Numerical analysis on the stability of highway embankment reinforced with spiral bladed drain pipe reinforcements

Kiyonobu Kasama i), Yasutaka Ito ii), Zentaro Furukawa iii), Tomohiro Hamasaki iv) and Kenji Matsuka v)

i) Associate Professor, Department of Civil and Environmental Engineering, Tokyo Institute of Technology, Japan.
ii) Master Student, Graduate School of Engineering, Kyushu University, Japan.
iii) Assistant Professor, Graduate School of Engineering, Kyushu University, Japan.
iv) Technical Division of Kyushu Branch, West Nippon Expressway Co. Ltd, Japan.
v) Geotechnical Design Department, NEXCO West Nippon Consultant Co. Ltd, Japan.

ABSTRACT

The purpose of this paper is to develop a new earth reinforcement technology called “The SDPR method” having both functions of a single earth reinforcement to increase the embankment strength and a drainage pipe to lower a ground water level in embankment at the same time. This paper summarizes the effectiveness of the SDPR method by means of unsaturated-saturated seepage analysis and slope stability analysis in terms of the drainage effect, reinforcement effect and unsaturation effect of SDPRs.

Keywords: earth reinforcement, drain pipe, suction, seepage analysis, slope stability analysis

1 INTRODUCTION

Since 40 % of current expressways in Japan have been used for more than 30 years after starting the service, it is generally known that the long use and the deterioration of expressways are becoming an important issue on the safety of expressways. For the expressway embankment constructed with slaking materials or cohesive soils or sandy soils with high water content, a large-scale repair such as drainage countermeasure and earth reinforcement is planning. However, to protect effectively against complex disasters caused by major earthquake and heavy rainfall, not only the countermeasure against single disaster, but also comprehensive countermeasure is required.

Therefore, the purpose of this research is to develop a new earth reinforcement technology having both functions of a single earth reinforcement to increase the embankment strength and a drainage pipe to lower a ground water level in embankment at the same time (Hamasaki et al., 2017 and 2018). This paper presents the development of “Spiral bladed Drain Pipe Reinforcement method”, called as the SDPR method. In particular, this paper summarizes the numerical results of saturated-unsaturated seepage analysis and slope stability analysis for the highway embankment reinforced with SDPRs.

2 THE SDPR METHOD

The SDPR method is an earth reinforcement technology to insert a steel pipe with square slits for water drainage and spiral shape blades for reinforcement on the surface of the pipe. The SDPR method is expected to decrease the water content and pore water pressure under rainfall situation, and to reinforce the embankment stability due to the resistance of spiral blades. Therefore, there are three effect of the SDPR method on stability of embankment; 1) drainage effect to lower the ground water level, 2) reinforcement effect of pullout strength of SDPR and 3) unsaturation effect for the area above the installed SDPRs to cause increases in shear strength due to suction force. The shape and size of a SDPR are shown in Fig. 1 and Table 1. The SDPR was used a general structural carbon steel pipe, outside diameter \( D_p = 48.6 \text{ mm} \), blade thickness \( t_p = 3.5 \text{ mm} \), blade interval \( P = \text{blade diameter } D_w \). The spiral blades are set over its entire length. The type I is a standard type \( (D_w / D_p = 1.5) \) while the type II is a wide type \( (D_w / D_p = 3.0) \). Further, the square-shaped slit \( (6 \text{ mm in width } \times 50 \text{ mm in length}) \) with the opening ratio of 10 % was arranged as a water drainage on the entire surface.

3 NUMERICAL PROCEDURE

Saturated-unsaturated seepage analysis followed by slope stability analysis was carried out for the cross section of highway embankment reinforced with SDPRs in Tosu City, Saga prefecture, Japan. Fig 2. shows a schematic diagram of highway embankment. The height of embankment was 13 m while the embankment consisted of clayey sand and sandy clay.
with gravel. The embankment was divided into Bs1, Bs2, Bs3 and Bs4 soil layers. The SDPRs of type I for the length of 6 m were installed for the spacing of 3 m at three different heights. Ground water level was measured at the top, No. 1, and middle, No. 2, of embankment. Tensiometer and soil moisture meter were set at the depth of 0.5, 1.0 2.0 and 3.0 m for four measuring points M1, M2, M3 and M4 on the slope of embankment. Fig 3. shows the amounts of hourly rainfall and effective rainfall used in the analysis. The numerical period was from 17th September to 1st October 2016 while the SDPRs were installed on 17th and there were heavy precipitations on 18th, 27th and 28th September. For seepage analysis, it was assumed that a ground water flow from the left-side of embankment as shown in Fig. 2 and expressed as a function of effective rainfall, ER, by proposed by Yano (1990) to match the ground water levels obtained by numerical simulation with measured those measured at Nos. 1 and 2. It is noted that ER was calculated for short-term rainfall index ER1.5 using the half-life of 1.5 hours and for long-term rainfall index ER72 using the half-life of 72 hours and the combination of ER1.5 and ER72 was used for several municipalities in Japan to evaluate the risk of shallow slope failure as shown in Siva Subramanian et al (2018).

Table 2 summarized input parameters for soil layer

| Soil layer | Bs1 | Bs3 | Bs2 | Bs4 |
|------------|-----|-----|-----|-----|
| Wet density (t/m³) | 1.47 | 1.72 | 1.10 | 1.33 |
| Dry density (t/m³)  | 1.10 | 1.30 | 1.00 | 1.00 |
| Coefficient of permeability (10⁻⁶ m/s) | 2.18 | 3.00 | 0.241 | 0.207 |
| Specific storage coefficient (10⁻⁴ l/m) | 1.00 | 1.00 | 1.00 | 1.00 |
| Effective porosity | 0.358 | 0.378 | 0.300 | 0.300 |
| Residual volume water content | 0.241 | 0.300 | 0.300 | 0.300 |
| Internal friction angle (°) | 30.0 | 30.0 | 30.0 | 30.0 |
| Cohesive strength c for unsaturated condition (kN/m²) | Fig. 4 | Fig. 4 | Fig. 4 | Fig. 4 |
| Cohesive strength c for saturated condition (kN/m²) | 20.0 | 20.0 | 20.0 | 20.0 |

Table 1. Shape and size of SDPR (dimension; mm).

| Type | Blade diameter (Dp) | Blade width (W) | Blade interval (P) | Blade thickness (t) (cm) | Remarks |
|------|---------------------|-----------------|-------------------|------------------------|---------|
| I    | 11.7                | 72              | 50                | 148                    | Standard type |
| II   | 50                  | 148             | 4.5-2.2           | Wide type              |          |

Table 2. Input parameters for soil layer

Fig 3. Hourly rainfall and effective rainfall ER.

Fig 4. The relationship between c and Sr.

determined as 10⁻⁶ [m³/min] * ER [mm] for the half-life of 72 hours by parametric simulations to match the numerical ground water level with measured one. After saturated-unsaturated seepage analysis, cohesive strength depending on the degree of saturation was determined based on the test result of triaxial compression test for unsaturated specimen as shown in Fig. 4 and then slope stability analysis using the modified Fellenius method were carried out. In order to investigate the effectiveness of SDPR, the ground water level and saturation with/without SDPRs was compared. Finally, the safety factor of the embankment was compared with/without SDPRs in terms of drainage effect, reinforcement effect and unsaturation effect.
4 SEEPAGE ANALYSIS

Fig. 5 shows comparison of numerical and measured ground water levels for Nos. 1 and 2. The numerical simulation can capture the sharp increase in ground water level just after precipitations on 18th and 28th September and gradual decrease as times elapsed. The numerical ground water level is larger than measured one especially about 0.5 m for No. 1 and 1.0 m for No. 2. In order to investigate the effectiveness of SDPRs, the ground water level without SDPRs was shown in Fig. 5. With SDPRs, ground water level decreases about 0.1 m for No.1 and 1.0 m for No.2. It can be seen that SDPR is effective for lowering the groundwater level of the slope of embankment especially for the shallow area above the position of SDPRs.

Fig. 6 shows the change in suction at the depth of 0.5, 1.0, 2.0 and 3.0 m for measuring points M1 and M3. When there is no rainfall, for example from 9th to 27th September, the suction near ground surface becomes larger. When there is precipitation, for example just after 9th and 82th, the suction in shallow area of embankment decreases due to the infiltration of precipitation into embankment and then gradually recovers. It can be emphasized that the reaction of suction close to ground surface becomes prompt.
compared to that in deep area due to the time lag of rainfall infiltration. As for the measuring point M3, the trend of suction except for depth of 2.0 m is very similar to that at measuring point M1. The change in suction at the depth of 2.0 m for M3 was very gentle, almost zero, irrespective of precipitation. This is the location of the tensiometer at the depth of 2.0 m for M3 is close the location of SDPR. It is confirmed that the soil over SDPR becomes unsaturated condition.

Fig. 7 shows the change in suction for M1 and M3 obtained by seepage analysis with/without SPDRs. It is seen that the result of seepage analysis roughly captures the trend of measured suction while the magnitude of suction of analysis is larger than measured one. There is a little effect of SDPR on the change in suction for M1. This is because the location of No. 1 is away from SDPR. However, the suction at all depths for M3 increases with SDPR because the location M3 is very close to SDPR. Particularly, with SDPR, the suction at depth 2.0 m increase 20 kPa while those at depth of 0.5 and 3.0 m increase 10 kPa. Therefore, it can be expected that SDPR is also effective for increasing the suction of soil.

Fig. 8 shows the ground water surface in the embankment of the seepage analysis on 19th September 2016. It can be seen that middle and bottom SDPRs are effective for lowering the ground water surface in Bs2 soil layer of the bottom embankment.

5 SLOPE STABILITY ANALYSIS

Fig. 9 shows change in safety factor of embankment with/without SDPRs during rainfall based on the slope stability analysis. It is noted that vertical axis is normalized by the safety factor of embankment without rainfall and SDPRs. The safety factor without SDPRs decreases due to 18th and the following rainfall on September rainfall, however the safety factor with SDPRs can improve the stability and recover quickly on 23rd September and 2nd October after rainfall. In the slope stability analysis, the improvement effect of SDPR on the safety factor is divide into drainage effect (lowering ground water), reinforcement effect (increasing pullout strength), and unsaturation effect (increase in shear strength due to the suction of unsaturated area). The drainage effect of SDPR on the stability of embankment considered to be larger than reinforcement and unsaturation effects of SDPR.

6 CONCLUSIONS

In order to investigate the effectiveness of SDPR, this paper summarizes the result of field observation and the numerical results of saturated-unsaturated seepage analysis and slope stability analysis for the highway embankment reinforced with SDPRs. 1) SDPR is effective for lowering the groundwater level of the slope of embankment especially for the shallow area above the position of SDPRs. 2) From field observation and saturated-unsaturated seepage analysis, it is confirmed that the soil layer near SDPR becomes unsaturated condition and SDPR is also effective for increasing the suction of soil due to the unsaturation. 3) SDPR is effective for improving the stability of embankment and particular recovering the safety factor just after rainfall.

REFERENCES

1) Hamasaki, T., Kasama, K., Tayama, S., Maeda, Y., Matsuoka, K. and Akiyoshi, R. (2018): Field Test for Embankment Reinforcement Using Spiral Bladed Drain Pipes, Journal of Japan Society of Civil Engineers, Ser. C (Geosphere Engineering), 74(1), 20-33 (Japanese).
2) Hamasaki, T., Kasama, K., Matsuoka, K. and Taguchi, K. (2017): Research for development of Spiral bladed Drain Pipe Reinforcement method, Proc. 19th International Conference on Soil Mechanics and Geotechnical Engineering, pp.2143-2146.
3) Hamasaki, T., Kasama, K., Matsuoka, K., Yakabe, H. and Ito, H. (2017): Field test for develop of spiral bladed drain pipe reinforcement method, Proc. of the 7th China-Japan Geotechnical Symposium, pp.78-82.
4) van Genuchten, M.Th. (1980): A closed-form equation for predicting the hydraulic conductivity of unsaturated soils, Soil Sci. Am. J., 44: 892-898.
5) Yano, K. (1990): Study of the method for setting standard rainfall of debris flow by the reform of antecedent rain. Jpn. Soc. Erosion Control Eng. 43 (4), 3-13 (in Japanese with English abstract)
6) Siva Subramanian, S., Ishikawa, T. and Tokoro, T. (2018): An early warning criterion for the prediction of snowmelt-induced soil slope failures in seasonally cold regions, Soils and Foundations 58(3), 582-601.