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An alternative shear strength reduction approach for the stability analysis of undeground excavations

Une approche alternative de réduction de la résistance au cisaillement pour l'analyse de la stabilité des excavations souterraines

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ABSTRACT: Conventional shear strength reduction methods are widely used in the numerical stability analysis of various geotechnical problems. They allow modelling the associated failure mechanisms as well as computing a stability indicator, the factor of safety. Nonetheless, due to the uniform and monotonic reduction scheme integrated in this method, it is not possible to identify the zones which are prone to failure more than others, and faster than others. Consequently, a kinetic shear strength reduction method that accounts for the influence of the physical behaviour of the model on its failure is proposed. The scheme of reduction is called kinetic since it is neither applied uniformly on the model zones, nor incremented monotonically along the calculation steps. The reduction depends on the accumulation of the strains. This method is implemented in the stability study of a braced excavation. Results are compared with those obtained using the conventional method. Results obtained show the applicability of the proposed method which in turn provides a better understanding of the evolution of the strain mechanisms, development of failure, and localization of the weak zones. The kinetic method can be generalized and used in the stability analysis of different geotechnical applications.

RÉSUMÉ: Les méthodes classiques de réduction de la résistance au cisaillement sont largement utilisées dans l'analyse numérique de la stabilité de differents problèmes géotechniques. Ils permettent de modéliser les mécanismes de rupture associés et de calculer un indicateur de stabilité: facteur de sécurité. Néanmoins, en raison du schéma de réduction uniforme et monotone intégré à cette méthode, il est impossible d'identifier les zones sujettes à la rupture plus que d'autres et plus rapides que d'autres. Par conséquent, une méthode de réduction de la résistance au cisaillement cinétique qui rendre compte de l'influence du comportement physique du modèle sur sa rupture est proposée. Le schéma de réduction est appelé cinétique car il n'est ni appliqué uniformément sur les zones du modèle, ni incrémenté de manière monotone tout au long des étapes de calcul. La réduction dépend de l'accumulation des deformations deviatoriques. Cette méthode est mise en œuvre dans l'étude de stabilité d'une excavation. Les résultats sont comparés à ceux obtenus par la méthode conventionnelle. Les résultats obtenus montrent que la méthode proposée est applicable, ce qui permet de mieux comprendre l'évolution des mécanismes de déformation, l'apparition de la rupture, et la localisation des zones faibles. La méthode cinétique peut être généralisée et utilisée dans l'analyse de la stabilité de différentes applications géotechniques.

Keywords: Numerical modelling, stability, failure mechanisms, shear strength reduction, degradation

1. INTRODUCTION

Underground space development requires the construction of large scale and depth excavations under retaining walls for deep basements, underground parking or tunnels. Due to space limitations in urban areas, deep excavations are often constructed in close proximity to surrounding buildings and services. Such excavations can induce major risks to man and properties nearby. Providing tools for instability prediction is essential in the design of excavations. Furthermore, consecrating greater focus on the understanding of deformational behavior and failure mechanisms of underground excavations remains of high importance.

Conventional methods, including Terzaghi's method (1943), and Bishop's method (1955) for examole are able to give reasonable estimates of stability of excavations. However, these methods could not help to understand sufficiently the failure mechanism of an excavation since plastic behaviors of structural elements are not considered and a rough assumption of the failure surface is made in these methods.

On the other hand, numerical methods, using shear strength reduction techniques are capable of modeling structural elements and automatically seeking for the failure surface of soil. They are considered a consistent and efficient alternative when it comes to profound stability studies of complicated geotechnical projects.

The characterization of the ground strain and failure mechanisms using numerical techniques demonstrates significant potential for broadening the understanding of the scenarios of rupture and the associated risks. In addition, a practical way to avoid dangerous conditions and prevent unsafe scenarios is to introduce a safety factor.

Shear Strength Reduction (SSR) technique is a common technique that permits the calculation of factor of safety using different numerical methods (Zienkiewicz 1975).

The strength reduction method has been used extensively in the context of Mohr-Coulomb material and, principally, the simultaneous reduction of the shear strength properties cohesion and friction (Dawson and Roth 1999, and Griffiths and Lane 1999).

2. OBJECTIVE

The shear strength reduction technique SSR is based on applying a uniform and monotonic progressive reduction of the shear strength properties of the soil until the soil is no more capable of undertaking the accumulated shear stresses and hence failure is detected.

In this paper, the aim is to present a new numerical technique to be used in the stability studies that accounts for the physical behavior of the stressed soil on the developing failure. This is based on integrating the accumulation of shear strains in the scheme of the reduction of the shear strength properties. The proposed technique is defined in this paper as the kinetic shear strength reduction technique, kinetic SSR and it is applied in the stability study conducted for a braced excavation.

In the stability analysis of underground excavations, several factors can play an important role in the overall behavior of the excavation and its stability as well. For instance, the geometry of the excavation, design of the retaining structure and selection of the support system, properties of the soil layers, presence a water table or a water flow, and the sequence of excavation stages. The effects of the mentioned factors are analyzed but not presented in this paper due to paper length restriction. The focus in this paper is on the analysis of the behavior of the soil as well as the structure while modelling failure using the proposed kinetic SSR method.

3. NUMERICAL MODELLING OF THE BRACED EXCAVATION

3.1 Case of study

A braced excavation in a non-saturated soil is considered in this work. The excavation is 20 m wide and has a final depth of 10 m. It is supported by diaphragm walls that extend to a 15 m depth and are braced at 2 m depth by horizontal struts at a 2 m interval. The ground consists of one soil layer, sand, which is underlain by a very stiff layer that reaches a great depth. The excavation extends largely in longitudinal direction. A 2D section of the geometry of this braced excavation is shown in Figure 1.

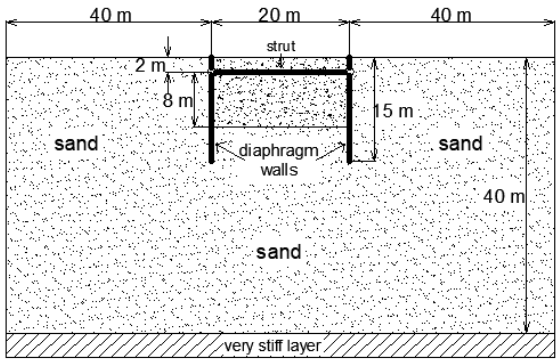

Figure 1 Geometry of the case of study

3.2 Flac3D

For the numerical model, the finite difference code FLAC3D is used. The purpose of the FLAC3D analysis is to evaluate (1) the deformation of the ground adjacent to the diaphragm walls and at the bottom of the excavation, and (2) the performance of the walls and struts, throughout the construction stages. FLAC3D is also used to simulate a stability analysis of the excavation under study. Two methods are used for this analysis: the conventional SSR which is originally built in FLAC3D, and the kinetic SSR proposed and implemented in FLAC3D.

3.3 Geometry and boundary conditions

Back to the case of study, a two dimensional analysis with plane strain conditions is used. A far-field location, soil layer of 100 m width and 40 m depth, is selected so that the results are not significantly influenced. Due to symmetry, one half of the geometry is modeled. Prescribed displacement boundaries that inhibit all displacements (fixed supports representing the very stiff underlain layer) are considered for the base. Smooth pins that block the horizontal displacements are assigned on the lateral boundaries. A fine mesh is generated for this analysis.

3.4 Stages of construction

The modelling of the braced excavation starts from the modelling of the initial state of soil at rest prior to any excavation. The initial conditions are considered by generating initial effective soil in situ stresses using k_0 procedure. After that the diaphragm walls are installed and new stresses are generated. Excavation and installation of struts are simulated in separate construction stages. In practice, the construction may involve several stages of, excavation and adding of support. For simplicity, in this example, only the following construction stages are analyzed: (1) excavation to a 2 m depth (always measured from the ground level); and (2) installation of a horizontal strut and excavation to a 10 m depth. For each stage, two calculation steps are taken. In the first step, the model is run elastically to remove any inertial effect caused by sudden removal of a large amount of material. Second, the model is run allowing plastic behavior to develop. At last, stability analyses, using both the conventional, and the kinetic SSR methods are simulated.

3.5 Material properties of the structural elements

The properties selected to simulate the behavior of the diaphragm wall and the struts are listed in Tables 1 and 2. The thickness of the diaphragm wall varies, and an equivalent thickness is estimated to be 1.26 m. The spacing of the struts is 2 m. The interaction between the wall and the soil is modeled at both sides by

means of interfaces. The interfaces allow a reduced wall friction and cohesion compared to those of the soil. The stiffness of the interface in the two directions is takes 550 MPa.

Table 1 Properties of the diaphragm wall

	Diaphragm Wall
Equivalent thickness (m)	1.26
Density (kg/m3)	2000
Young's modulus (GPa)	5
Poisson's ratio	0.2
Moment of inertia (m4)	0.167
EA (kN)	6.30E+06
EI (kN.m2)	8.33E+05

Table 2 Properties of the strut

	Strut
Cross-sectional area (m2)	1
Spacing (m)	2
Density (kg/m3)	3000
Young's modulus (GPa)	4
Moment of inertia (m4)	0.083
EA (kN)	4.00E+06

3.6 Soil properties and law of behaviour

An elastic perfectly plastic model with a Mohr Coulomb failure criterion *f* is used to illustrate the effect of the material model on the calculated deformational response of the soil when subjected to this construction sequence.

$$f(\sigma,\tau) = \tau - (\sigma \tan(\varphi) + c)$$

where c and φ are the cohesion and friction of the soil.

Regarding the plasticity effects, the stress state related to the matrix criterion is checked and plastic corrections are done if the stress state exceeds the failure surface. Soil properties considered for sand are listed in Table 3.

Table 3 Sand properties

	Sand
Dry density (kg/m^3)	1700
Young's modulus (MPa)	40
Poisson's ratio	0.3
Cohesion (kPa)	1
Friction angle (degrees)	32
Dilation angle (degrees)	2

4. STABILITY ANALYSIS OF THE BRACED EXCAVATION

4.1 Conventional SSR

The conventional shear strength reduction technique is typically applied in factor-of-safety calculations which is a common indicator of stability. Conventional SSR is based on the monotonic and uniform progressive reduction of the shear strength properties until they are no more capable of undertaking the accumulated shear stresses and hence failure is detected. A series of simulations are made using trial values of the factor F trial, where actual shear strength properties cohesion (c) and internal friction angle (φ) are reduced for each trial using equations (1) and (2). The trial factor of safety is increased until the failure is detected. Failure occurs naturally through the zones within the soil mass in which the soil shear strength is unable to sustain the applied shear stresses. At failure, the safety factor equals the trial safety factor.

$$c^{trial} = \frac{c}{F^{trial}}$$

$$\varphi^{\mathrm{trial}} = \arctan\left(\frac{\tan\varphi}{F^{\mathrm{trial}}}\right)$$

$$f(\sigma,\tau) = \tau - \left(\sigma \frac{\tan(\varphi)}{F^{\mathrm{trial}}} + \frac{c}{F^{\mathrm{trial}}}\right)$$

4.2 Kinetic SSR

The idea of the kinetic SSR is based on implementing a reduction scheme of the shear strength parameters, cohesion and friction, in a non-static

kinetic manner. Unlike the conventional SSR technique, it aims to apply a non-monotonic and non-uniform reduction of initial values of cohesion and friction, progressively until failure is detected. The reduction is achieved by multiplying the current shear parameters by a degradation factor Dn less than or equal to 1. This least value of Dn, which is obtained at failure, can be considered the indicator of stability in the kinetic SSR method.

$$f(\sigma,\tau) = \tau - (\sigma \tan(\varphi) + c)(Dn)$$

The degradation factor concept is inspired from the hypothesis of influence of accumulated strains and their evolution on the development of failure. Dn is written in function of the deviatoric shear strains γ_d and a degradation function D.

$$\gamma_d = \int \sqrt{\frac{2}{3} de_{ij} de_{ij}}$$

$$e_{ij} = \varepsilon_{ij} - \frac{1}{3} tr(\varepsilon_{ij})\delta_{ij}$$

$$D_n = A(1 - a(D)$$

$$A = 0.9 + \frac{\gamma_d}{0.1 + 30\% \, \gamma_d}$$

$$a = 2/3$$

D in turn depends on γ_d and time. It is a degradation function that increases with the accumulation of deviatoric strains γ_d with time. This is inspired from the works of same authors (Rafeh et al, 2015) and used in the current excavation analysis.

$$\dot{D}(\mathrm{t}) = \alpha\big(\gamma_d(t) - D(t)\big)$$

$$D(t) = \int_0^t \alpha \, \gamma_d(u) \, e^{-\alpha(t-u)} du$$

In this analysis time is implicit. It designates the incremental process where at each step of calculation new deviatoric strains are accumulated, then a new degradation factor in each zone of the model Dn is calculated. After that, the shear strength parameters are multiplied by the obtained values of Dn, and automatically reduced. The new stresses and thus new deviatoric strains are generated, and then the equilibrium is verified. This cycle is repeated until failure is detected.

5. RESULTS OF THE MODELLING OF THE REDUCTION SCHEME

5.1 *Analysis of the scheme*

The illustration of variation of Dn among the zones as well as among the calculation steps gives an idea of the scheme. Since Dn is not the same in all zones, and in order to calculate an indicative safety factor so that it can be compared with the conventional method, the average of Dn is calculated and the variation of 1/(average Dn) which designates the indicative safety factor in kinetic method is plotted (Figure 3). Figure 3 shows that neither Dn is the same at all zones, nor its evolution is the stationary (Figure 4).

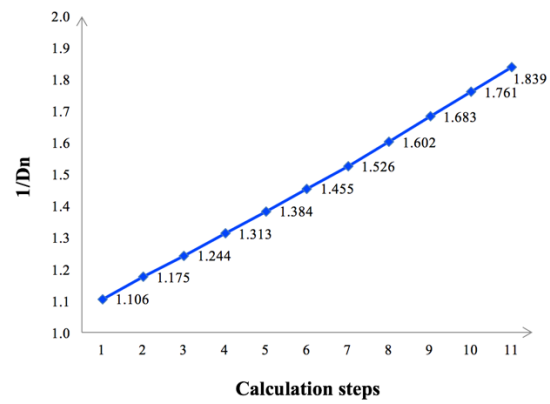

Figure 3 Variation of 1/(average Dn) in function of stability modelling calculation steps.

5.2 Behaviour of the soil

Stability analysis of the braced excavation model in sand is performed using both SSR techniques presented in the section above. The results of the analyses are shown for both cases and a comparison between the methods is

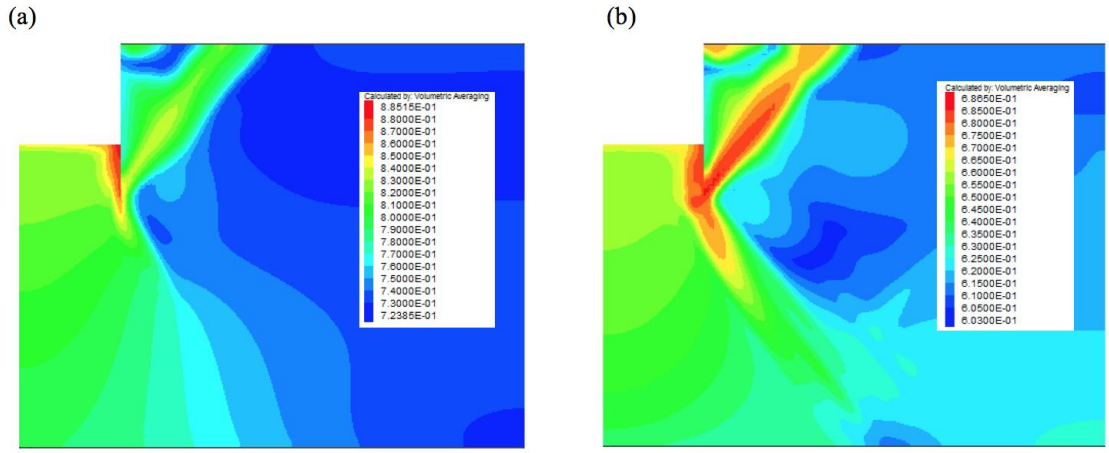

Figure 4 Evolution of Dn among different zones at different calculation steps using kinetic method (a) corresponding to F^{trial}= 1.3, (b) corresponding to F^{trial}= 1.6.

provided. Once unstable or steady plastic flow has been identified, the location of failure surface can be judged by plasticity indicators, displacement field and localization of shear strain.

Plastic indicators

In order to analyze the failure behavior of the braced excavation under study, the plastic indicators are displayed. These indicators represent the zones that have satisfied the yield criterion and have reached the plasticity state. Figure6 shows that both reduction methods give the same results in terms of shear failure mechanism its profile.

Shear strain rate

By looking at the shear strain rate pattern in the model in Figure 7, it can be deduced that the failure surface determined from both methods is the same. At failure, analysis is dedicated to the failure profile; the values are not indicative when failure occurs.

Displacement

An unstable model can be also characterized by the increasing displacements. Since at failure, the values of displacement are not indicative, the focus is on the failure profiles. Figure 8 shows that both methods give almost same profiles.

5.3 Performance of the structure

In the braced excavation problem, it is important to analyze the behavior of the structure and not only the soil. In this paper, the behavior of the diaphragm wall according to different calculation methods is illustrated and discussed.

Shear stress

The distribution of shear stresses on the diaphragm wall can be a good indicator of the applicability of the proposed method. The results are presented in figure 9.

The blue graph corresponds to the calculation step when the excavation sequence is finished and before initiation the stability analysis, the red and green are the shear values at the end of the stability analysis using the conventional method (in red) and the kinetic method (in green). The profile of the shear distribution is the same. Comparing the results of the two stability methods it can be also seen that the difference is almost negligible.

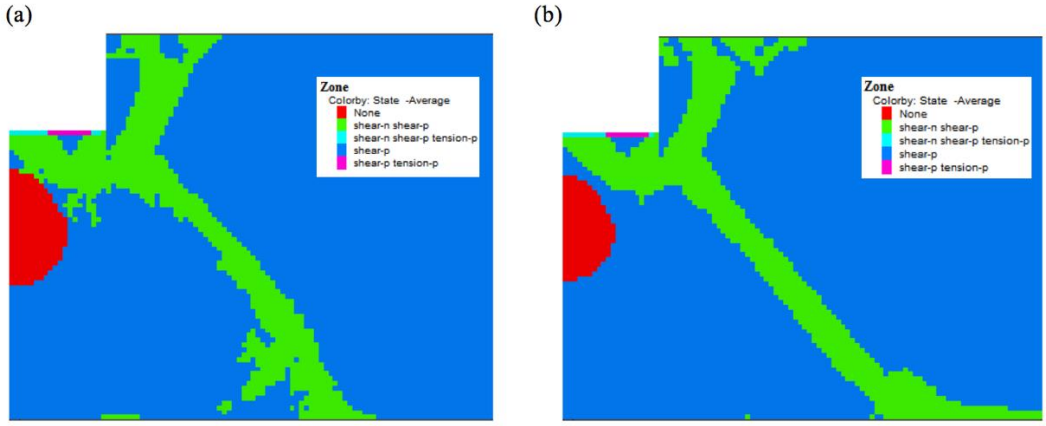

Figure 6 Distribution of plastic indicators using both methods: (a) conventional, (b) kinetic.

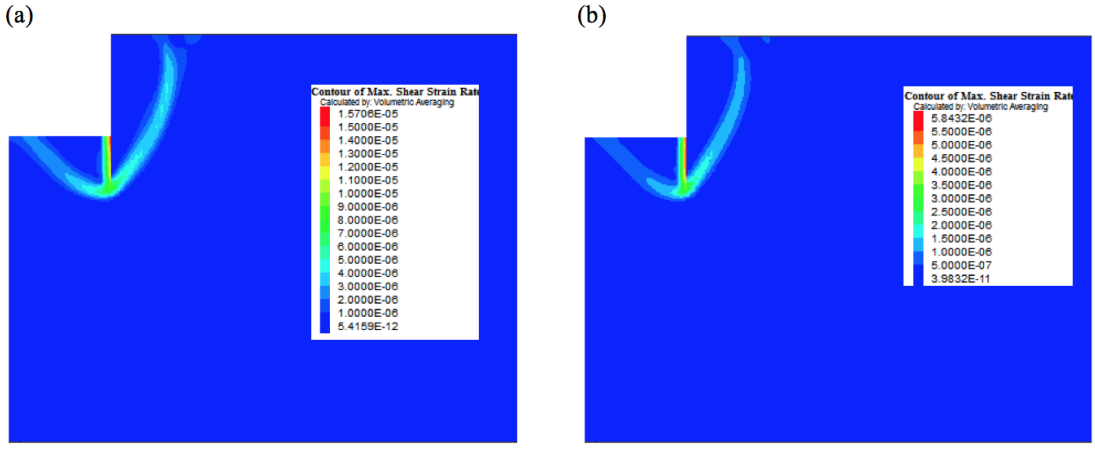

Figure 7 Profile of maximum shear strain rate using both methods: (a) conventional, (b) kinetic.

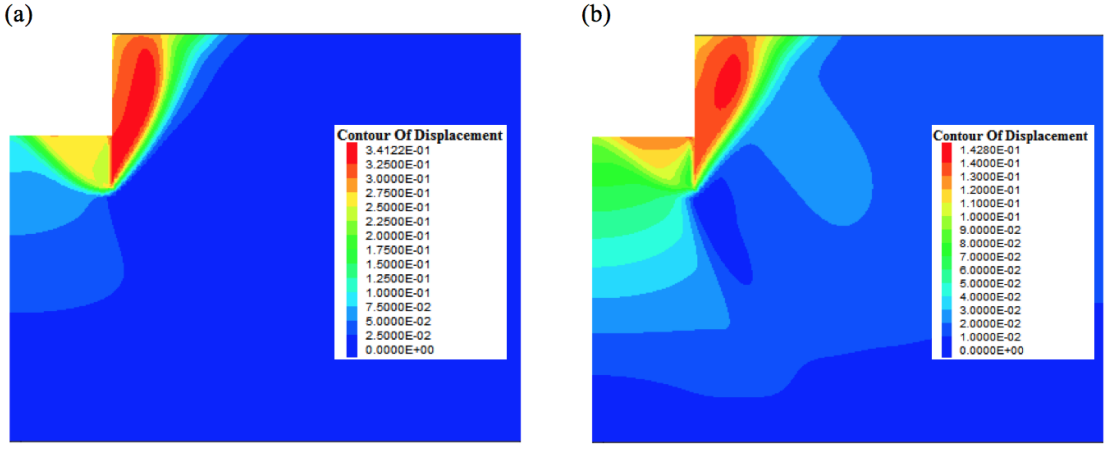

Figure 8 Displacement contours using both methods: (a) conventional, (b) kinetic.

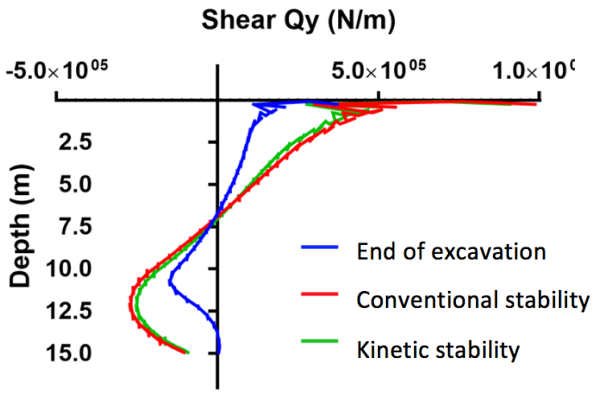

Figure 9 Shear stress distribution on the diaphragm wall

Bending moment

For more emphasis on the pertinence of the method, the bending moment diagram all along the diaphragm wall is given (Figure 10). The legend is the same as in Figure 9. Similar to the observation in the shear diagram, the results show big proximity between the methods.

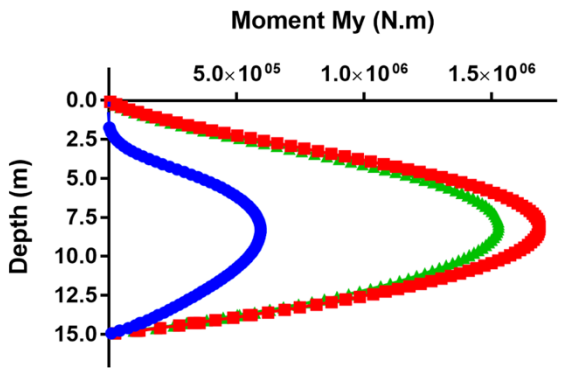

Figure 10 Bending moment distribution on the diaphragm wall.

6. CONCLUSION

To model failure, it is not necessary to impose the failure in all zones uniformly at one hand, and in same amount at each consecutive step on the other hand. This is misrelated to the actual physical failure behavior as defined in the conventional SSR; however, this drawback is avoided in the proposed kinetic method. This latter is numerically integrated in the stability study of a braced excavation. The results illustrated in terms of both soil behavior and structure performance confirm the applicability of the method. It is quite important not only to detect the limit prior to failure, but also to be able to identify the zones which are prone to failure more than others, and faster than others. This is possible using the kinetic method. This proposed method can provide a better understanding on the localization and development of failure. It can be generalized and used in the stability analysis of different geotechnical applications.

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