Strengthening tensile cracks in Dougaeri No.2 kiln by micro-pile technique

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Introduction

Dougaeri No.2 kiln site, one of the Funasako historical kiln sites, located at North Kyushu, Japan, was used for baking the tiles for Buzen Kokubuji (a temple founded in the year 756 AD). A photo of the Dougaeri No.2 kiln site taken during investigation (1994) is shown in Fig. 1. For public exhibition purpose, the integration of exterior and interior is required. The reinforcement method was designed as using the combined technology of chemical grouting and soil nailing. The new technique was named as Earth Sewing Technique (EST) (Hayashi, Chai et al 2004) due to it small diameters of drill hole and tendon.

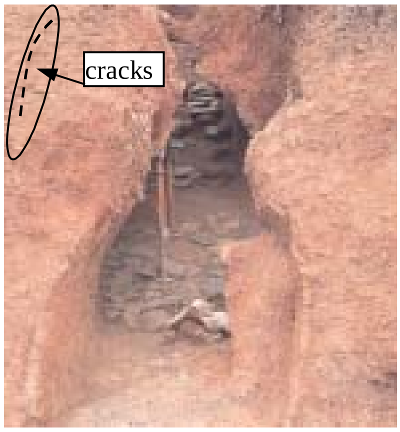

Fig. 1 Photo of Dougaeri No.2 historical kiln

In July 2004, the backfill soils were to remove from the kiln for performing the chemical grouting and mini-scale EST reinforcement. During that process, the tensile cracks was developed and observed in the ridge of Cave-type cross-section, as marked in Fig. 1. The backfill soils were replaced as temporary support. The micro-pile technique was selected for strengthening the developed tensile cracks. In this study, based on the filed pulling tests and laboratory parameter study, finite difference method code- FLAC has been employed to perform numerical simulation and reinforcement design. The practical reinforcement layout has been recommended and carried out in the filed work.

Field model kiln test

A field model kiln site was excavated and built up, which is nearby the actual Dougaeri No.2 kiln site to simulate the field kiln condition. The developed EST technique has been performed in the model kiln site before its application to the actual Dougaeri No.2 kiln. The mini-scale soil nailing was grouted in both chemical grouted soils(termed as Soil A) and natural soil (termed as Soil B). The tendon is threaded steel bolt with diameter of 3 mm and a tensile capacity of 6.95 kN. The borehole was set as 7 mm in diameter and 300 mm in length. Cement slurry (water/cement ratio = 0.45) was adopted as grouting mortar. Figure 2 shows the pulling test results in both Soil A and Soil B. It indicate that the nailing in Soil A present obviously higher pulling capacity than that of in Soil B.

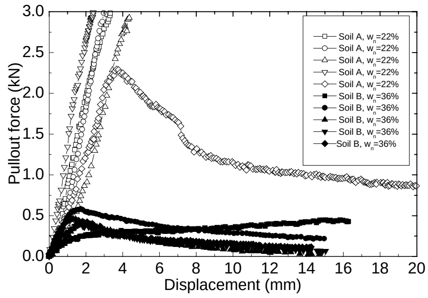

Fig. 2 Pulling tests in field model kiln

Laboratory triaxial tests were conducted to investigate the shear strength parameters (total strength) of Soil A and Soil B. All the samples were prepared with a dry density 1.30 g/cm^3 and water content 26%. For samples of Soil A, the soil was mixed with chemical grout (Silicic acid ethyl) with the same injection ratio 8% as that in the field model kiln. All the samples were sealed up with wrap and cured 28 days for testing. Figure 3 shows the failure envelop of the total stress on t-s stress field for Soil A and Soil B. The results reveals that the chemical grouting can increase cohesion effectively, but has little influence on internal friction angle.

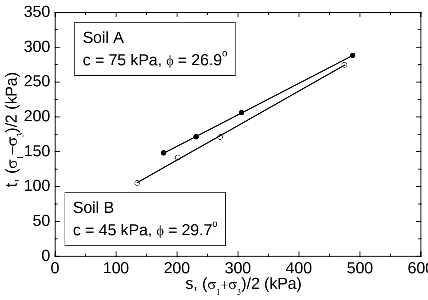

Fig. 3 Failure envelop of total stress on t-s stress field for Soil A and Soil B

Critical situation investigation

Field and laboratory pulling tests and parameter investigation indicate that water content is one of important factors influencing the shear strength parameters (Chai, Hayashi, 2004). Therefore, the natural soil with water content 33% is selected as the dummy state for stability evaluation. The soil can be classified as SC-SM by USCS, which are modeled as Mohr-Coulomb material in the simulation. The soil parameters are back calculated from pulling tests and parameter study, as listed in Table 1. The shape and geometry of Dougaeri No.2 are idealized into three types (Chai, Hayashi, 2004). The critical geometry pointed out is Cave-type cross section, and the critical failure mode is tensile failure under higher water content (lower tensile strength) [1], as shown in Fig. 4. The corresponding factor of safety is 1.45 in the given condition, which is much lower than that

Table 1 Soil parameters used in the simulation

Density, ρ_d (g/cm^3)	Shear modulus **G** (kPa)	Bulk modulus **K** (kPa)	Cohesion c (kPa)	Friction angle, ϕ (^{o})	Tensile strength (kPa)
1.30	3000	5000	40	20	4

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of other cases (FS ≥ 3.0). The simulation results are consistent with the field tensile failure phenomenon.

Reinforcement design by FLAC

Micro-pile method is selected to strengthen the developed tensile cracks. The tendon is threaded steel bolt with diameter of 12 mm. The borehole diameter was set as 50 mm. The finite difference method code-FLAC is employed to evaluate the layout design of piles. Three parameters are investigated: Length of pile (L), Spacing of pile (S) and Inclination angle (α), as sketched in Fig. 5. The micro-pile is simulated as pile element in FLAC, and the axial force, shear and bending effect are considered in the simulation. The failure is assumed at the soil-grouted body interface.

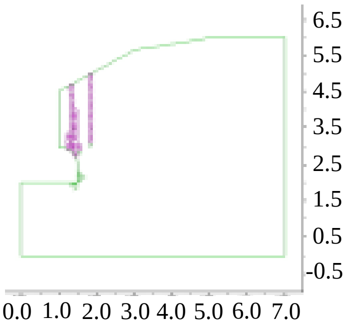

Fig. 4 Tensile failure for Cave-type of geometry (FS = 1.45)

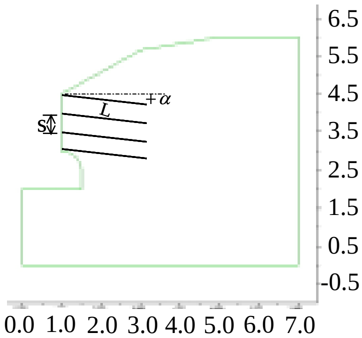

Fig. 5 Sketch of the reinforcement Design for Cave-type of geometry

Figure 6 shows the FS vs. length of the pile relationship, in which the inclination angle and spacing are assumed constant (α = 0°, S = 0.3 m). It indicates that there is no contribution to increasing FS in case the length of the pile is less than 1.0 m. The recommended length of pile is more than 2.0 m.

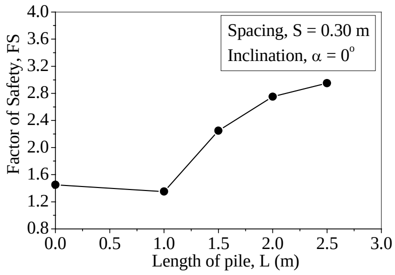

Fig. 6 FS vs. length of pile

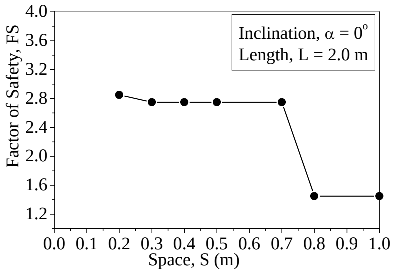

Fig. 7 FS vs. Spacing of pile

Figure 7 shows the FS vs. Spacing of the pile relationship, in which the length and inclination angle are maintained constant (L = 2.0 m, α = 0°). The figure clearly reveals that the critical spacing of the pile is 0.7 m at the given condition. Beyond the critical spacing, the FS decrease to the lowest value equal to that of without pile. The recommended spacing is 0.3 m.

To study the effect of inclination angle, the length and spacing are assumed constant, which are L = 2.0 m (or 2.5 m), and S = 0.3 m. Figure 8 shows the FS vs. inclination angle relationship. It indicates that the horizontal layout (α = 0°) is the most effective one in all the cases. For cases with the same inclination angle, layout with negative inclination angle (-α) is more effective than that of positive inclination angle (+α).

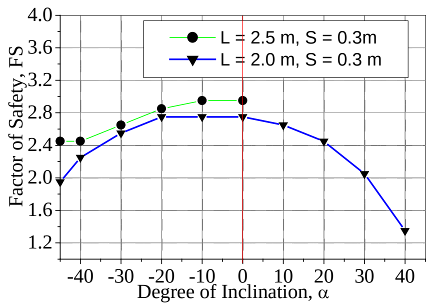

Fig. 8 FS vs. Inclination angle of pile

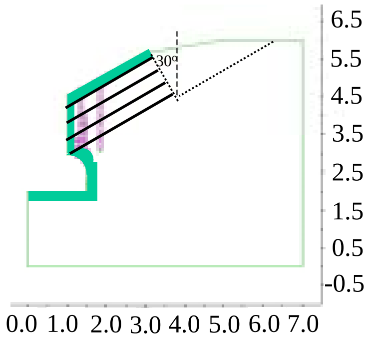

Fig. 9 Practical rehabilitation design

Field practice

In field practical condition, due to the narrow spacing inside the kiln, it is impossible to perform the horizontal installation of the pile. Considering the field situation, fewer disturbances on the appearance of the kiln, the layout of the piles are determined as: L = 2.0-2.5 m, S = 0.3 m, α = -30°. One have to be mentioned procedures is that the method of pile installation. A V-type practice pit was excavated with an interface inclined 30°, as shown in Fig. 9. The drill hole and pile installation were carried out in the practice pit, which were backfilled with the same soil after the field practice. The exterior surface layer (0.3 m to 0.5 m) is solidified by chemical grouting method to resist the weathering and degradation, as show in Fig. 9. The field practice was carried out in Oct. 2004 and completed in Jan. 2005. The tensile crack in the kiln has been strengthened by the micro-pile method and in good performance.

Conclusions

In this study, from the objective of strengthening the tensile cracks developed in the Dougaeri No.2 kiln, the following conclusions can be drawn: 1) Field pulling tests indicate that the nails grouted in chemical grouted soil present higher pulling capacity than that of in natural soil. 2) The micro-pile technique is selected to strengthening the developed cracks in the Dougaeri No.2 kiln. The layout of the micro-piles has been evaluated by the finite difference method code-FLAC, the recommended design has been successfully applied to the filed practice work and in good performance.

References:

[1] Chai, X. J., Hayashi, (2005). "Stability evaluation on Dougaeri No.2 kiln by numerical methods", *Proceedings of Annual Conference of the Japan Society of Civil Engineering*, Kyushu branch, Kyushu University, Japan, pp.543-544.