (2014), and Son & Adedokun (2015) reported their results of the earth pressures in jointed rock masses. Their results suggested that the earth pressure can be higher for rock strata than a soil ground when the rock and joint characteristics are under unfavorable conditions, such as joint sliding conditions and weathered joint and rock conditions. On the other hand, the results showed that the earth pressure can be much lower than the soil ground when the rock conditions are favorable.

This study extended previous studies, focusing on the effects of different joint spacing for varying rock types and joint conditions. A series of numerical parametric analyses were conducted based on a physical model test and numerical simulation. The advantages of numerical analysis are that a range of conditions can be considered easily with a limited time, cost and space, and reproducible analyses are possible. This characteristic allows the effects of a joint spacing on the earth pressure to be examined under a number of rock and joint conditions. These results are expected to provide a better understanding of the earth pressure on the support system in a jointed rock mass by considering the rock-structure interactions.

2. Numerical Parametric Study

A large-scale physical model test was carried out previously at Daegu University’s Geotechnical Engineering Laboratory using concrete blocks with man-made joints to represent a jointed rock mass (Fig. 2). The purpose of the test was to provide a strong base to simulate the physical model test numerically and confirm that the applied numerical approach and methodology are suitable for further extending numerical parametric studies. The numerical simulation was performed based on the measured properties of the physical model structure and by following the same procedures used in the physical model test. The results from the physical model test and numerical simulation were compared, and relatively good agreement was observed between the physical model and numerical tests (Fig. 3). Details of the results of these two tests can be found in a previous paper (Son & Park, 2014).

Verification of the numerical approach was extended to this parametric study, which considered the effects of the joint spacing as well as the rock type and joint condition (joint shear strength and joint inclination angles).

This study adopted the 2-D Universal Distinct Element Code (UDEC, 2004), which can allow for large displacements between the rock blocks. The rock blocks, wall and struts were simulated as separate elastic units. The joints between the rock blocks and the interface between wall and rock were modeled using the Coulomb slip model, in which the contact loses strength and sliding occurs when the contact shear stress exceeds the contact shear strength.

The model dimensions were 68.8 m × 31.5 m and the excavation wall was installed at a depth of 20.5 m (Fig. 4). The final excavation depth and width were assumed to be
Fig. 3. Comparison of the physical model test and numerical simulation (Son & Park, 2014)

Table 1. Controlled parameters for numerical analyses

| Rock type            | Joint       | Joint shear condition | Joint spacing (m) |
|----------------------|-------------|-----------------------|-------------------|
| Hard                 | Good        | 0.5, 1, 2, 3, 4, 8    |
| Slightly weathered   | Fair        | 0.5, 1, 2, 3, 4, 8    |
| Moderately weathered | Poor        | 0.5, 1, 2, 3, 4, 8    |

19 m and 20 m, respectively. A strut-supported system was used because the apparent earth pressure (Peck, 1969), which was compared with the results in this paper, was obtained from many sets of comprehensive measurements of the strut load in the strut-supported excavation walls for the soil ground. This study considered a different joint set, rock type, and joint condition (see Figs. 5 and Table 1). The joint inclination angle was measured in an anticlockwise direction from the horizontal plane. For each of the aforementioned cases, the analysis was carried out using the soldier pile and timber lagging wall.

To reflect a typical excavation condition in the field, eight stages of excavation were carried out to obtain the distribution and magnitude of the earth pressure. Before carrying out the first excavation, the initial equilibrium was obtained with the
earth pressure coefficient of 0.5 at rest. At this stage, the boundary condition was a roller at each end of the two vertical boundaries and at the bottom boundary. After ensuring the initial equilibrium condition, all the displacements were reset to zero, and the wall was installed at a depth of 20.5 m. The first excavation was conducted up to 1.0 m, which was followed by installation of the first strut at 0.5 m over the excavation line. After the first excavation, there was additional excavation work every 3 m, which was followed by the strut installation every 3 m interval (which is 0.5 m above each excavation line). Wall stabilization was ensured after each excavation stage. The final excavation was carried out up to 19.0 m, and no strut was installed in the final stages (see Fig. 6).

Even though, the shape of a typical excavation wall (i.e. soldier pile and timber lagging wall) has little effect on the earth pressure and wall displacement in the field provided that the flexural stiffness of the wall is equivalent, numerical analysis can have a considerable influence on the results because of the stress concentration in modeling. On the other hand, it is difficult to fully simulate the shape of an actual wall through numerical analysis. To address this issue, this study transformed the excavation wall into a simple section to represent the equivalent flexural stiffness of the wall (see Fig. 7). Table 2 lists the properties of the wall, rocks, joints, and interfaces used in numerical analysis. The properties were determined based on Bieniawski (1976), Hoek & Brown (1988), and Goodman (1989).
Table 2. Properties of wall, rock, joints and interfaces used in the numerical analysis

| Rock type           | Wall  | Rock and Joint | Rock/Wall interface |
|---------------------|-------|----------------|---------------------|
|                     | EI (MPa.m^3) | E_r (MPa) | γ_r (MN/m^3) | Joint condition | φ, σ_t (°) | k_n (MPa/m) | k_s (MPa/m) | \( c, \sigma \) (MPa) | δ (°) | k_n (MPa/m) | k_s (MPa/m) |
| Hard                | 23.20 | 1.0×10^4 | 0.2 2.7×10^5 | Good        | 0 35 | 2.33×10^3 | 0.96×10^3 | 0 33 | 2.33×10^3 | 0.96×10^3 |
| Slightly weathered  |       | 1.0×10^4 | 0.22 | 2.6×10^2 | Fair    | 0 40 | 2.33×10^4 | 0.96×10^4 | 0 27 | 2.33×10^4 | 0.96×10^4 |
| Moderately weathered|       | 1.0×10^4 | 0.25 | 2.5×10^2 | Poor    | 0 35 | 2.33×10^4 | 0.96×10^4 | 0 23 | 2.33×10^4 | 0.96×10^4 |

EI = Wall bending stiffness, E_r = Intact rock elastic modulus, \( \nu \) = Poisson’s ratio, γ_r = Unit weight of intact rock, \( c, \sigma \) = Joint or interface cohesion, \( \sigma_t \) = Joint or interface tensile strength, \( \phi \) = Joint friction angle, \( \phi_r \) = Joint residual friction angle, δ = Interface friction angle, k_n = Joint or interface normal stiffness, k_s = Joint or interface shear stiffness.

3. Effect of Joint Spacing on the Earth Pressure

The effects of different joint spacing on the magnitude and distribution of earth pressure were investigated. The joint spacing was varied from 0.5 m to 8 m and the considered joint inclination angles were 0°, 30°, 60°, and 90° for a single joint set. The results of numerical tests are discussed below.

Fig. 8 compares the apparent earth pressures for hard rock due to the varying joint spacing and joint inclination angles with Peck’s empirical earth pressure based on sand ground with a friction angle of \( \phi = 35° \). Fig. 9 shows the total earth pressure ratios between the earth pressure induced from numerical analysis and Peck’s empirical earth pressure for sand ground.

The induced earth pressures were very small for joint inclination angles of 0°, 30° and 90°, where no sliding was induced at the joint inclination angle regardless of joint spacing. On the other hand, the earth pressure increased significantly for a joint inclination angle of 60°, where joint sliding occurred at the inclination angle. For the joint sliding condition, the earth pressures were similar for joint spacing ranging from 0.5 m to 3.0 m, but they decreased when the joint spacing was larger than 3.0 m. The total earth pressure ratio ranged from 0.01 to 0.19 for the joint inclination angles of 0°, 30° and 90° depending on the joint spacing and joint inclination angles. For a joint inclination of 90° with a joint spacing of 0.5 m, the ratio was 0.19 and it decreased gradually with increasing joint spacing. On the other hand, when joint sliding occurred with a joint inclination angle of 60°, the total earth pressure ratio increased significantly to approximately 0.8 for joint spacing up to 3 m and it decreased to approximately 0.5 with joint spacing larger than 3 m (see Fig. 11).

Fig. 10 compares the apparent earth pressures for slightly weathered rock due to the varying joint spacing and joint inclination angles with Peck’s empirical earth pressure. Fig. 11 shows the total earth pressure ratios between the earth pressure induced from numerical analysis and Peck’s empirical earth pressure for sand ground.

The earth pressure increased considerably compared to those of hard and slightly weathered rocks, regardless of the
joint spacing and joint inclination angles. The earth pressure difference between the no joint sliding condition and joint sliding condition was relatively small compared to those of hard and slightly weathered rocks. In addition, for joint inclination angles of 0°, 30° and 90°, where there was no joint sliding failure, the change in earth pressure was more apparent with the change in joint spacing when compared with those of hard and slightly weathered rocks. The total earth pressure ratio ranged from 0.57 to 0.85 for joint inclination angles of 0°, 30° and 90° depending on the joint spacing and joint inclination angles. For a joint inclination of 90° with a joint spacing 0.5 m, the ratio was 0.85 and it decreased gradually with increasing joint spacing. When joint sliding occurred with a joint inclination angle of 60°, the total earth pressure ratio increased to approximately 0.95 for joint spacing up to 3 m and it decreased to approximately 0.76 with a joint spacing larger than 3 m (see Fig. 13).

These results suggest that the earth pressure increases significantly as the rock condition deteriorates regardless of
the joint spacing and joint inclination angles. In addition, the change in earth pressure with the change in joint spacing is more significant as the rock type worsens. For joint inclination angles of 0°, 30° and 90°, where there was no joint sliding failure, the change in earth pressure is more apparent as the joint inclination angle is increased.

4. Conclusions

The magnitude and distribution of the earth pressure on the support system in a jointed rock mass were investigated numerically. The controlled parameters included a varying joint spacing as well as different rock types and joint conditions (joint shear strength and joint inclination angle). The following conclusions were drawn:

(1) The effects of the joint spacing were not as important for hard rock when there was no joint sliding condition.
On the other hand, for the joint sliding condition with a joint inclination angle of 60° the earth pressure increased significantly and showed a clear difference when the joint spacing became smaller than 3 m.

(2) As the rock condition deteriorated, the effect of the joint spacing increased further. For no joint sliding condition, the effect was most significant for a joint inclination angle of 90°. For the joint sliding condition with a joint inclination angle of 60°, the effect of the joint spacing was apparent when the joint spacing became smaller than 3 m regardless of the rock type. The earth pressure increased significantly as the rock condition deteriorated, regardless of the joint spacing and joint inclination angles.

(3) The induced earth pressure for hard rock was quite small for no joint sliding condition regardless of the joint spacing when compared with Peck’s empirical earth pressure for moderately weathered rock and Peck’s empirical earth pressure for sand ground. On the other hand, when a joint sliding
was occurred, the earth pressure increased significantly to approximately 70% of Peck’s earth pressure under a joint spacing less than 3 m and it decreased to 50% with a joint spacing larger than 3 m.

(4) For slightly weathered rock, the induced earth pressure increased higher than for hard rock and the effect of joint spacing and inclination angle was more evident. For moderately weathered rock, the induced earth pressure was much higher than for slightly weathered rock. The increase of earth pressure was more significant under no joint sliding condition, which resulted in the smallest difference between no joint sliding condition and joint sliding condition. In addition, the effect of joint spacing and inclination angle was more clearly indicated.

(5) This study clearly showed that the magnitude and distribution of earth pressure were affected by a certain spacing of joints as well as the rock type and joint condition. In addition, the results showed that the earth pressure in a jointed rock mass could be significantly different from that in soil ground. Accordingly, the joint spacing as well as the rock type and joint condition should be considered when designing a support system in a jointed rock mass.

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