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Earthquake Effects on Slope Stability by Using Finite Element Method. Case Study: Brazzaville City, Republic of Congo

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

The slopes are affected by the variations of slope gradient combined with the driving forces including external actions such as earthquake forces, producing shear stresses in the slopes, which are opposed to the soil shear resistance. Therefore, landslides are one of the most important

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worries on the social and economic viewpoint and for the quality of life of a local people. The present study is carried out in Brazzaville City, Republic of Congo where the region in its southern part is recognised to be geologically active, due to its tectonic background which has some influence on surrounding slopes or embankments. Then, it was used the shear strength reduction method to assess the slopes stability by using pseudo-static and static methods. Effects of various parameters on slopes stability are discovered by achievement of numerous analyses. Two magnitudes effects of earthquake on slopes stability for different height, slope gradient and shear resistance parameters were assessed by using the finite element code. Slope stability was evaluated considering its factor of safety from the usage of strength reduction method.

Keywords: Earthquake; slope; landslides; finite element; strength reduction; environment.

1. INTRODUCTION

The landslide incidence depends on the shear stresses development inside the soil when they exceed the soil strength. Landslides causes can be associated with liquefaction of layers of fine grain of because of a general failure, considering the increase of loads from earthquake occurrence which increases pore pressure and reduces the soil shear strength [1].

Failure of Slope is a great hazard which significant attention needs to be taken care of. Then, the seismic action on a slope, always represents a significant problem for construction works and humanity as well. Therefore, the usage of finite element methods for slope analysis can predict the slopes behavior including the beforehand determination of the failure surface. This method makes easy the computation of stresses, pore pressures, deformations and failures under seepage easily [2,3]. By consequent, the seismic analysis of slope stability, uses prominent methods such as pseudo-static approach, static approach and numerical analysis. While, the pseudo-static method being the simplest analysis approach is used widely which the analysis results of seismic force are converted into an equivalent horizontal and vertical force [4].

In Congo, the years 80's were considered less warm than the years 90's. Two periods plainly distinguish the current temperatures evolution before 1970 and after. While Brazzaville City poses a net temperature variation from 1932 to 2010 with an increase of average temperatures from +0.5˚C to 1˚C in the earlier two decades [5]. The maximum and minimum average of temperatures in the 1990s shows an increase for the two latest decades. The relief presents altitudes of 1100 m and 360 m as maximum and minimum respectively. The climate is considered as tropical characterized by a rainy season from October to May and dry seasons between January-February and June-September.

The annual rainfall varies between 1250 mm and 1350 mm/year [5]. The hydrogeology is governed by the Bateke's water table, which has 270 km^2 of area. The aquifer is made of sandstone with a little groundwater mineralogy contribution. The soils rest on three sedimentary series from the base to the top, made of the sandstone series of Inkisi, the sandstone series of the Stanley Pool and the series of Bateke's plateau. These soils contain very low clay percentage [6]. The Central Basin, iincludes the Central Africa intracratonic depression with sediments accumulation, tectonic activity and erosion process through a large history. The geological background belongs to a Precambrian to Paleozoic age which supports a Mesozoic to Cenozoic sedimentary cover that reposes unconformably over a Precambrian basement. The basement from Precambrian to Paleozoic appears downstream of Stanley Pool and the sedimentary cover formed basically by sandy materials of Stanley Pool series [7]. Then, Congo Republic with a complexity of geological structure and tectonic stress, in the past time and now has suffered and still suffers always from the destructive effects of geological phenomena [6]. Therefore, it is necessary to evaluate the slope stability in order to develop techniques which are able to solve this problem. Then, it is also indispensable to know about the effects or impacts caused by landslides and the failure mechanisms they present as well, in order to go on with the slope stability analysis and the computation of an adequate factor of safety.

Slopes problems are often noticed in Congo republic mostly in the northern region of Brazzaville City. Buildings are ruined by land movements each year. Manifestation regularity of this disaster is up during the rainy periods. Everywhere 70% of the total rainfall in Congo

Republic takes place in rainy season. Hence, landslides event is more concentrated in this rainy period [8]. Construction works accompanied by deforestation of friable soil found on steep slopes is the origin of slope insecurity and the complex tectonic features existing in City as well. Among all the damages produced by slopes instability in Brazzaville City, 45% of losses is found in mountain areas [9,10].

Slope stability analyse remains one of the main subjects in environmental engineering because of particular slope behaviour when earthquake occurs, and its modest application has been advanced rapidly in current years. So, some approaches have been expressed for slopes stability analyse. The limit equilibrium approach is one of the more widespread methods for slopes stability analyse [11]. This method uses horizontal constituents, in its place of vertical constituents for studying slope soil stability. The vertical constituent's technique collects forces that not appear among constituent's boundaries. Various methods are based on defining critical slip surface [12,13]. The Rectilinear slip surface is considered for the slope's stability analyse by using limit equilibrium approach. Deplorable findings of rectilinear slip surface made scientists advise other types of sliding surface. Among optional slip surface tactics, log-spiral slip surface can remain as one of the utmost precise and valid methods. Additional uncertainties of studying stability of slopes by limit equilibrium approach is the non-existence of distortions estimation occurring on the time where the soil behaviour on slip surface is supposed to be stiff and plastic. Moreover, the limit equilibrium approach, other techniques counting numerical codes for example Finite Element and finite difference methodologies [14,15], the stress conditions method [16] and other advantageous methods were applied as well [17,18].

Some problems found in slopes stability study is modelling the forces produced by earthquake. But some simulations were performed using pseudo-static approach earlier. Moreover, vertical forces produced by earthquake has been ignored in some prior studies [19,20]. In the current study, the shear strength reduction technique is used for slope stability from finite element skill. Currently, the shear strength reduction approach has been advanced significantly than earlier. Supremacy of this technique to limit equilibrium approach has advanced this approach and various software.

This study aims to perform the slope stability analysis by Finite Element Method based on PLAXIS 2D software. Then the slope stability evaluated from its Safety Factor considering slopes of various heights of different gradients or inclinations, different parameters of soil and with consideration two different earthquake intensities.

2. MATERIALS AND METHODS

In this section the slope was considered totally under saturated conditions. Therefore, slopes of various heights of 4 m, 7 m, and 10 m, each of different side slopes of 2.5 H: 1V, 2H: 1V, 1.5H: 1V, 1H:1V were taken for the current study. Founded on the hypothesis that the slope is completely drained, a finite element model was created and applied by using PLAXIS 2D. Basic model of pressure was approved due to its uniform cross-section considering an element of 15 noded plain strain for the discretization of slope material. The seismicity effects analysis was based on pseudo-static method which was assisted by the usage of PLAXIS 2D. Then, the slope stability was evaluated for wo different earthquake accelerations of 0.2g and 0.4g.

2.1 Analysis

A mesh generation was carried out considering a global coarseness set to medium. Mesh generation can be seen in Fig. 2. Computation procedure by using PLAXIS possess various calculation steps. The first computation step (initial phase) computes the initial stress field by gravity process or 'K0 method'. The second step consists in loads activation. The third steps consist in the analysis of slope safety where the slope safety factor is computed under loading conditions. After all steps execution, the software is now able to calculate and give all results about values of different factors of safety. The slope model and deformed mesh can be seen in Figs. 1 and 2 respectively.

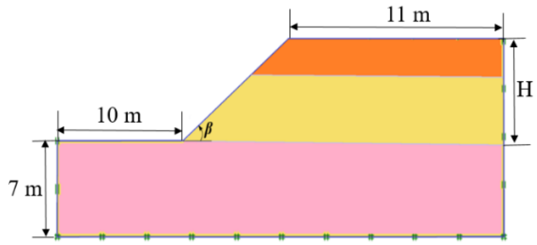

Fig. 1. Slope model

3. RESULTS AND DISCUSSION

A slope with less cohesive soil of 5 m height was erected above a cohesive soil bedrock with 7 m of height (Fig. 1). Table 1 illustrates physical properties of soils strength. The filling was erected in 3 weeks and 5 days. The modelling of soil slope was carried out by using Plaxis 2D software and the model agenda is in sequence method.

The filling analyse along X direction was fixed with zero displacement. The inferior boundary of filling along X and Y directions was fixed as well. The modelling of soil comportment was carried out by elasto-plastic model and Mohr–Coulomb perfect.

Figs. 3, 4 and 5 show values of safety factor of 4 m high slope inclinations of 2.5H:1V, 1.5H:1V and 1H:1V respectively. Each of this slope stability was evaluated for a no surcharge case under 0.2g and 0.4g earthquake accelerations. These figures show a significant reduction in slopes safety factor with an increase in earthquake acceleration. Only a small change in slope stability factor is observed where slope inclination increases from 2.5H: 1V to 1.5H: 1V, then the reduction increases when the inclination of slope moves to 1.5H:1V. Once it is observed an increase in the values of cohesion and frictional angle, the slope safety factor increases as well. It is also noted that when there is an increase in the earthquake acceleration, the slopes with lower combination of soil parameter have tendency to fail earliest.

Figs. 3 and 5 show the values of safety factor for a 7 m high slope with inclinations of 2.5H:1V, 1.5H:1V and 1H:1V respectively under 0.2g and 0.4g of earthquake accelerations. It is noticed that around 7 m high slopes are similar as that we observed from slopes of 4 m high.

Figs. 3-5 shows the values of safety factor for a slope of 10 m high of inclinations 1H:1V, 2.5H:1V and 1.5H:1V respectively under earthquake accelerations of 0.2g and 0.4g. A same remark is noted for 4 m and 7 m high slopes which seems to be made out here as well.

3.1 Discussion

The slopes analysis with PLAXIS 2D based on soils properties showed in Table 1, was efficient and made possible to note the safety factor variation with the slope angles variation, slope heights, values of cohesion, values of frictional angle and magnitudes of earthquake accelerations as well as can be seen from Figs. 3 to 5 showing values of safety factor of 4 m high slope inclinations of 2.5H:1V, 1.5H:1V and 1H:1V respectively. The factor of safety decreases with an increase in earthquake acceleration [19]. While when there is noticed a change into earthquake acceleration in less steep slopes compared to very steep slopes which are vulnerable to failure under an increase in earthquake acceleration [20]. Under lower earthquake acceleration, all slopes are safe except when it is very steep including very low values of cohesion and frictional angle and slopes with low inclination and low values of cohesion are stable [3]. while a decrease in values of safety factor is related to slope inclination when it tends to decrease as well. As the cohesion and friction angle being parameters of soil strength show an increase in their values, the values of safety factor tend to increase too and making the slope in a stable state [4].

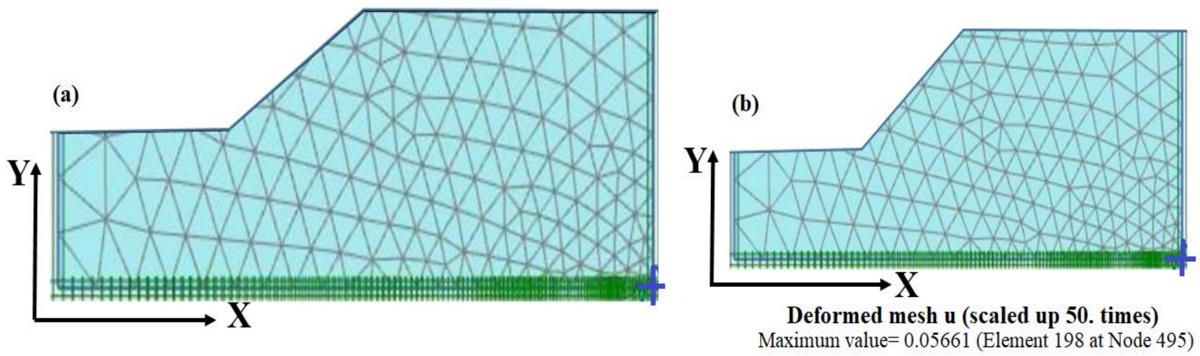

Fig. 2. (a) Generated mesh; (b) Deformed mesh

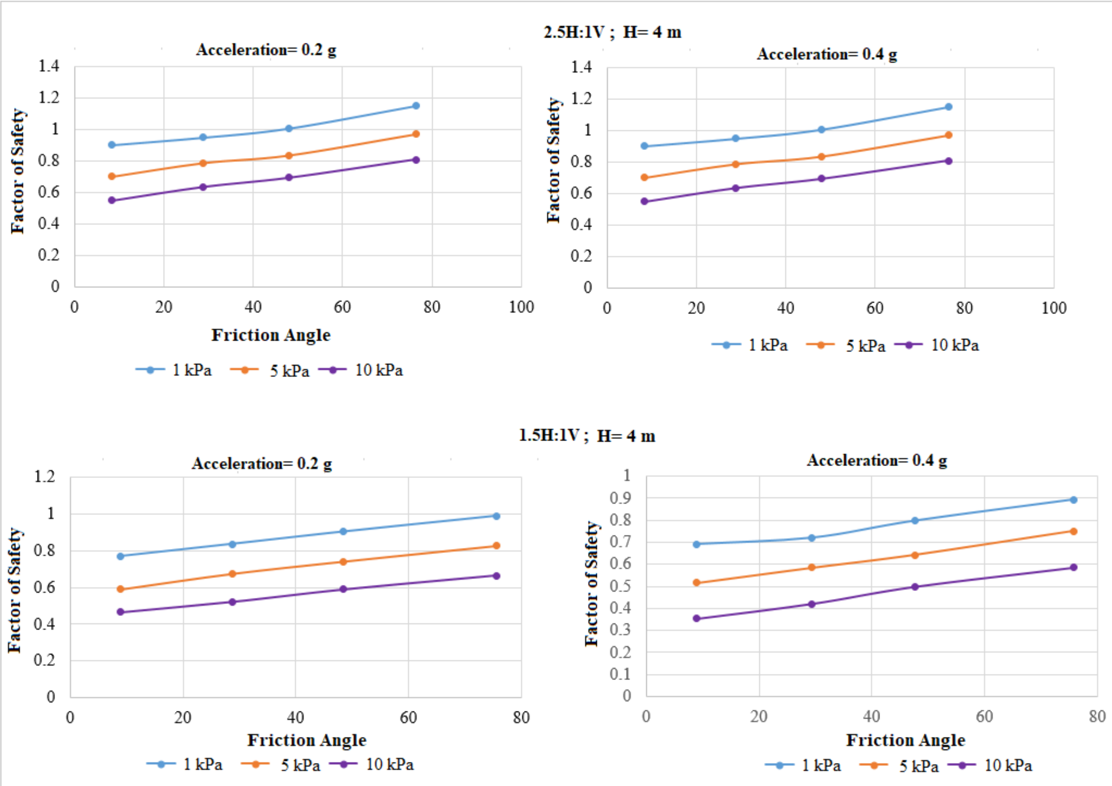

Fig. 3. Variation of safety factor vs friction angle (H= 4 m)

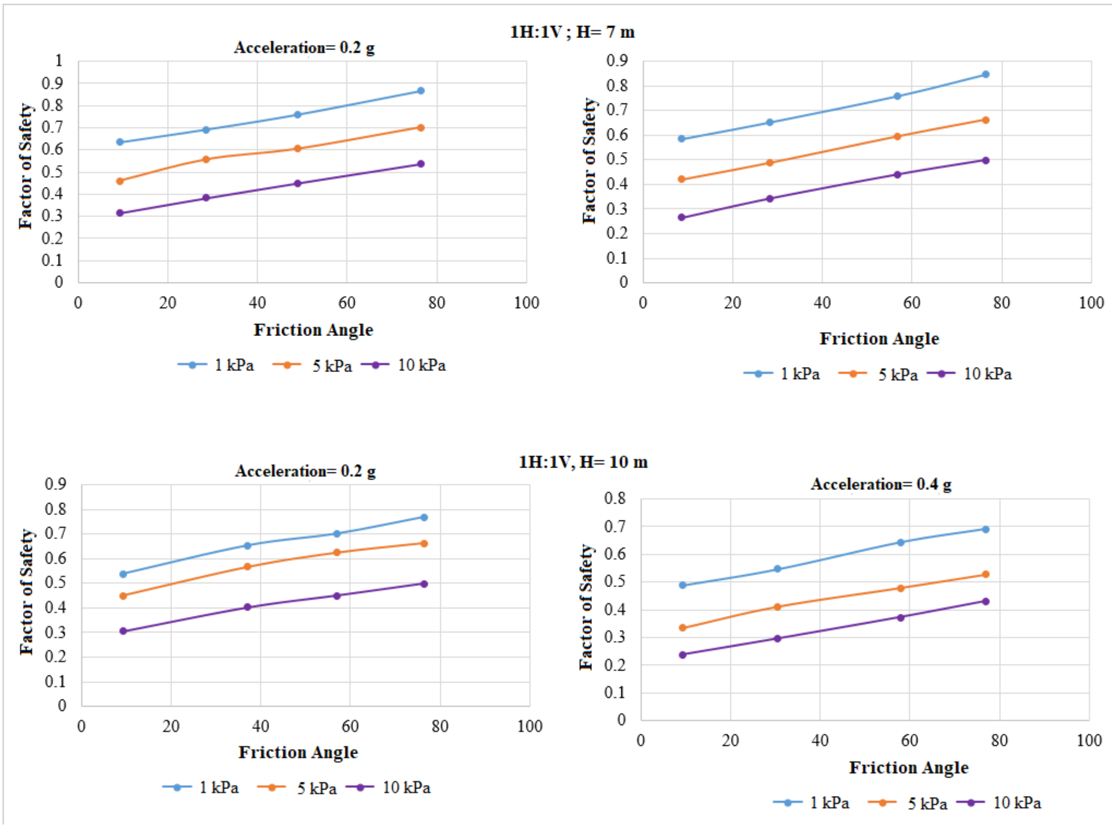

Fig. 4. Variation of safety factor vs friction angle (H=7 m and H= 10 m)

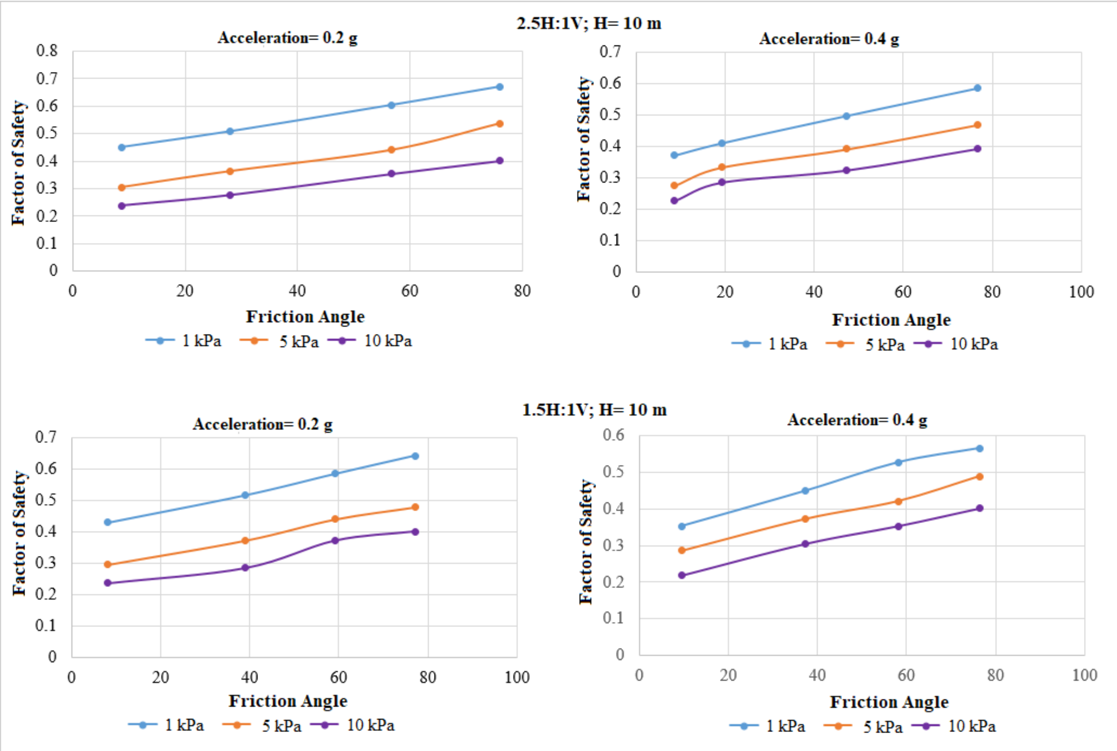

Fig. 5. Variation of safety factor vs friction angle (H= 10 m)

Table 1. Properties of soil parameters

Parameters	Unit	Soil types		
		1-Sand (SP)	2- Sandy Clay (SC)	3- Organic clay (CL)
Unit weight (γ)	kN/m^3	17	15	12.50
Saturated unit weight (γ_{sat})	(kN/m^3)	21	19	16
Cohesion (c)	(kPa)	1	5	10
Friction Angle (ϕ)	(^{o})	32	21	-
Elasticity Modulus (E)	(MPa)	100	25	18
Poisson's ratio (μ)	-	0.3	0.25	0.5

4. CONCLUSION

The present study carried out determined certain aspects of the slope behaviour such as: slope stability study using the method of shear strength reduction managed to particular humble analyses producing satisfactory outcomes.

Considering the increase of slope angle with the factor of safety decrease, the slope runs to more devastations. The increment of angle of internal friction conducts to slope in a stable state. While, the seismic forces existence causes an increase in the slope failure in part.

Slopes analysis by using PLAXIS software provided a vision into the safety factor variation considering the variation in angles of slope, heights of slope, values of cohesion, angle of friction and earthquake accelerations.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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