Stability evaluation on Dougaeri No.2 kiln by numerical methods

Saga Univ. S. mem. ○ X. J. Chai
Saga Univ. F. Mem. S. Hayashi
Saga Univ. S. Mem. Y. Iribe

Introduction

Dougaeri No.2 kiln, one of the Funasako historical kiln sites, located at North Kyushu, Tsuiki-machi, Japan, was used for burning the tiles for Buzen Kokubunji (founded in the year 756 AD). The excavation and investigation began in 1994, and a photo of Dougaeri No.2 kiln site taken during excavation is shown in Fig. 1. For public exhibition purpose, the reinforcement and integration of exterior with interior are required. Considering the complex of geometry of Dourgaeri No.2 kiln, the reinforcing method was designed using the combined technology of chemical grouting and soil nailing. The new technique was named as the Earth Sewing Technique (EST) (Hayashi, Chai et al, 2004) due to its small diameters of drill hole and tendon. The characteristics of EST are its simplicity, portability, adaptability and less disturbing in the kiln.

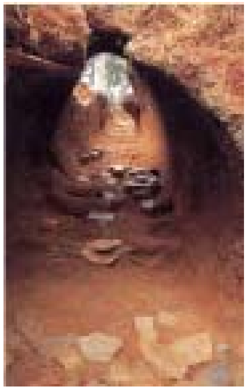


Fig. 1 Photo of Dougaeri No. 2 historical kiln

A field model kiln was excavated and built up near Dougaeri No.2 kiln. The EST was performed in the model kiln site. The effectiveness and feasibility of EST has been verified, and the obtained parameters will be utilized in the reinforcing design of Dougaeri No.2 kiln. (Chai, Hayashi, 2004).

Shear strength reduction (SSR) method has been gradually used to analyze the stability of slope by FEM and FDM. One of the main advantages of SSR method is that the yielding plane emerges naturally from the analysis without the user having to commit to any particular form of the mechanism a priori, this is particularly of advantage at complicated geometry and conditions. In this study, based on field and laboratory pulling tests and parameter investigation, finite difference method code-FLAC has been employed to perform stability analysis. The shape and geometry of Dougaeri No.2 kiln are idealized into three types; their stability and possible failure mode were evaluated by SSR method. The objectives of the present study are: 1) to determine the critical cross-section of Dougaeri No.2 kiln, and 2) to evaluate the critical parameters and corresponding failure mode. The simulation results are helpful and instructive for the final reinforcing design of Dougaeri No.2 kiln.

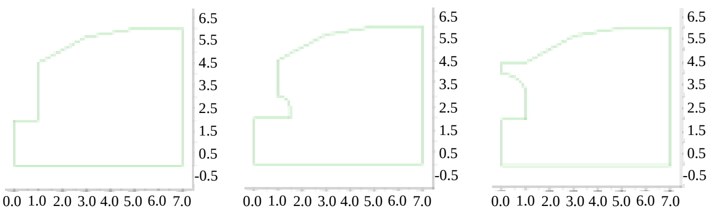
Analysis method

Table 1 Soil parameters used in 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 and 20

Parameters used in the simulation. Field and laboratory pulling tests and parameter investigation indicate that water content is one of important factors affecting 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 considering parameter study, as listed in Table 1. Tensile strength is a serious parameter in some situation, yet difficult to determine. Therefore, 4 kPa, and 20 kPa are assumed for comparison purpose.

Three idealized geometry. The shape and geometry of Dougaeri No.2 are idealized into three types to investigate the critical cross-section and possible failure mode, which are termed as: V-type, Cave-type and Arch-type, as shown in Fig. 2. The difference and characteristics are: the facing is vertical for V-type, there is a small cave (0.5 m width) at the bottom corner for Cave-type, for Arch-type, the top connection shape is arch form. In this study, a reasonably fine grid is selected to ensure the localized failure plane develops clearly, and also the dimension of mesh is large enough to minimize the boundary effect.



(a) V-type (b) Cave-type (c) Arch-type

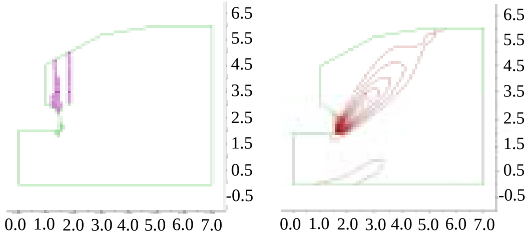
Fig. 2 Three idealized geometry of Dougaeri No. 2 kiln (unit, m)

SSR Technique. For slopes and embankments, the factor of safety FS is traditionally defined as the ratio of the actual soil shear strength to the minimum shear strength required to prevent failure (Bishop, 1995). As Duncan (1996) points out, FS is the factor by which the soil shear strength must be divided to bring the slope to the verge of failure. Since the factor of safety is defined as shear strength reduction factor, an obvious way of computing it with finite difference code is to reduce the soil shear strength until collapse occurs. This approach was used as early as 1975 by Zienkiewicz, Humpheson & Lewis (1975), and has since then been applied by Naylor (1982), Donald & Giam (1988), Ugai (1989), Ugai & Leshchinsky (1995) and others. To perform slope stability analysis with the shear strength reduction technique, in FLAC, both friction angle and cohesion are reduced simultaneously by a strength reduction factor, f_s, according to the equation:

$$c_r = c / f_s \qquad (1)$$

$$\phi_r = \arctan(\tan\phi / f_s) \qquad (2)$$

The convergence criterion in FLAC to determine if the simulation has reached equilibrium is the maximum nodal unbalance force. In this simulation, we can also monitor the displacements along the slope to determine the strength reduction factor at which slope failure occurs. The FLAC runs are made with each new pair of strength parameter, c_r and ϕ_r. At some point, the reduced cohesion and friction angle will become too low to sustain the slope, and unstable movement will occur. The strength reduction factor f_s at this point is termed as factor of safety FS.



(a) Tensile failure (4 kPa, FS=1.45) (b) Shear failure (20 kPa, FS=3.65)

Fig. 3 Failure mode for Cave-type geometry with different tensile strength

Table 2 Summary of FS and failure mode

Tensile strength	V-type	Cave-type	Arch-type
4 kPa	T + S: 3.45	T: 1.45	T + S: 3.85
20 kPa	S: 4.15	S: 3.65	S: 4.45

Results and discussion

As an example of illustrating the failure mode by SSR method, the failure mode of Cave-type geometry are shown in Fig. 3 (a) and (b), corresponding to the cases with tensile strength 4 kPa and 20 kPa, respectively. Figure 3 (a) indicates that the tensile failure is the dominant failure mode in case the tensile strength is of 4 kPa, and the corresponding FS is 1.45. Figure 3 (b) indicates that shear failure is governing the failure behavior in case tensile strength equal to 20 kPa, with the corresponding FS 4.15.

Table 2 summarizes the FS and failure mode for the idealized three types of geometry, wherein, T and S represent tensile failure mode and shear failure mode, respectively. It can be seen that the FS is more than 3 for all the cases except one case (Cave-type, tensile strength of 4 kPa, FS = 1.45). The simulation results reveal that the Cave-type geometry is the critical cross-section, and the serious condition is lower tensile strength at higher water content.

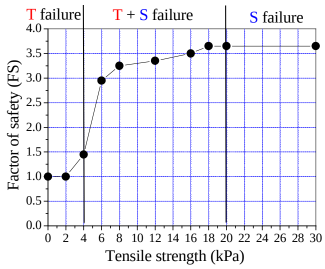


Fig. 4 FS vs. tensile strength for Cave-type geometry

To investigate the sensitivity of FS (and also failure mode) to tensile strength for Cave-type geometry, a series of tensile strength are selected and perform SSR analysis. Figure 4 illustrates the relationship of FS vs. tensile strength. The plot clearly indicates that for Cave-type of geometry, FS (and Failure mode) is very sensitive in case tensile strength is less than 20 kPa, tensile failure is the most critical failure mode.

Conclusions

In this study, the shape and geometry of the Dougaeri No.2 kiln are idealized into three types to perform stability evaluation. Finite difference method code-FLAC is employed to investigate the factor of safety and corresponding failure mode. The following conclusions can be drawn:

1) In the given condition, Cave-type of geometry is more critical than V-type and Arch-type.
2) For Cave-type of geometry, the failure mode and FS are very sensitive to the tensile strength of the soil. Tensile failure is the dominant failure mode in case the tensile strength less than 4 kPa, which corresponding the lowest factor of safety.
3) The simulation result is helpful and instructive for the preservation design of the Dougaeri No.2 historical kiln. In practical work, maintaining low water content of kiln soil should be considered in the design of long-term preservation.
4) The effectiveness of Earth Sewing Technique (EST) should be evaluated by numerical simulation method, especially, its feasibility for reinforcing the tensile failure mode of Cave-type of geometry.

References

Bishop, A. W. (1995). The use of the slip circle in the stability analysis of slopes. *Geotechnique* 5, 7-17.

Chai, X. J., Hayashi, S. and Du, Y. J. (2004). Earth sewing technique for preservation of Funasako historical kiln sites, *Lowland Technology International*, vol.6, n.1, pp.33-41.

Ugai, K. (1989). A method of calculation of total factor of safety of slopes by elasto-plastic FEM. *Soils and Foundations* 29, No.2, 190-195. (in Japanese).

Ugai, K. & Leshchinsky, D. (1995). Three-dimensional limit equilibrium and finite element analysis: a comparison of results, *Soils and Foundations* 35, No. 4, 1-7.