Numerical study of the effect of shear keys on the stability of cantilever retaining walls

Changcheng Du[1], *Jianfeng Chen[1]

[1]Department of Geotechnical Engineering, College of Civil Engineering, Tongji University, China

*Presenting author: duchangcheng@tongji.edu.cn

Corresponding author: 01016@tongji.edu.cn

Abstract

Shear keys can enhance the slip resistance of cantilever retaining walls (CRWs), but their mechanisms are still not clear. In this paper, a numerical model for a CRW built and instrumented in Minnesota was carried out using a two-dimensional finite element program. The validated numerical model and Strength Reduction Method (SRM) were employed to investigate the effect of lengths and positions of the shear key on the stability of the CRW. The analysis shows that the slip surface passes the bottom of the shear key and is deepened and lengthened when a shear key is provided. The stability of the CRW with a shear key is improved because of better anti-slip capacities. The factor of safety of the CRW gradually increases from 1.038 to 1.268, approximately 22%, as the length of the shear key increases from 0 m to 0.6 m. The factor of safety of the CRW increases and then decreases as the shear key moves from the toe to the heel. The factor of safety is maximized when the shear key is set near the middle of the heel. This is because the rotation of the CRW results in a reduction in the effective length of the shear key at the end of the heel.

Keywords: Numerical method, Soil-structure interaction, Soil slope analysis

Introduction

Cantilever retaining walls (CRWs) are light in weight, low in cost, and simple in structure, which have been widely used in filling with low-bearing capacity foundations and limited construction space [1]-[3]. The anti-slip stability of the CRW is generally ensured by the friction resistance between the bottom of the footing and the foundation soil, but this kind of resistance is usually insufficient when the height of the wall stem is too large. Shear keys are often provided at the bottom of the footing to enhance the anti-slip resistance of CRW. For instance, the Minnesota Department of Transportation built a CRW with a shear key at the bottom of the footing to widen the width of an existing roadbed [1]. The monitoring results showed the CRW had been operating well.

At present, scholars have conducted some research on CRW mainly in terms of its earth pressure distribution characteristics, wall back thrust calculation methods, and wall movement characteristics. Kamiloğlu and Şadoğlu (2007) [4] proposed an earth pressure analytical solution considering the friction between the back of the wall and the backfill, based on the limit equilibrium method. Huang and Luo (2009, 2010) [5][6] experimentally investigated the effect of foundation settlement on the performance of CRWs. Al and Sitar (2010) [7] investigated the magnitude and distribution of lateral earth pressures acting on a CRW under dynamic action. Bentler and Labuz [1] monitored earth pressures, wall displacements, and wall rotation angles of a CRW constructed in Minnesota.

To date, few studies have been carried out on the shear key of CRWs. Horvath (1991) [8] discussed the effect of footing shape on the performance of a CRW. It was found that the shape of the footing had a significant influence on the anti-slip resistance. The anti-slip resistance was enhanced in turn by shear keys located at the end of the toe, the underside of the wall stem, and the end of the heel, but there is no explanation for this phenomenon. Moreover, the anti-slip capacity is also not clear for the shear keys located in the middle of the heel. Although it is recognized that shear keys have a significant effect in improving slip resistance, current theory on the subject only treats them as a useful structural measure. It is still unclear where the shear keys should reasonably be located.

In this paper, a numerical model for a CRW built and instrumented in Minnesota was carried out using a two-dimensional finite element program. The validated numerical model and Strength Reduction Method (SRM) were employed to investigate the effect of lengths and positions of the shear key on the stability of the CRW. The research results are of some reference value for the reasonable consideration of the shear keys.

Project description

A 0.8 km long poured-in-place reinforced concrete CRW was constructed by the Minnesota Department of Transportation (Mn/DOT) on the south side of I - 494 near the West Bush Lake crossing in Bloomington, Minnesota (Latitude N 44°51′36″, Longitude W 93°22′36″) from 2002 to 2003. The location of the project is shown in Figure 1. The CRW consists of a wall stem, a footing, and a shear key. Displacements (2 survey reflectors 16 E and 25 E) and earth pressures (EPC_1, EPC_5, EPC_7, EPC_9) were monitored continuously for more than 12 months. The dimensions of the CRW, the location of the survey reflectors, and the location of EPCs are shown in Figure 2.

Figure 1. Project location [2]

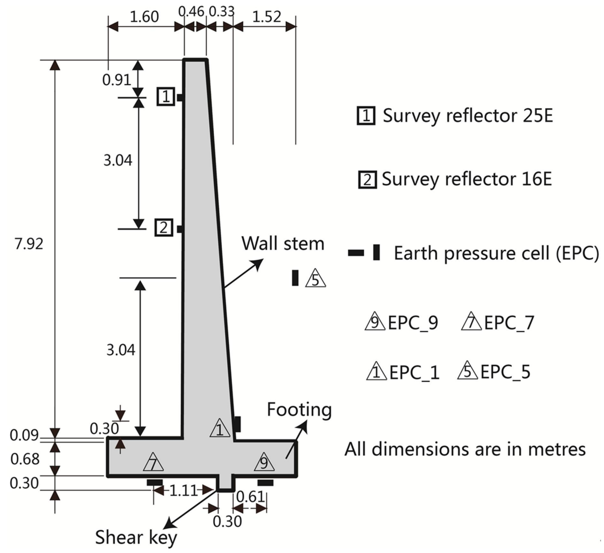


Figure 2. Schematic illustration of the CRW

Backfilling in layers after the wall construction. Drilling data shows that the foundation in the area is poorly graded sand and gravelly sand with an average moisture content of 12 %. The depth of bedrock is more than 7 m and the depth of groundwater burial is 1 - 1.5 m. The backfill and front fill are medium and fine sand with poor grading, gravity γ= 18.9 kN /m^3, internal friction angle φ' = 35° - 39°, cohesion c' = 0.

Numerical modeling

Overview

The finite element program was employed to develop a plane strain model, as shown in Figure 3. The numerical model is 13.6 m in height and 30 m in width. It consists mainly of concrete CRW, front fill, backfill, and foundation. An unstructured finite element mesh consisting of triangular elements with 15 nodes was chosen. The wall and its surrounding soil were encrypted with group encryption and envelope point encryption respectively. In addition, the effect of groundwater was not considered in the model, so all materials were set to drain.

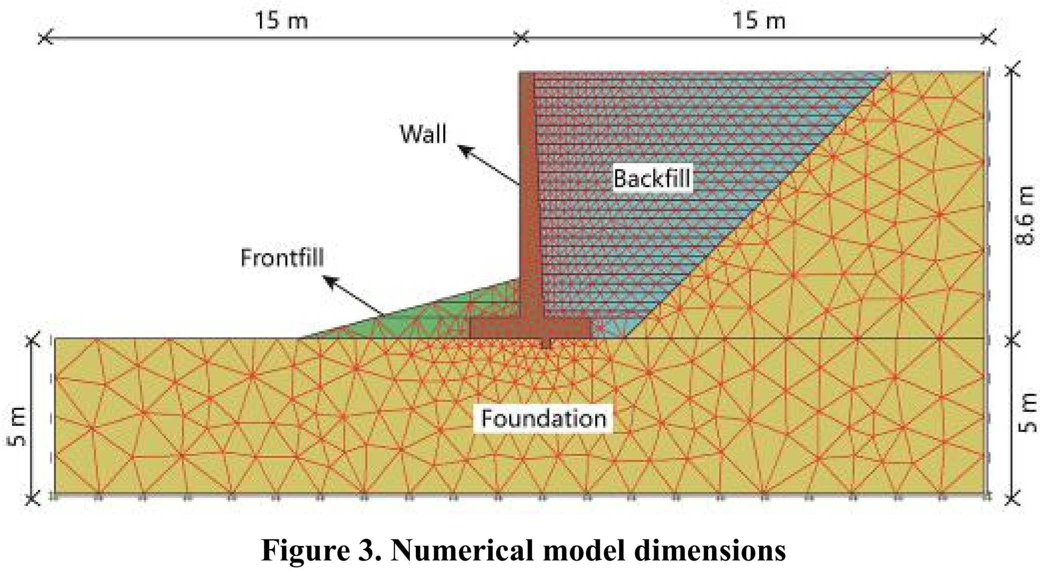


Figure 3. Numerical model dimensions

Material constitutive models and parameters

The Mohr-Coulomb (MC) constitutive model was selected to simulate the behavior of the front fill, the backfill, and the foundation. The isotropic linear elastic solid element was selected for the CRW. The material parameters for this model are summarized in Table 1. The material parameters were referenced from Chugh and Labuz (2011) [2]. It should be noted that some of the material parameters (e.g. the modulus of the soil) had been adjusted during the progress of numerical simulations in this paper.

Table 1 Material properties

Material	Constitutive model	γ_{unsat} (kN/m^3)	v (-)	E_{ref} (MPa)	c' (kPa)	ϕ' (°)	Ψ (°)
Backfill	MC	18.81	0.33	35.1	0.1	38	8
Front fill	MC	17.64	0.33	30.2	0.1	36	6
Foundation	MC	15.68	0.33	70.0	10	30	0
Concrete	Elastic	23.52	0.16	32500	--	--	--

Notations: MC = Mohr-Coulomb model; γ_{unsat} = unit weight above the water table; v = Poisson's ratio; E_{ref} = Young's modulus; c' = effective cohesion; ϕ' = effective friction angle; ψ = dilation angle.

Interfaces and boundary conditions

Five types of interfaces were considered in the numerical model, as shown in Table 2. These interfaces were modeled as MC failure criteria. The interfaces were implemented by the interface strength reduction factor R_{inter} in the software PLAXIS 2D 8.5. It should be noted that the relationships between the actual parameters and the input parameters of the interfaces are as follows**:**

$$c_i = R_{inter} c_{\text{soil}} \tag{1}$$

$$\tan \varphi_{\text{i}} = R_{\text{inter}} \tan \varphi_{\text{soil}} \tag{2}$$

where c_{i}、φ_{i} is the actual parameters of the interfaces；c_{soil}、φ_{soil} is the input parameters of the interfaces

Table 2 Interface properties

Interface	Constitutive model	γ_{unsat} (kN/m^3)	v (-)	E_{ref} (MPa)	c' (kPa)	ϕ' (°)	Ψ (°)	R_{inter} (-)
BW	MC	18.81	0.33	35.1	0.1	38	8	0.67
FFW	MC	17.64	0.33	30.2	0.1	36	6	0.67
FW	MC	15.68	0.33	70.0	10	30	0	0.67
FFF	MC	15.68	0.33	70.0	10	30	0	0.67
BF	MC	15.68	0.33	70.0	10	30	0	0.60

Notations: BW = backfill–wall interface; FFW = front fill–wall interface; FW = foundation–wall interface; FFF = front fill–foundation interface; BF = backfill–foundation interface.; R_{inter} = reduction factor of property of interfaces.

In addition, the boundary conditions of the model were set as follows: The top surface was free displacement constraint; The left and right sides were horizontal displacement constraint ($u_x = 0$); The bottom surface was fully constrained for horizontal and normal displacements ($u_x = u_y = 0$).

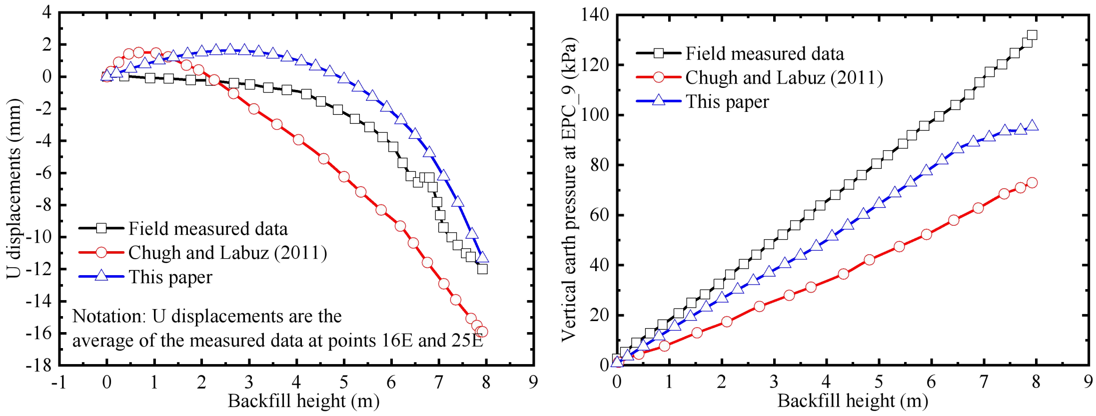
Construction process

The construction process was simulated in the following order:

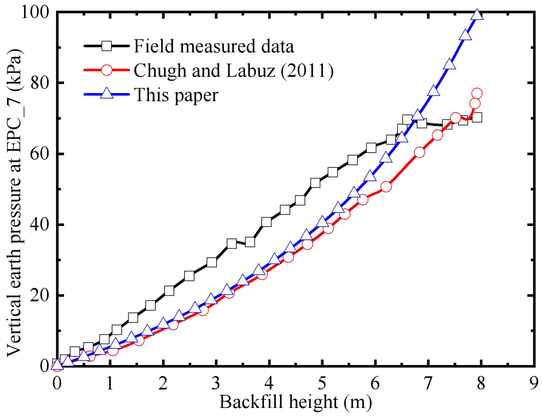
(i) Gravity loading to generate the initial stress field in the foundation;
(ii) Freezing of the foundation at the shear key;
(iii) Activation of the footing and wall stem;
(iv) Activation of the front fill;
(v) Activation of backfill on the side of the footing;
(vi) Activation of the rest of the backfill in layers.

Model validation

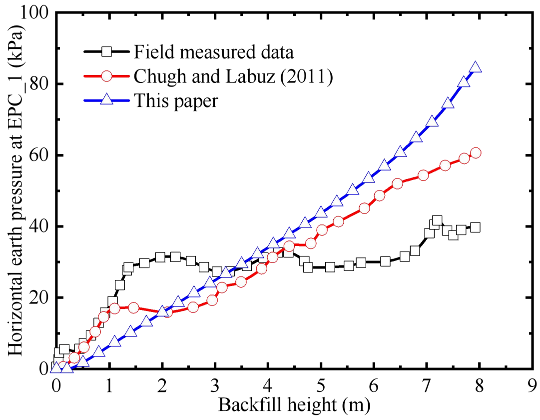
Comparisons of the results in this paper, the measured data in the field, and the results from Chugh and Labuz (2011) [2] are shown in Figure 4. The horizontal displacement, earth pressure of EPC_9, and earth pressure of EPC_7 are in good agreement with the measured data in the field. Although the earth pressures for EPC_1 and EPC_5 differ somewhat from the measured data in the field, the trend is consistent. In conclusion, the results in this paper are more satisfactory than those from Chugh and Labuz (2011) [2]. This numerical model is therefore acceptable and suitable as a typical example to analyze the mechanical behavior of CRWs



(a) (b)



(c)



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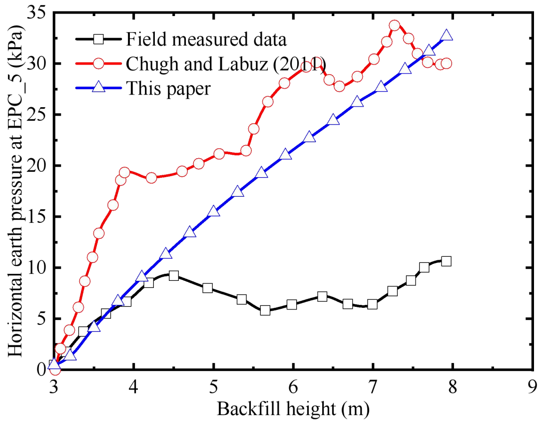

(e)

Fig. 4 Comparison between the results in this paper, the field measured data and the results from the literature [2]: (a) Horizontal displacement of the CRW; (b) Vertical earth pressure of EPC_9; (c) Vertical earth pressure of EPC_7; (d) Horizontal earth pressure of EPC_1; (e) Horizontal earth pressure of EPC_5.

Research programs

Ten types of shear keys were considered to investigate the effect of the length and position of the shear key on the anti-slip capacity of the CRW, as shown in Figure 5. The SRM built in the program was employed to analyze the stability of CRWs. Finally, the factor of safety was obtained [9].

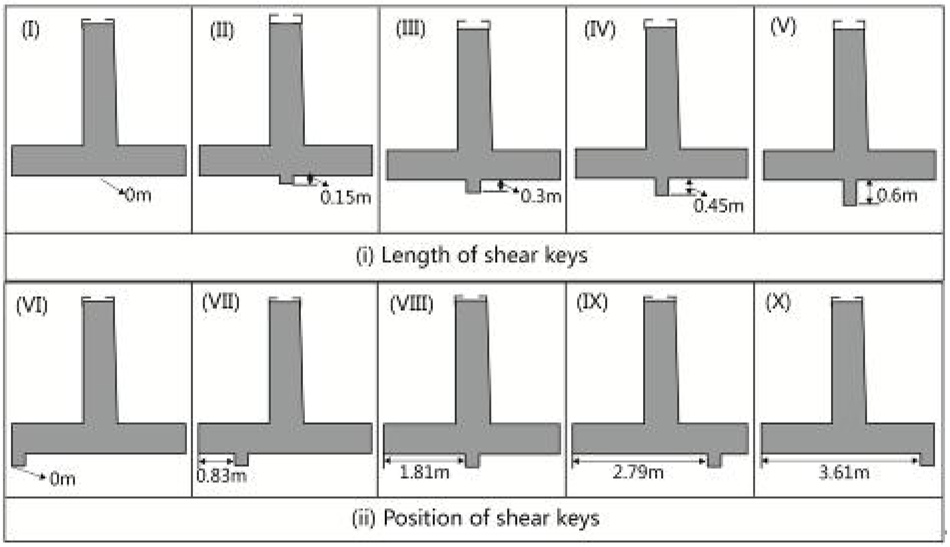

Figure 5. Ten types of shear keys considered in this paper

Results and discussion

Effect of the length of shear keys

Figure 6 shows the variation curve of the factor of safety of the CRWs with different lengths of shear keys. The lengths of the shear keys have a significant effect on the stability of CRWs. The factor of safety gradually increases from 1.038 to 1.268, an improvement of approximately 22%, as the lengths of the shear key increase from 0 m to 0.6 m.

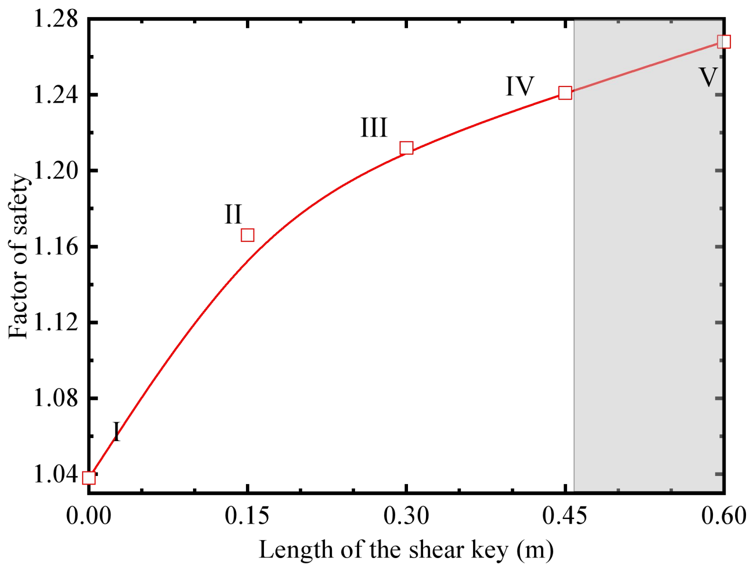

Figure 6 Variation curve of the factor of safety of the CRWs with different shear key lengths

The total displacement contours of CRWs based on SRM are plotted, as shown in Figure 7. The slip surface is the shortest and shallowest for a shear key of 0.15 m. The slip surface is the longest and deepest for a shear key of 0.6 m. The longer the shear key, the longer and deeper the slip surface. Therefore, foundation soils can provide a greater passive earth pressure and the stability of the retaining structure can be better. In practice, shear keys of a certain length can be added to improve the anti-slip stability of CRWs.

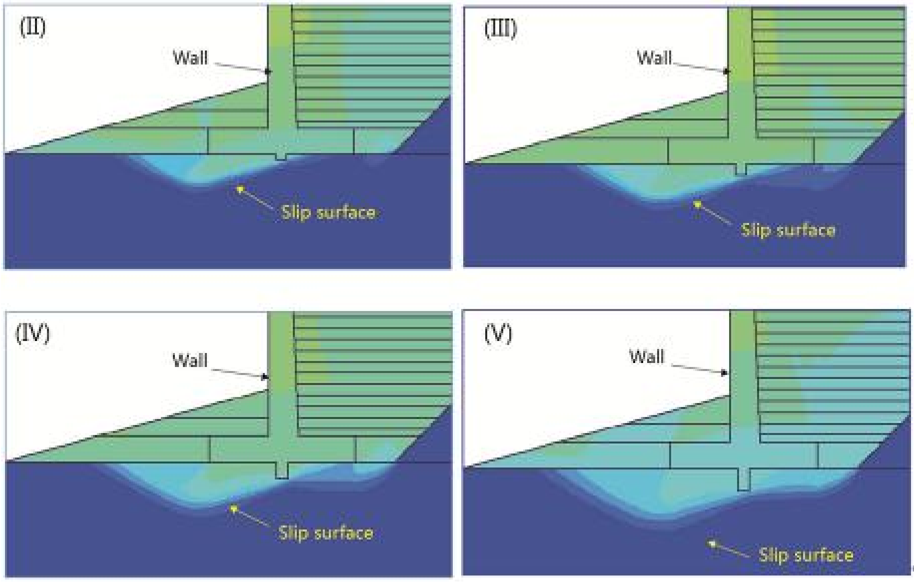

Figure 7 Total displacement contours for CRWs with different shear key lengths

Effect of the position of shear keys

Figure 8 shows the variation curve of the factor of safety of the CRWs with different shear key positions. The positions of the shear keys have a significant effect on the factor of safety. The factor of safety at X (1.215) and IX (1.228) is greater than that at VIII (1.212), VII (1.153), and VI (1.066). The factor of safety of the CRW with a shear key at the heel is greater than that with a shear key at the wall stem and the toe, which is consistent with the results of Horvath (1991) [8]. However, the factor of safety increases continuously and then decreases as the distance from the shear key to the end of the toe increases. An inflection point occurs at IX. This indicates that the factor of safety is maximum when the shear key is set near the middle of the heel. This did not describe in the analysis of Horvath (1991) [8].

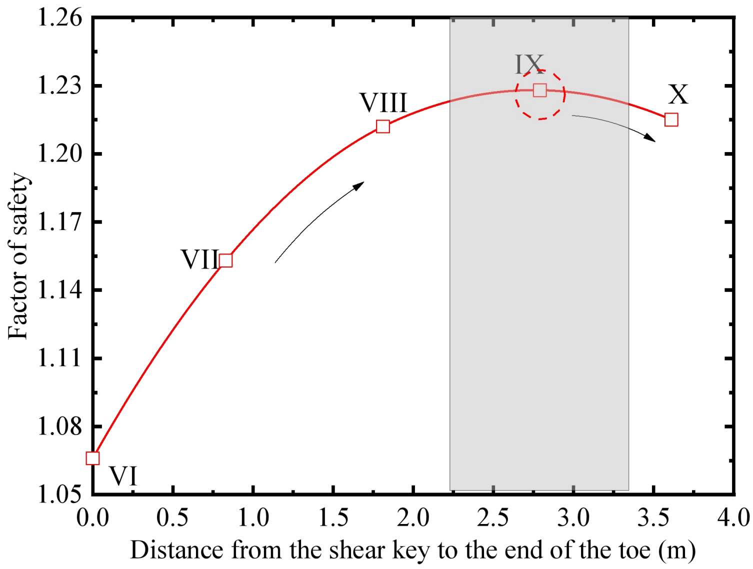

Figure 8 Variation curve of the factor of safety of the CRWs with different shear key positions

To investigate the reasons for these results, the total displacement contours of CRWs based on SRM are plotted, as shown in Figure 9. The depth and length of the slip surface first increase and then decreases, as the shear key moves from toe to heel. The slip surface of CRW with a shear key set near the middle of the heel is the deepest and longest. This is because CRWs not only translate but also rotate when backfilling, which results in a reduction of the effective length of the shear key set at the end of the heel, as shown in Figure 10. In practice, shear keys are suggested to be set near the middle of the heel to achieve the strongest slip resistance.

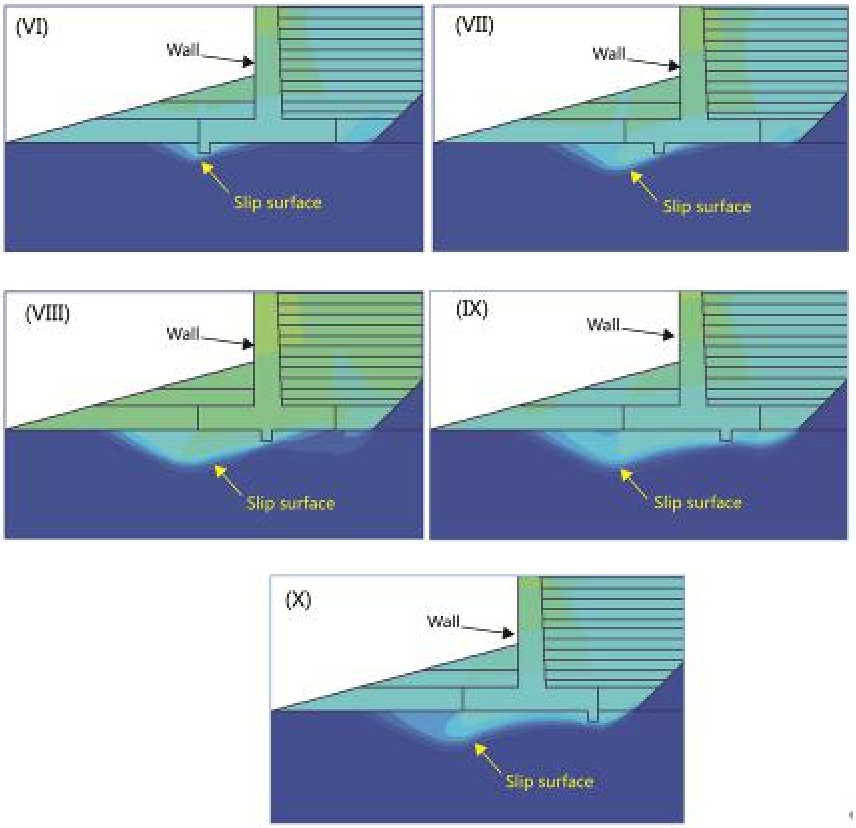

Figure 9 Total displacement contours for CRWs with different shear key positions

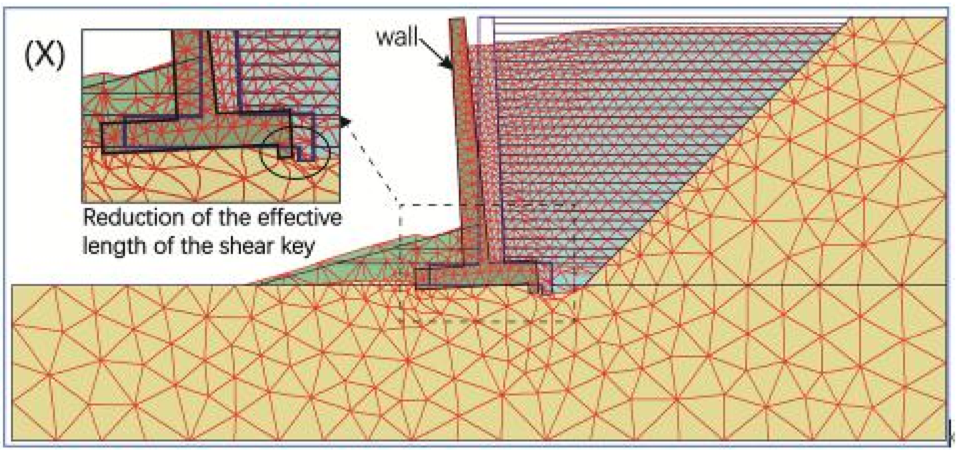

Figure 10 Grid deformation of the CRW with a shear key at the end of the heel

Conclusions

In this paper, a numerical model for a CRW built and instrumented in Minnesota was carried out using a two-dimensional finite element program. The validated numerical model and Strength Reduction Method (SRM) were employed to investigate the effect of lengths and positions of the shear key on the stability of the CRW. The main conclusions were summarized as follows:

(1) The analysis shows that the slip surface passes the bottom of the shear key and is deepened and lengthened when a shear key is provided. The stability of the CRW with a shear key is improved because of better anti-slip capacities.

(2) The factor of safety of the CRW gradually increases from 1.038 to 1.268, approximately 22%, as the length of the shear key increases from 0 m to 0.6 m. The factor of safety of the CRW increases and then decreases as the shear key moves from the toe to the heel.

(3) The factor of safety is maximized when the shear key is set near the middle of the heel. This is because the rotation of the CRW results in a reduction in the effective length of the shear key at the end of the heel.

Acknowledgments

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Conflict of interest

The authors declare that they have no conflict of interest.

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