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Stability Analysis of Double V-shaped Gully Embankment: A Dimension-reduced Calculation Method

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Abstract: The slope stability is generally analyzed by a 2D method, ignoring the spatial effect (SE), which no longer meets the evaluation accuracy requirement. This problem is particularly prominent for the embankment built on the double V-shaped gully (E-DVSG), which is a typical but unique topography in the mountainous area. Moreover, the technical requirements for engineers will increase sharply if a 3D slope stability calculation method is adopted. To tackle this issue, pragmatically, a dimension-reduced slope stability analysis method (DR-SSAM) considering the SE of the E-DVSG was proposed and verified by a case study. Specifically, the DR-SSAM obtained the 3D safety factor of the E-DVSG by using the spatial effect curves and the safety factor from the 2D model. The results showed that the method was rational and efficient for engineering applications. Besides, the SE generation mechanism and condition along with its influences resulted from the major factor were addressed thoroughly.

Key Words: Double V-shaped gully; Embankment; Slope stability; Dimension-reduced; Spatial effect; Finite element method

1 Introduction

Highway construction in the mountainous area involves plenty of tunnel excavation, cutting and digging, which always results in abundant earth and stone wastes. Therefore, the high-filled embankment has been extensively implemented to consume these wastes instead of using a bridge, especially in the area with numerous gullies, leading to significant environmental and economic benefits.

Double V-shaped gully (DVSG), the side banks of which not only gradually contract or expand to the valley mouth in the direction of the gully but also gradually narrow and contract from the top down in the vertical direction, is one of the most common terrains. Thus, an embankment built on the DVSG (E-DVSG) can be easily found in this area (shown in Fig. 1). For instance, within 14km of Jinshan to Hongfang section, in Fujian province, of the extension project of Xiarong highway and Nanjing section of Zhangwu highway, there are 10 and 8 double V-shaped gully filled embankments respectively.

Slope stability is the primary aspect of a high embankment. However, currently, the slope stability is generally analyzed by a two-dimensional (2D) method, which ignored the influence of side banks, namely the spatial effect (Lu 2015). This can no longer meet the evaluation accuracy requirement of the slope stability for the E-DVSG, of which the terrain constrains is considerably unique, resulting in considerable engineering waste. Therefore, many researchers and engineers have tried to find a practical 3D stability analysis method, which can consider the spatial effect (Chakraborty & Goswami 2018; Li, Merifield, & Lyamin 2010; Yu, Li, & Huang 2018). However, the calculation workload and technical requirements for engineering personnel will increase sharply if a 3D slope stability calculation method is adopted. Thus, pragmatically, there is a great need to propose an efficient slope stability evaluation method considering the spatial effect.

Some studies have been done related to the spatial effect of slopes. However, the research objects are mainly focused on the general embankments (GEs, without constraints of the side banks) and the embankment on the single V-shaped gully (SVSG) (only with the vertical constraint, narrowing gradually from top to bottom of the gully). For example, researchers have investigated the spatial effects of the GEs under geometric variables, such as different slope morphology, slope body width, width-height ratio, and surface curvature of 2D and 3D slopes (Chen & Zhu 2010; Farzaneh, Askari, & Ganjian 2008; Fattah, Saba'a, & Yousif 2010; Fattah, Mohammed, & Hassan 2016; Liu et al. 2011; Zhang, et al. 2011; Zhang, et al. 2013).

Moreover, it should be noted that, Lu, et al. (2012a and 2012b) have revealed the relationship between several variables and the spatial effect, and at the same time, they proposed a calculation curve for rapidly calculating the 3D slope safety factor according to the related parameters of the slope. However, the results of the study are only applicable to GEs, rather than to embankments under complex terrains, such as the SVSG or DVSG. In terms of the SVSG, Wu et al. (2013) and Ding et al. (2010) found that the spatial effect was caused by the side bank slope, width of the embankment, and bottom width of the gully. Chugh (2014) analyzed the influence of spatial geometry on the stability of the earth dam and found that the spatial effect was between 1.03 and 1.30. Also, Zheng et al. (2019) verified that the SVSG had an apparent constraint effect on the embankment deformation based on the simulation of high filled loess in gully terrain.

To sum up, the terrain characteristics of the E-DVSG were found to considerably differ from that of the GE or E-SVSG. However, the generation mechanism of the spatial effect of the E-DVSG and its relationship with various geometric variables is still unclear. At the same time, a reliable and convenient calculation method, considering the spatial effect of slope stability is urgently needed in order to meet the requirements of engineering calculation accuracy and reduce the calculation work.

To this end, this paper aims to verify the existence and reveal the generation mechanism of the spatial effect of the E-DVSG and its relationship between geometric variables and to propose an efficient method for calculating the slope stability. To be specific, the objectives of this paper are three-fold: (1) to analyze the deformation and stability performance of the E-DVSG under different terrain conditions by using the finite element strength reduction method, based on which the existence and generation mechanism of the spatial effects will be discussed; (2) to quantitatively determine the degree and weight of correlation between various variables and the spatial effect by the grey correlation method; and (3) to propose an efficient dimension-reduced slope stability analysis method (DR-SSAM) of the E-DVSG using the spatial effect curve.

2 Methodology

2.1 Overall design

The overall design of this study can be found in Fig. 2. In order to systematically address the spatial effect of the E-DVSG, two 3D slope stability analysis methods will be first introduced, especially for the finite element strength reduction method (FEM-SRM). And then, the numerical models, including the geometry model, parameters and boundaries, and model mesh, are going to be discussed. To be noted, the sensitivity analysis of the mesh will be conducted in detailed. Then, the calculation scenarios are listed, mainly consisting of the 3D and 2D simulation model of the E-DVSG. Based on the finite element models and the FEM-SRM, the parameter sensitivity analysis is going to be conducted on slope stability and deformation. The parameters include opening angle (α) and slope (β) of the side bank, the width of the gully top (W), the embankment filling height (H), and the rear edge slope (θ). After that, based on the grey correlation analysis, the correlation degree and weight relationship between the major influencing factors and spatial effects will be

quantitatively evaluated. Finally, a dimension-reduced slope stability analysis method (DR-SSAM) is proposed, and the feasibility will be verified by a case study.

2.2 Finite Element Strength Reduction Method, FEM-SRM

Currently, the limit equilibrium method (Cai, Nakamura, & Ugai 2012; Huang & Tsai 2000; H. Zheng 2012; Zhou & Cheng 2013) and finite element strength reduction method (Lefebvre, Duncan, & Wilson 1973; Ugai & Leshchinsky 1995; Wang 2009; Zienkiewicz, Humpheson, & Lewis 1975) are the most commonly used in evaluating the 3D slope stability. However, the 3D sliding surface search technology has some defects in the limit equilibrium method (Cheng, et al. 2005; Wei, Cheng, & Li 2009). By comparison, the FEM-SRM does not need to assume the sliding surface in advance so that it can be used in the stability analysis of 2D and 3D slopes (Nian, Huang, Wan, & Chen 2012).

The safety factor and the position and shape of the critical sliding surface can be obtained by utilizing the combining of the finite element method with the strength reduction method. In the calculation, the strength parameters of soil are reduced until the slope is in the critical state of instability, of which the reduced factor is defined as the safety factor (Griffiths & Marquez 2007; Manzari & Nour 2000; H. Zheng, Tham, & Liu 2006). The following shows the definition of the major parameters:

$$c' = c / F_r \quad (1)$$

$$\varphi = \tan^{-1}(\tan\varphi/F_r) \quad (2)$$

Wherein, c , φ and c' , φ' are respectively the cohesion and internal friction angle before and after reduction, and F_r means the reduction factor.

2.3 Numerical Models

2.3.1 Geometric Models

The actual topography of the gully is extremely complex. In order to quantitatively analyze the spatial effects of the E-DVSG, it was simplified into two types: Necking DVSG (N-DVSG) and Flaring DVSG (F-DVSG). Fig. 3a and 3b are the 3D models of N-DVSG and F-DVSG, respectively. A-A section is the characteristic section at the center of symmetry, and the 2D analysis model is built based on this section and is shown in Fig. 3c.

In this paper, the variables are considered as follows: opening angle of the side banks, slope of the side banks, gully top width, embankment filling height, and rear edge slope, represented by α , β , W , H and θ , respectively (Hereafter, $\alpha > 90^\circ$ is N-DVSG; $\alpha < 90^\circ$ is F-DVSG, and $\alpha = 90^\circ$ is SVSG).

2.3.2 Parameters and Boundaries

Model parameters refer to the indoor measured data of soil, as shown in Table 1. The side boundary of the model is bounded by normal constraints; the bottom boundary is fixed, and the gully top and embankment are free. The contact surface between the embankment and the foundation is set as hard contact, and the friction coefficient is taken as 0.51. The process of simulation analysis is simplified into two steps: first, initial stress balance is carried out for foundation; secondly, layered embankment filling is not considered. It is assumed that the embankment is a one-time filing, and only gravity load is considered. To be noted, the initial stresses is achieved by the geostatic analysis step, where the force is in balance with the initial stress of the soil, so that the initial displacement of the soil is zero (Fei & Zhang 2010)

2.3.3 Model Mesh

The computational efficiency and accuracy were studied by changing the number of embankment

grids. Eight-node linear hexahedral element (C3D8) was used in this study. Fig. 4 shows the safety factors of the N-DVSG ($\alpha=110^\circ$, $\beta=60^\circ$, $W=130$ m, $H=40$ m, $\theta=30^\circ$) and F-DVSG ($\alpha=70^\circ$, $\beta=60^\circ$, $W=50$ m, $H=40$ m, and $\theta=30^\circ$) under a different number of embankment grids.

It can be inferred that with the increasing number of embankment grids, the calculation accuracy tends to be stable, and the efficiency decreases (the computation time increased when the grids increased.). Besides, an inflection point appears when the number of embankment grids is around 2200. Considering the efficiency and accuracy of numerical simulation, for the similar embankment geometry under the same order of magnitude, the number of embankment grids is basically controlled at 2500-4000 in the following analysis models. It is worth mentioning that when we study the variable of the valley top width, its geometric size changes greatly. Therefore, the mesh should be encrypted according to the actual situation to ensure the accuracy of the results.

2.4 Scenarios

In order to fully understand the correlation degree and weight of various variables with the spatial effect of the E-DVSG, the control variable method was used to design the working conditions, as shown in Table 2, and the 3D analysis model was established on this basis.

It can be seen from Fig. 3 that the characteristic section of the 3D model has little relation with the opening angle, side bank slope, and gully top width, and its geometric size is only related to the embankment filling height and the rear edge slope. Thus, the calculation scenarios of the 2D N-DVSG and F-DVSG models are respectively shown in scenarios 4, 5 and 9, 10 in Table 2.

3 Results

3.1 Spatial Effect and Mechanism Analysis

3.1.1 Spatial Effect

To verify the existence of the spatial effect in the E-DVSG, Scenarios 3 and 8 with a gully width of 110 m and the corresponding 2D model were analyzed. The results are shown in Table 3. As noted, the safety coefficient obtained by the 2D model is lower than that of the 3D model, showing that the spatial effect did exist in both the N-DVSG and F-DVSG models. Moreover, the 3D safety factor of the N-DVSG is larger than that of the F-DVSG, which indicates that the spatial effect changed with topographic conditions.

3.1.2 Mechanism

To explore the generation mechanism of the spatial effects, the XZ horizontal and YZ vertical cutting sections at Y=55m and X=60m were taken as analytic objects, and the displacement vector map and minor principal stress contour nephogram of each section are shown in Figs. 5 and 6.

For the N-DVSG, seen from Figs. 5a and 5b, it can be found that the lateral deformation of embankment mainly follows the trench way direction of the gully. In the process of deformation, the sliding outlet of the embankment soil shrinks due to the inward contracting of the base bank on both sides of the gully, narrowing of the distance between the valley mouth. During this process, the further deformation of the embankment soil is obstructed, which results in a kind of locking effect. This is similar to the "topographic soil arch" (Zhang 2017), which is called the 'horizontal V effect.' However, as shown in Figs. 6a and 6b, there is no horizontal locking effect due to the expansion of the sliding "outlet" of the F-DVSG. This explained why the spatial effect of the N-DVSG was stronger.

As shown in Figs. 5c and 5d, similar locking effects can be found in the vertical direction of both the N-DVSG and F-DVSG. This is mainly due to two major reasons. One is that the vertical "V" gradually narrows and contracts from top to bottom, which restrains the vertical deformation of the embankment and squeezes the embankment. Another is the friction between the two sides of the embankment and the foundation. This will produce an uneven displacement of the soil so that the internal stress of the soil will deflect and redistribute, and part of the earth pressure will be transferred to the foundation. That results in the locking effect of topographic soil arch,' which is called the 'vertical V effect.' Moreover, it can be observed that when the top width reaches a specific value, the vertical V effect disappears gradually.

To be concluded that the spatial effect of the N-DVSG is stronger than that of the F-DVSG with all the factors are consistent, and the spatial effect will disappear when the gully top width reaching a specific value.

3.2 Sensitivity Analysis

3.2.1 Opening Angle of Side Banks, α

The relationship curves of the E-DVSG spatial effect coefficient (F_3/F_2), displacement ratio (U_3/U_2), lateral displacement (U_X) with the opening angle (α) are shown in Fig. 7. As noted, when $\alpha = 90^\circ$, and the gully top width (W) increases from 50m to 130m, the spatial effect coefficient drops abruptly from 1.22 to 1.05, a decrease of 13.9%. It indicates that the W has a great influence on the spatial effect; (2) when $W=50$ m, the α increases from 65° to 90° , and the F_3/F_2 increases from 1.06 to 1.22, increasing by 15.1%. At the same time, the U_3/U_2 decreased by 17.5%, from 0.8 to 0.66. Also, the U_X decreased by 50%, from 4.4cm to 2.2cm, showing that the horizontal V effect was evident. When $W=130$ m, the F_3/F_2 , U_3/U_2 , and U_X all changes slightly.

Therefore, it can be found that the strength of the spatial effect in embankments built on the gully terrain was: N-DVSG > SVSG > F-DVSG. At the same time, the opening angle of the side bank (α) and the gully top width (W) were the main factors affecting the spatial effect of the E-DVSG.

3.2.2 Slope of Side Banks, β

The relationship curves of the E-DVSG spatial effect coefficient (F_3/F_2), displacement ratio (U_3/U_2), vertical displacement (U_Y) with the slope of side banks (β) are shown in Fig. 8. It can be found that: (1) with the β increasing from 50° to 70° , the F_3/F_2 of the F-DVSG and the N-DVSG declines from 1.1 to 1.05 and from 1.12 to 1.08, a decrease of 4.5% and 3.6%, respectively. Besides, a similar uptrend of the U_3/U_2 was also found for these two structures, increasing from 0.58 to 0.88 and 0.94 to 0.98 by 51.7% and 4.3%, respectively. This means that the larger the β was, the smaller the squeezing clamping effect on the embankment was. It indicates that β was a major factor affecting the spatial effect.

(2) With the β increasing from 50° to 70° , the vertical displacement (U_Y) of the F-DVSG increased rapidly from 5.9cm to 9cm, with an increase of 52.5%, while that of the N-DVSG increased by only 4.2%, but the spatial effect of the latter one was still stronger. This phenomenon indicates that although the vertical V effect was weaker than that of the F-DVSG due to its larger gully top width, the existence of the horizontal V effect made its overall spatial effect maintaining at a higher level. At the same time, it also showed that the valley top width (W) was another major factor.

3.2.3 Gully Top Width, W

The relationship curves of the E-DVSG spatial effect coefficient (F_3/F_2), displacement ratio (U_3/U_2),

lateral displacement (U_X), and vertical displacement (U_Y) with the gully top width (W) are shown in Fig. 9. As noted, with the gradually increasing W , the stability and deformation of the embankments first rapidly decreases, and then slowly tends to the 2D structure ($F_3/F_2=1.0$ and $U_3/U_2=1.0$). This phenomenon shows that the spatial effect is significant when the W is small and sensitive to the increasing W , presenting an inverse trend. This is mainly due to the gradually decreased obstruction effect of the deformation, resulted from both sides of the banks with the increasing W . Besides, when the width of gully top is the same, the spatial effect of the N-DVSG is stronger than that of the F-DVSG, indicating that the width of valley top is a main factor affecting the spatial effect.

3.2.4 Height of Embankment, H

The relationship curves of the E-DVSG spatial effect coefficient (F_3/F_2), displacement ratio (U_3/U_2), the safety factors of the 2D and 3D embankments with the fill height (H) are shown in Fig. 10. As noted, with the H increasing from 30m to 50m, the 3D safety factor of the F-DVSG and N-DVSG decreases from 1.72 to 1.63 and from 1.75 to 1.67, with a drop of 5.2% and 4.6%, respectively. This phenomenon shows that the stability of both 2D and 3D slopes decreases with the increase of embankment fill height, indicating that H is an important factor affecting the slope stability. In addition, the 2D slope safety factor also shows a decrease from 1.61 to 1.52, a decrease of 5.6%. In addition, it should be noted that the F_3/F_2 of both necking and flaring DVSG are stable at 1.09 and 1.07 respectively, which indicates that the stability of the 3D model was improved by 9% and 7% compared with that of the 2D model, and at the same time, it also showed that the H was not the major influencing factor to the spatial effect.

3.2.5 Rear Edge Slope, θ

The relationship curves of the E-DVSG spatial effect coefficient (F_3/F_2), displacement ratio (U_3/U_2),

the safety factors of the 2D and 3D embankments with rear edge slope (θ) are shown in Fig. 11. As noted, the stability of 2D and 3D slope is gradually increased with the increasing θ . At the same time, the F_3/F_2 of both the necking and flaring DVSG is stable at 1.08 and 1.06, respectively, showing an improvement of 6% and 8% compared with that of 2D slopes. However, due to a stable trend of the F_3/F_2 of the 2D and 3D slopes, the θ was not the primary factor affecting the spatial effect.

3.3 Grey Correlation Analysis

As mentioned before, the opening angle (α), side bank slope (β), and top gully width (W) are the main influencing factors. In order to study the degree of correlation between these factors and the spatial effect, grey correlation analysis (Miao et al. 2019; Wang, Wu, & Zhao 2013; Xie, Yan, Ren, & Lu 2015) is introduced. The correlation coefficient is:

$$\zeta_i(k) = \frac{\min_i \min_k |x_0(k) - x_i(k)| + \rho \max_i \max_k |x_0(k) - x_i(k)|}{|x_0(k) - x_i(k)| + \rho \max_i \max_k |x_0(k) - x_i(k)|} \quad (3)$$

$$x_i(k) = \frac{x'_i(k) - \bar{x}'(k)}{s} \quad (4)$$

$$s = \max_i x'_i(k) - \min_i x'_i(k) \quad (5)$$

Wherein, $x'_i(k)$ is the i th variable of the k th indicator data before non-dimensionalization; $x_0(k)$ represents the spatial effect coefficient; $x_i(k)$ is indicator data after non-dimensionalization; ρ is the discrimination coefficient, usually equals 0.5.

The correlation degree between variables and spatial effect coefficient is denoted as:

$$\gamma_i = \frac{\sum_{k=1}^N \xi_i(k)}{N} \quad (6)$$

The weight of each variable factor is:

$$\omega_i = \frac{\gamma_i}{\sum_{i=1}^n \gamma_i} \times 100\% \quad (7)$$

According to the above methods, the correlation degree of major factors and the spatial effect coefficient and their corresponding weights are calculated, as shown in Table 4.

It can be found that for the necking or flaring DVSG, the correlation order of main influencing factors and the spatial effect is respectively: $W > \alpha > \beta$ and $\alpha > W > \beta$. Moreover, the influencing weight of these factors is close, with a relatively small value for the β .

3.4 Proposed Reduced Dimension Slope Stability Analysis, DR-SSAM

3.4.1 Spatial Effect Curves

Through the sensitivity analysis, the opening angle (α), side bank slope (β), and gully top width (W) were found to be closely related to the spatial effect of the E-DVSG. In order to apply the research results in engineering practice, the relationship curves between the spatial effect coefficient (represented by F_3/F_2) and the major influencing factors were fitted by using the dimensionless data.

For the N-DVSG, as shown in Fig. 12(a), the relation curve is:

$$F_3/F_2 = 0.0345 \ln(\chi) + 0.996 \quad (8)$$

wherein,

$$\chi = -10000 \cos \alpha / [\sin \beta \tan \beta (W/H)^4] \quad (9)$$

For the F-DVSG, as shown in Fig. 12(b), the relation curve is:

$$F_3/F_2 = -0.06 \ln(\psi) + 1.0618 \quad (10)$$

wherein,

$$\psi = W \tan \beta / (H \tan \alpha) \quad (11)$$

3.4.2 Procedures

The calculation steps of the DR-SSAM of the E-DVSG are as follows, and the workflow is presented in Fig. 13.

1. Acquire the F_2 from 2D slope model;
2. Determine the value of the α , β , W , and H ;
- 3a. For N-DVSG, the F_3/F_2 can be calculated from Equations 8 and 9;
- 3b. For F-DVSG, the F_3/F_2 can be calculated from Equations 10 and 11;
4. F_3 can be calculated from the known F_3/F_2 and F_2 .

$F_3/F_2 > 1$ demonstrates the existence of the spatial effect. According to Equations 8 and 9, the existence of the spatial effect of N-DVSG should satisfy $[\sin\beta \tan\beta (W/H)^4] / \cos\alpha > -8904.720$, indicating that a spatial effect occurs when $\alpha=110^\circ$, $\beta=60^\circ$ and $W/H < 6.713$. Similarly, for F-DVSG, it should meet $W \tan\beta / (H \tan\alpha) < 2.801$, based on Equations 10 and 11. That is to say, if $\alpha=70^\circ$, $\beta=60^\circ$ and $W/H < 4.442$, a spatial effect can be found.

4 Case Study

4.1 Project Profile

Two field embankments were selected as a case study to verify the proposed DR-SSAM. To be noted, both slopes were found a slight lateral sliding under inclement rainy. The N-DVSG is in Ningwu Highway from BK102+600 to BK102+728, which was completed and opened to traffic in October 2012 and obvious deformation and collapse of the embankment were found under the continuous heavy rainfall in early June 2016. The terrain of this embankment is shown in Fig. 14a. Moreover, the F-DVSG is located at K102+286 of the Jiaoyang Highway in Fujian province. The terrain is shown in Fig. 14b.

4.2 3D Stability Analysis

4.2.1 Based on the DR-SSAM

N-DVSG: based on the calculation workflow shown in Fig. 13, the calculation process of the 3D

safety factor is as follows: (1) 2D analysis model is established, as shown in Fig. 15a. The length of the model is about 162m, and the height is about 49-90 m. Model parameters are measured from the site, as shown in Table 5. Through numerical simulation, F_2 is obtained as 1.05. (2) According to the design document and topographic map (Fig. 14), α , β , W , and H are respectively 116° , 36° , 110 m, and 22 m. (3) Based on Equations 8 and 9, χ and F_3/F_2 were 16.4 and 1.09, respectively. (4) Fed $F_2=1.05$ into $F_3/F_2=1.09$, the 3D safety factor F_3 is calculated as 1.14.

The 2D analysis model of the F-DVSG is shown in Fig. 15b and the model parameters are shown in Table 5. Followed the same producers mentioned before, the 3D slope safety factor of the F-DVSG is 1.27.

4.2.2 Based on the 3D FEM Models

According to the design document and topographic map, the 3D analysis models of the N-DVSG and F-DVSG are established respectively, as shown in Fig. 16a and 16b. Through the 3D numerical simulation, the relationship curve between slope displacement and the reduction coefficient can be derived (Fig. 17). The reduction coefficient corresponding to the displacement mutation point is the safety coefficient.

It can be found that the safety factors of the N-DVSG and F-DVSG based on the 3D FEM model are 1.13 and 1.22, respectively.

4.3 Feasibility Analysis

Compared with the results obtained by the DR-SSAM and the 3D FEM model, there were only 0.9% and 4.1% difference, showing that the accuracy of the proposed DR-SSAM is very high. Therefore, the analysis results verified the rationality of the proposed method, and it can be deemed as an efficient method to evaluate the stability of the E-DVSG.

5 Discussion

The DVSG is a complex but common terrain in the mountainous area, showing in the unique spatial effect that does not exist in the general embankment. This paper conducted a systematic and comprehensive analysis of the E-DVSG, which has not been fully discussed before. There are three particularity aspects as follows:

(1) In terms of the generation mechanism of the spatial effect, Lu et al. (2012a and 2012b) pointed out that the essence of the spatial effect was the constraints of the soil around the sliding surface, which was not considered in the 2D slope stability analysis. By contrast, this paper found that the cause of the spatial effect is the uneven displacement of the soil resulted from the constraints of the side banks. This deflected the internal stress, leading to the stress redistribution and the earth pressure was partly transmitted to the side banks.

(2) In terms of studying the relationship between variables and the spatial effects, only qualitatively analysis was performed in previous studies. In this paper, the correlation degree and weight between them were quantified based on the grey correlation method. Besides, it is worth noting that it is generally believed that the rear edge slope and embankment fill height have a significant impact on the spatial effect. However, the research conclusion in this paper is contrary to this, but it still has a significant impact on slope stability and deformation. This conclusion can provide a reference for simplifying spatial effect analysis under similar terrain conditions.

(3) In terms of the 3D slope stability evaluation method proposed by Lu et al. (2012a and 2012b), when evaluating the stability of a specific 3D slope, one should first determine the sliding surface, and then obtain the relevant parameters of the sliding body of the slope (width, height, slope ratio, etc.). Finally, using a series of safety factor calculation curves (obtained in advance using the 3D limit equilibrium method) and the sliding body parameters, the 3D slope safety factor

can be queried. In this paper, based on the FEM-SRM, the 3D spatial effect curves of the E-DVSG are determined in advance. When evaluating the stability of a specific 3D E-DVSG, the safety factor of the corresponding 2D slope must be calculated at first. Then, combined with the geometric parameters of the 3D slope (α , β , W , and H) and the above space effect curves, the 3D slope safety can be obtained. That is a dimension-reduced method, transferring the slope stability analysis from 3D into 2D.

It should be noted that the previous method is only applicable to the stability analysis of the GEs, and at the same time, there still exists a major drawback, which is the prerequisite, determining the location of the 3D slope sliding surface. This unmaturing nature significantly raises the difficulty in the stability analysis of the slope. Therefore, its popularization is poor. In contrast, although the method proposed in this paper is only suitable for evaluating the slope stability of the E-DVSG, the difficulty in determining the sliding surface does not exist. One should only need to determine the safety factor for the corresponding 2D slope. This method is easy to master and popularize for engineers and technicians.

6 Conclusions

Based on the preceding analysis, the main research conclusions are as follows:

(1) The spatial effect did exist in the E-DVSG, which is caused by the uneven displacement of embankment soil under the constraints of side banks, causing the internal stress deflection and the earth pressure redistribution; thus the earth pressure was partially transmitted to the side banks, even forming a topographic soil arch.

(2) The opening angle of side banks, the slope degree of side banks, and the top width of the gully were the major influencing factors of the spatial effect. It was found that the spatial effect gradually increased with the increasing opening angle of the side bank, that is, the order of the

strength of the spatial effect was: N-DVSG > SVSG > F-DVSG. Besides, the squeezing effect (a spatial effect) formed by the side banks declined under the higher slope degree. Moreover, the spatial effect was significant when the width of the top gully was small, while this effect gradually disappeared and was close to the results of the 2D slope under the larger width. This was due to the gradually declined obstruction effect of side banks on embankment deformation with the rising width of the gully top.

(3) Embankment filling height and rear edge slope were not the major factors affecting spatial effect, but they were important factors affecting embankment stability.

(4) For the N-DVSG and the F-DVSG, the correlation order between the major influencing factors and the spatial effect was respectively: $W > \alpha > \beta$ and $\alpha > W > \beta$.

(5) The spatial effect occurrence conditions of N-DVSG and F-DVSG were $[\sin\beta\tan\beta(W/H)^4]/\cos\alpha > -8904.720$ and $W\tan\beta/(H\tan\alpha) < 2.801$, respectively.

(6) The dimension-reduced slope stability analysis method of the E-DVSG was a rational 2D approach, which can significantly reduce the workload of the 3D slope stability analysis and had great theoretical and engineering significance.

Conflicts of interests

None.

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Figure legends

Fig.1: Typical double V-shaped gully. a) N-DVSG b) F-DVSG

Note: Divided by the side banks contracting or expanding to the valley mouth horizontally, the embankments are separately named necking or flaring DVSG (N-DVSG or F-DVSG) in this research, respectively.

Fig. 2 Overall design

Fig. 3 Simulation models (unit: m). a) N-DVSG, b) F-DVSG, and c) A-A section (2D model)

Fig. 4 Model mesh sensitivity analysis

Fig. 5 Displacement vector and Minor principal stress contour nephogram of the N-DVSG. a)

Displacement vector at $Y=55\text{m}$, b) Minor principal stress at $Y=55\text{ m}$, c) Displacement vector at $X=60\text{m}$, and d) Minor principal stress at $Y=60\text{ m}$.

Fig. 6 Displacement vector and Minor principal stress contour echogram of the F-DVSG. a) Displacement vector at $Y=55\text{ m}$, b) Minor principal stress at $Y=55\text{ m}$, c) Displacement vector at $X=60\text{ m}$, and d) Minor principal stress at $Y=60\text{ m}$.

Fig. 7 Spatial effect vs. Opening angle of side banks

Fig. 8 Spatial effect vs. Slope of side banks

Fig. 9 Spatial effect vs. Width of gully top

Fig. 10 Spatial effect vs. Height of the embankment

Fig. 11 Spatial effect vs. Rear edge slope

Fig. 12 Spatial effect curves of the E-DVSG. a) N-DVSG and b) F-DVSG

Fig. 13 Calculation workflow of the 3D safety factor based on the DR-SSAM

Fig. 14 Topography of the embankments. a) N-DVSG, b) F-DVSG

Fig. 15 2D FEM models. a) N-DVSG, b) F-DVSG. In Fig a) 1, 2, 3, and 4 are Plain fill soil, Silty clay, Residual sandy cohesive soil, and Sandy strongly weathered tuff lava, respectively; In Fig b) 1, 2, and 3 are Plain fill soil, Residual sandy cohesive soil, and Sandy strongly weathered tuff lava, respectively.

Fig. 16 3D FEM models. a) N-DVSG, b) F-DVSG

Fig.17 Displacement vs Reduction coefficient curves

Table legends

Table 1 Material parameters of soil

Table 2 Scenarios

Table 3 Safety factors of the 2D and 3D models

Table 4 Correlation degree and weight of variables

Table 5 Soil material parameters

Draft

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Fig. 6 Displacement vector and Minor principal stress contour echogram of the F-DVSG.
a) Displacement vector at Y=55m, b) Minor principal stress at Y=55m, c) Displacement vector at X=60m, and d) Minor principal stress at Y=60m.

Fig. 7 Spatial effect vs. Opening angle of side banks

Fig. 8 Spatial effect vs. Slope of side banks

Fig. 9 Spatial effect vs. Width of gully top

Fig. 10 Spatial effect vs. Height of the embankment

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Table 1 Material parameters of soil

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Table 1 Material parameters of soil

	Unit weight (kN/m ³)	Elasticity modulus (MPa)	Friction angle (°)	Cohesion <i>c</i> (kPa)	Poisson ratio
Embankment	18.5	45	38.9	9	0.35
Foundation	25	2000	-	-	0.2

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Table 2 Scenarios

Scenarios	α (°)	β (°)	W (m)	H (m)	θ (°)
N-DVSG (3D)					
1	90/95/100/ 105/110/115	60	130	40	30
2	110	50/55/60/65/70	130	40	30
3	110	60	110/130/150/ 170/190/210	40	30
N-DVSG (2D/3D)					
4	110	60	130	30/35/40/45/50	30
5	110	60	130	40	25/30/35/40
F-DVSG (3D)					
6	65/70/75/ 80/85/90	60	50	40	30
7	70	50/55/60/65/70	50	40	30
8	70	60	40/50/70/90/ 110/130/150	40	30
F-DVSG (2D/3D)					
9	70	60	50	30/35/40/45/50	30
10	70	60	50	40	25/30/35/40

Table 3 Safety factors of the 2D and 3D models

		α (°)	β (°)	W (m)	H (m)	θ (°)	Safety factor
3D	N-DVSG	110	60	110	40	30	1.73
	F-DVSG	70	60	110	40	30	1.59
	2D	-	-	-	40	30	1.55

Draft

Table 4 Correlation degree and weight of variables

Variables	N-DVSG			F-DVSG		
	$\alpha / (^{\circ})$	$\beta / (^{\circ})$	$W / (\text{m})$	$\alpha / (^{\circ})$	$\beta / (^{\circ})$	$W / (\text{m})$
Correlation	0.731	0.660	0.784	0.844	0.656	0.793
Weight	33.63%	30.33%	36.05%	36.81%	28.60%	34.59%

Draft

Table5 Soil material parameters

DVSG	Soil layers	Unit weight (kN/m ³)	Elasticity modulus (MPa)	Cohesion (kPa)	Friction angle (°)	Poisson ratio
Necking	Plain fill soil	18.7	38.8	10.5	18.6	0.35
	Silty clay	17.8	40.6	18.4	22.3	0.35
	Residual sandy cohesive soil	19.6	42.4	9.7	26	0.32
	Sandy strongly weathered tuff lava	21.8	210	-	-	0.2
Flaring	Plain fill soil	17.6	39.6	11.6	18.2	0.35
	Residual sandy cohesive soil	18.4	41.5	17.3	23.4	0.32
	Sandy strongly weathered tuff lava	22.1	210	-	-	0.2

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Highlights:

1. A dimension-reduced slope stability analysis method of the E-DVSG was proposed.
2. Generation mechanism of the spatial effects of the E-DVSG was clarified.
3. Correlation degree and weight of variables to the spatial effect were quantified.

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