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Stability analysis of cemented soil slopes in a geotechnical centrifuge

Analyse de stabilité des pentes du sol cimenté dans une centrifugeuse géotechnique

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ABSTRACT: Geotechnical centrifuge technology is a strong and successful method for physical modeling of slopes. It provides the benefit of studying the slopes' failure mechanisms. In this research, slope models of cemented and non-cemented soils were tested in a geotechnical centrifuge. The tests were conducted according to self-weight of the slopes by increasing the acceleration of the geotechnical centrifuge. The images of the slope models were captured in 10 seconds intervals until the failure of the slopes. Particle Image Velocimetry (PIV) method was used to analysis the images of the slope models. Results of the tests indicated that cement has an important effect on slope stabilization. Soil particle displacement was much lower in cemented models. In addition, using PIV method along with geotechnical centrifuge tests was found useful to study displacement and deformation behavior of slopes.

RÉSUMÉ : La technologie de centrifugeuse géotechnique est une méthode solide et réussie pour la modélisation physique des pentes. Il offre l'avantage d'étudier les mécanismes de défaillance des pentes. Dans cette recherche, des modèles de pente de sols cimentés et non cimentés ont été testés dans une centrifugeuse géotechnique. Les tests ont été effectués en fonction du poids propre des pentes en augmentant l'accélération de la centrifugeuse géotechnique. Les images des modèles de pente ont été capturées par intervalles de 10 secondes jusqu'à la défaillance des pentes. La méthode PIV (Particle Image Velocimetry) a été utilisée pour analyser les images des modèles de pente. Les résultats des essais ont indiqué que le ciment a un effet important sur la stabilisation des pentes. Le déplacement des particules du sol était beaucoup plus faible dans les modèles cimentés. En outre, l'utilisation de la méthode PIV ainsi que des tests de centrifugeuse géotechnique s'est avérée utile pour étudier le comportement de déplacement et de déformation des pentes.

KEYWORDS: geotechnical centrifuge; slope stability; cemented soil; particle image velocimetry.

1 INTRODUCTION

One of the significant research tools in geotechnical engineering is physical modelling. Small-scale physical modeling of earth structures has been used to provide insight into the behavior of reinforced soil structures,(El-Emam & Bathurst 2005). A restriction of the physical models scaled down under standard gravity conditions is that in models stress levels are much less than in prototypes, which lead to various soil properties and loading conditions,(Schofield 1980). The centrifuge modeling technique will obtain an equal stress field both for sample and for prototype. The centrifuge modelling is a successful method in geotechnical engineering. The model must be evaluated in a gravity area N times greater than that of a prototype structure, in order to reproduce the gravity induced stresses of a prototype structure in a geometrically 1 / N reduced model,(Viswanadham & König 2009).

Slope stability analysis is one of the basic problems in soil mechanics and has vital importance in geotechnical engineering. Slope stability analysis is a process where safety of natural or artificial slopes is controlled. The experimental studies of slope stability can be classified in three groups: a) Physical modelling or 1g condition (Evirgen et al. 2017, Arya et al. 2018, Daraei et al. 2018), b) Big scale modelling or prototype (Collins & Sitar 2011), c) Modelling by geotechnical centrifuge or Ng condition (Hayward et al. 2000, White et al. 2003, Zornberg & Arriaga 2003, Viswanadham & Mahajan 2004, Mandal et al. 2005, Viswanadham & Mahajan 2007, Ling et al. 2009, Viswanadham & König 2009, Ling & Ling 2012, Aklik & Wu 2013, Costa et al. 2013, Kitazume & Takeyama 2013, Li et al. 2013, Ling et al. 2016, Luo et al. 2018, Zhao et al. 2018). Although there are several researches on reinforced slopes in Ng condition, investigations of soil slopes stabilized by cement are rather limited (Park & Kutter 2012).

In this research, a series of cemented and non-cemented slopes are tested in a geotechnical centrifuge. Centrifuge modeling and Particle Image Velocimetry (PIV) method are used in this study. The main aim of this research is to study the failure mechanism of the slopes. The test data provide interesting insight into the failure mechanisms and the progressive failure characteristics of cemented slopes.

2 MATERIALS AND METHODS

2.1 *Geotechnical Centrifuge*

Geotechnical centrifuge is a device that satisfies reduced stress of small prototype through increasing gravitational acceleration. The linear dimensions (l/N) of a model are reduced based on the ratio of gravitational acceleration to earth's gravitational acceleration (N). All the tests of this paper were performed in the IGT Beam Centrifuge (Figure 1) at the Institute of Geotechnical Engineering, University of Natural Resources and Life Sciences in Vienna. The components of the centrifuge are: swinging basket, balancing counterweight, DC motor and aerodynamic enclosure. It has 56 electric slip rings for monitoring of processes and collection of data. The technical properties of the centrifuge are described in Table 1. The centrifuge tests of this study were performed up to 95 G.

2.2 *Model Box*

The model box (Figure 2) is rectangular with dimension of 48 cm in length, 15.5 cm in width and 45 cm in height. In order to take digital images during the tests, a transparent plexiglass plate was used on one side of the model box with thickness of 3 cm. The other walls of the model box are aluminum plates with thickness of 1.5 cm. The model box is rigid enough to keep plane strain condition in the model.

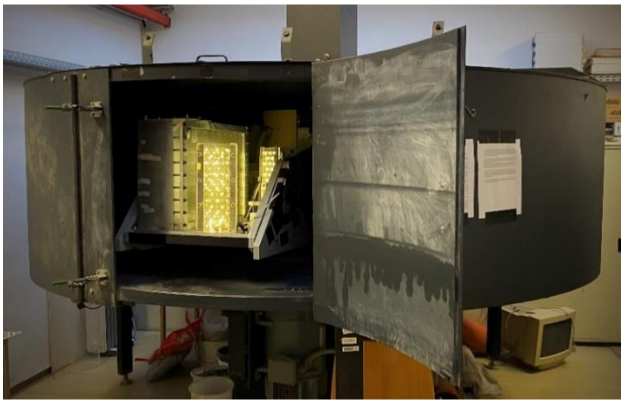


Figure 1. IGT Beam Centrifuge.

Figure 2. Model box mounted on the swing basket.

Table 1. Technical specifications of the geotechnical centrifuge.

Diameter of the centrifuge	m	3
Radius of the swinging basket	m	1.3
Maximum angular velocity	1/min	400
Maximum radial acceleration	g	200
Maximum model weight	kg	90
Maximum Load Capacity	t	10
Maximum model Dimensions W*D*H	cm	54*56*56

2.3 *Slope Model*

Slope models have a slope inclination of about 70 and 90 degrees. The heights of the slopes are 25 centimeters. The cement content in cemented slopes is 3% of weight of dry soil. All the slope models were built on a base layer. The base layer has a height of 5cm and length of 48cm.

2.4 *Soil*

The soil type (Table 2) is categorized as SP-SC according to USCS. The soil contains 73% of sand, 21% of gravel and 6% of fine content. The tests were performed under wet condition by adding optimum moisture content of 6.7 % to the soil. The relative density of about 72% is considered for the soil sample preparation.

Table 2. Parameters of the soil used.

Specific Gravity		2.58
D 60	mm	2.061
D 50	mm	1.503
D 30	mm	0.611
D 10	mm	0.245
PL	%	24
LL	%	31
$\gamma_{d\ min}$	kN/m^3	16
$\gamma_{d\ max}$	kN/m^3	18

2.5 *Instrumentation*

A 14.7 MP digital camera (Canon G10) was used to take high resolution pictures from soil grains behind the plexiglass wall of the model box. On left and right side of the plexiglass two panels of light containing 33 LED lights on each were used for preparing a good illumination condition. All the test data and taken images during the test were observable from a PC inside the control room.

2.6 *Particle Image Velocimetry (PIV) Method*

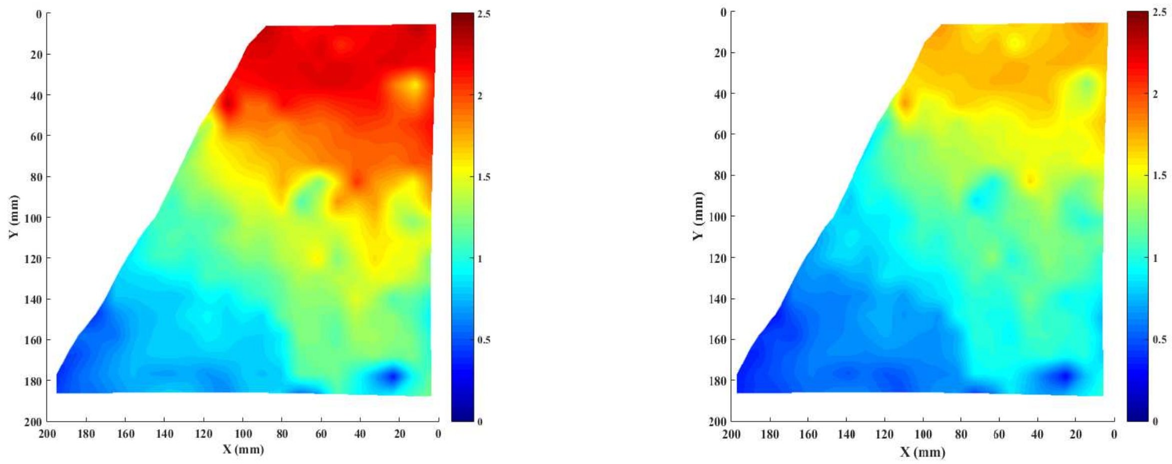
The displacement of the slope models was measured by PIV method. The GeoPIV8 codes, developed by (White & Take 2002), was used to analyze the images in MATLAB software. The images were captured in 10 seconds intervals until the failure of the slopes. Measuring displacement is possible through tracking plane soil patches that are prone to deformity. In the process of image analysis by PIV, images are taken using digital camera from soil during deformation, then soil deformation is determined using particle images velocimetry between a pair of consecutive images.

3 RESULTS AND DISCUSSION

The results of the centrifuge model tests are presented in this section. The images of the slope models are evaluated by PIV method 10 seconds before the failure. The contours of shear strain in the model slopes are shown in Figures 3-6.

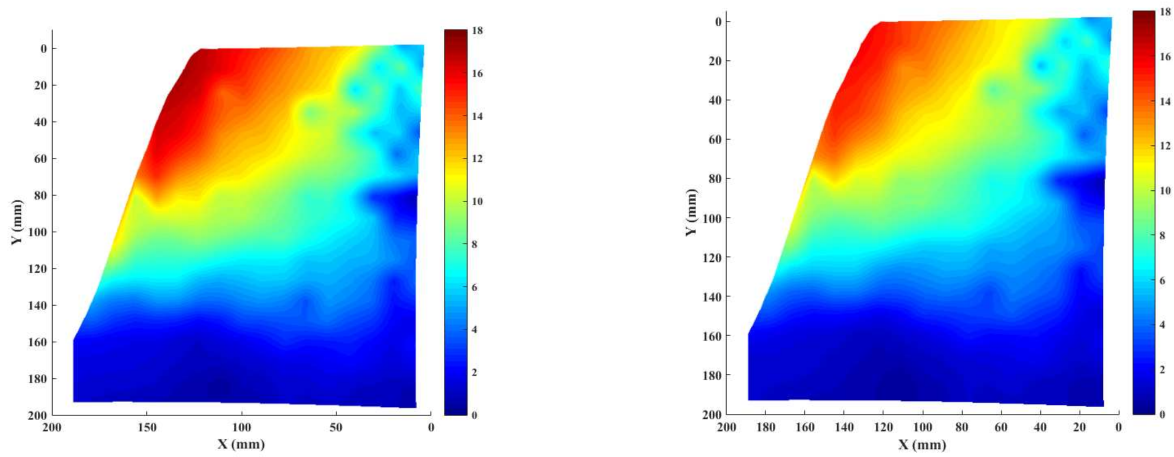
In Figure 3a and 3b, the slope has an inclination of 70 degrees. The slope model did not fail. However, the soil failures observed close to the slope crest. The failure was started from upper side of the slope and tends to progress to the lower part. Strain concentration is at upper part of the slope, between 0 to 100 mms in X direction and between 0 to 60 mms in Y direction. The non-cemented slope model with inclination of 70 degrees (Figure 4) failed at 35G. The soil displacements are observed more clearly in this model. The soil failures are close to the slope crest; the failure has started from upper side of the slope and tends to expand to lower part along the slope surface. Strain concentration is at slope crest, between 80-150 mms in X direction and between 0-60 mms in Y direction. By comparing the shear strain distribution in models with inclination of 70 degrees, it is observed that maximum shear strain reduced significantly by adding 3% cement to the soil.

Figures 5a and 5b show the strain distribution in a steeper slope with an inclination of 90 degrees. The slope model failed at 59.5G. The soil failure was initiated at slope crest and was developed in both X and Y directions. Strain concentration is at upper part of the slope, between 80-140 mms in X direction and between 0-60 mms in Y direction. By comparing this slope model and the slope models with inclination of 70 degrees, it is observed that the failure location is not changing by varying the inclination. Soil deformations of the slopes (both 70° and 90°) has the same properties. The deformations were observed along the slope crest. The non-cemented slope with an inclination of 90 degrees (Figure 6), failed at 13G. The soil failure has started at lower part of the slope and at upper part of the slope, in the opposite side of slope surface.



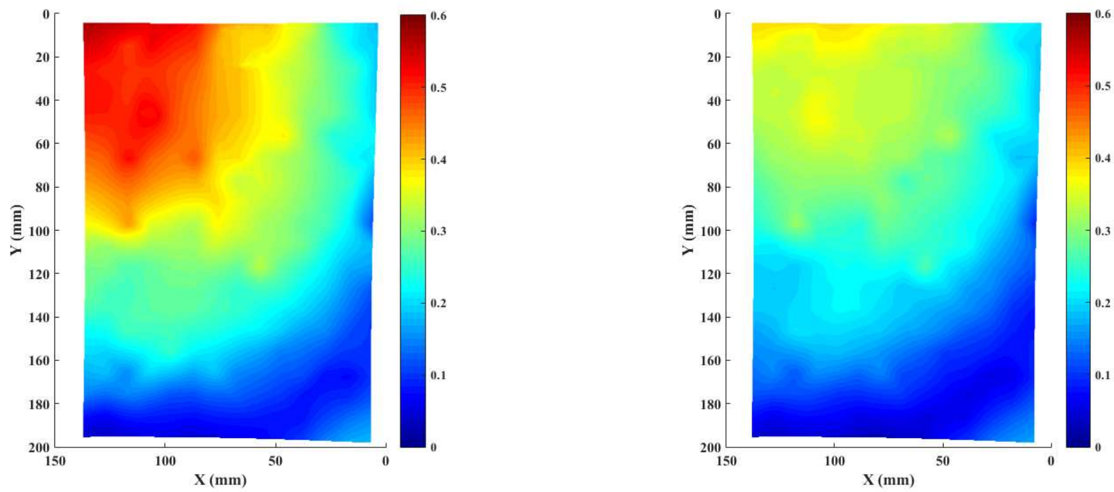
(a) (b)

Figure 3. Shear strains of cemented slope with a slope inclination of 70 degrees, a) maximum acceleration, b) 60s before the maximum acceleration.



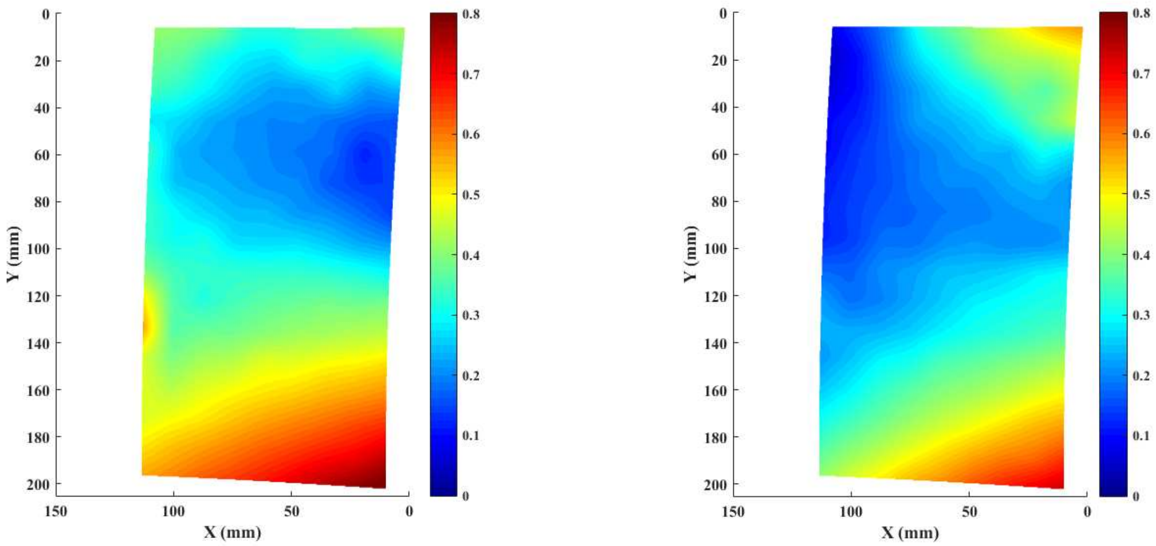
(a) (b)

Figure 4. Shear strains of non-cemented slope with a slope inclination of 70 degrees, a) 10s before the failure, b) 60s before the failure.



(a) (b)

Figure 5. Shear strains of cemented slope with a slope inclination of 90 degrees, a) 10s before the failure, b) 60s before the failure.



(a) (b)

Figure 6. Shear strains of non-cemented slope with a slope inclination of 90 degrees, a) 10s before the failure, b) 60s before the failure.

4 CONCLUSIONS

Cemented and non-cemented slope models were tested in a geotechnical centrifuge to identify the possible failure mechanisms. Increasing the slope inclination decreased the required acceleration of the centrifuge to cause failure of the slopes. In addition, adding 3% cement to slopes, decreased the soil displacement and shear strain, delayed the time of the failure and increased the required acceleration of the centrifuge. Soil deformations of the slopes have the same properties. The deformations were observed along the slope crest. In addition, the location of the slope failures is not changing in cemented and non-cemented slopes. The failure starts at the slope crest. Using PIV method along with geotechnical centrifuge tests was found very valuable and useful to study displacement and deformation behavior of the soil slopes. From the results of the experiments, it was concluded that the addition of cement to the soil have increased the shear resistance against slope failure. Also, with steeper angle of the slope, the slope can stand without failure. The cement addition can be used to improve the slope behavior.

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