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Influence of composite slope geometrical parameters on soft rock slope stability

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Abstract

Purpose. To analyze the key parameters influencing the stability of a composite soft rock slope.

Methods. Description of the key geometrical parameters of a composite slope and their influence on soft rock slope stability. Numerical simulation is performed to validate the primary effects of the key geometrical parameters of a composite slope on stability without consideration of external factors such as ground water, seismic and blasting factors.

Findings. This paper put forward the influence pattern of the dumping height, excavation depth, slope angle, dumping angle, and dumping position on the safety factor of the composite slope. Furthermore, the results prove that as the dump is moved away from the reference crest or toe, the factor of safety increases. Thus, improvement of the safety factor on the critical sliding surface is defined by the area of the parallelogram. Also, when the critical position of the dump away from the edge is exceeded and the lateral pressure induced by the superimposition of the waste dump has no influence on the critical sliding surface, failure takes place in the surface mines slope and stability is relatively controlled by the mechanical strength and geometrical parameters of the surface mines slope.

Originality. The paper provides a pioneering detailed description of the interactions of the key geometrical parameters of a composite slope and their influence on stability and the factor of safety.

Practical implications. The results can be used for designing and stability analysis of composite slopes.

Keywords: *Composite slope; dumping angle; geometrical parameters; lateral pressure*

1. Introduction

Regardless of the fact that surcharge loading caused by structures is a common destabilizing force in most mining and civil engineering projects, slope stability analysis considering surcharge, particularly its effect on the factor of safety, has not received proper attention in the past. The problems of slope stability have been discussed in several articles and books related to rock engineering and there have been several developments [1]-[15]. However, there is little known about the interactions and influence of the key geometrical parameters of a composite slope and how they influence stability and the factor of safety.

Different researchers have utilized finite element methods for slope stability [16]-[23]. Since the stability of composite slope is extremely important in open cast mining, an opposite direction piecewise local control which was based on the composite high slope was utilized to calculate the composite slope stability.In order to obtain the influence rule of the key geometrical parameters of a composite slope on stability, FLAC/Slope is employed. FLAC/Slope provides a full solution of the coupled stress/displacement, equilibrium and constitutive equations. Given a set of properties, the system is determined to be stable or unstable by automatically performing series of simulations while changing the strength properties. The factor of safety can be found to correspond to the point of stability, and the critical failure surface can be located. The strength reduction technique is typically applied in factor of safety calculations by progressively reducing the shear strength of the material to bring the slope to a state of limiting equilibrium. The factor of safety F_s is defined according to the following equations:

$$c^{trail} = \left(\frac{1}{F_s^{trail}}\right)c\,; \tag{1}$$

$$\phi^{trail} = \arctan\left(\frac{1}{F_s^{trail}}\tan\phi\right). \tag{2}$$

A series of simulations are made using trail values of the factor F_s^{trail} to reduce the cohesion, c, and friction angle, ϕ, until slope failure occurs.

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A detailed parametric study is presented to investigate the effect of the key geometrical parameters of a composite slope on stability. The essence of this analysis is to create a framework that improves the idea for computing composite slopes stability and to compare with results obtained from stress computations.

2. Materials and methods

In the current research, Datang Surface coal mine located within the eastern part of Shengli coalfield which is a project of Datang international power generation co., LTD located in Xilingol league, Inner Mongolia autonomous region is considered as a case study. In order to study the effect of the geometrical parameters on the factor of safety of a composite slope, a control variant method using FLAC/Slope is adopted. The strength parameters used in this analysis are shown in Table 1.

Table 1. Composite slope physico-mechanical parameters

Name	Cohesion c (KPa)	Internal friction angle ϕ (°)	Unit weight (kg/m^3)
Bed rock	40	20	2270
Foundation slope	25	20	1400
Dump	16	8	2120

The influence pattern of the excavation depth, dumping height, slope angle, dumping angle, and dumping position on the factor of safety of the composite slope has been analyzed using FLAC/Slope. Detail analysis and results are presented.

3. Results and discussion

3.1. Effect of surface mines slope angle on the stability of composite slope

In order to study the variation of surface mines slopes angle on the stability of composite slope, a control variant technique was used to calculate the factor of safety of a Surface mine slope by varying the slope angles. Two sets of analysis (under the action of an external load and without an external load) were done in order to analyze the slope angle influence rule. The essence of these analyses is to obtain the relative influence and interaction of the slope angle under the action of loading on the stability of composite slope. In the first sets of analysis, only the foundation slope strength parameters were used to analyze the factor of safety.

The slope angles were varied in all models from $\psi_f = 20°$ to $\psi_f = 40°$ at an interval of 5°. At the same time a constant slope height of $H = 100$ m and strength parameters were adopted for the analysis. The strength properties used in these analyses are those shown in Table 1 for foundation slope and bed rock. The importance of these analyses is to understand different mode of failure and how the factor of safety behaves without the application of a surcharge load. The results are then compared with slopes with a surcharge. Figure 1, shows the graphical output of the numerical analysis when the models are run without the application of a surcharge while Figure 2 depicts its influence rule. From Figure 2, it is seen, that with increase in the angle of the slope, the factor of safety decreases indicating a quadratic change rule. The results shows that the slope angle influences not only the factor of safety but also the mode of failure.

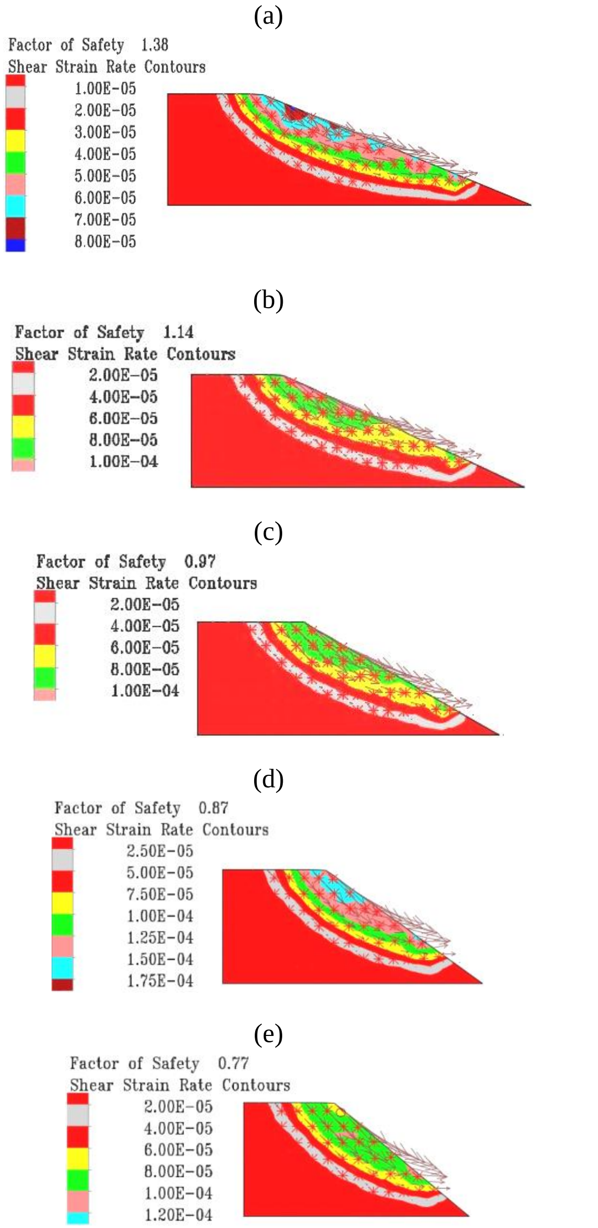

Figure 1. Graphical output of numerical results by variation in slope angle: (a) $\psi_f = 20$; (b) $\psi_f = 25$; (c) $\psi_f = 30$; (d) $\psi_f = 35$; (e) $\psi_f = 40$

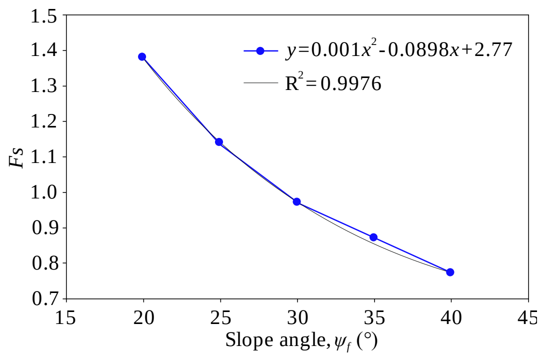

Figure 2. Stability factor influence rule due to Slope angle variation

For the second set of models, with a surcharge such as the waste dump, the basic geometrical parameters used in the analysis were such that $\Delta H = 20$ m, $\theta = 33°$, $d = 10$ m; and $H = 100$ m.

The strength parameters are those shown in Table 1, and only the slope angle was interchange within all models. Figure 3 shows the graphical outputs from the numerical simulations while Figure 4 shows the influence rule of the slope angle on the factor of safety under the action of an applied load.

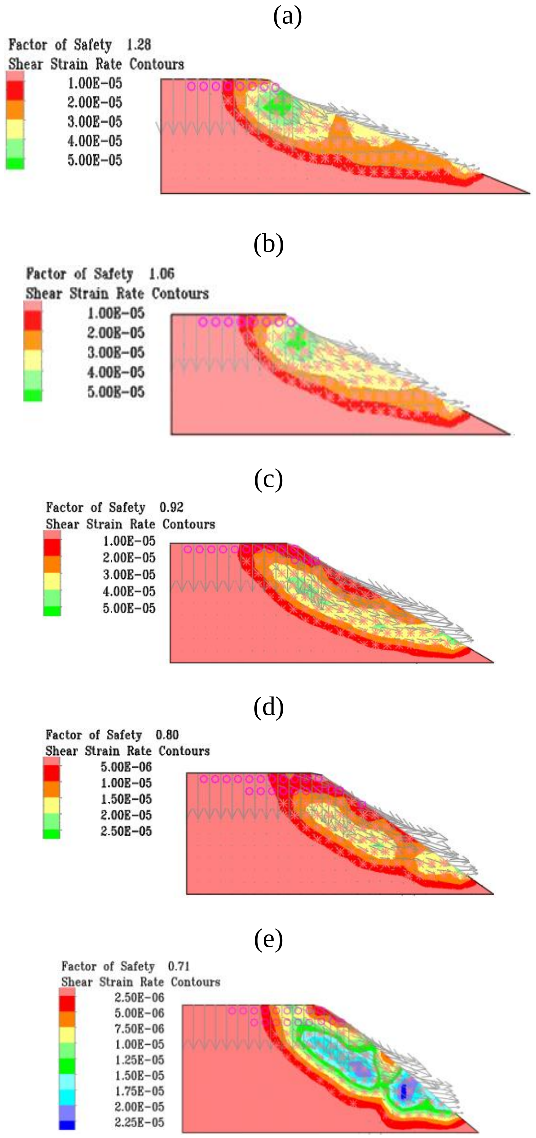

Figure 3. Graphical output of numerical results by variation in slope angle under the action of applied load: (a) $\psi_f = 20$; (b) $\psi_f = 25$; (c) $\psi_f = 30$; (d) $\psi_f = 35$; (e) $\psi_f = 40$

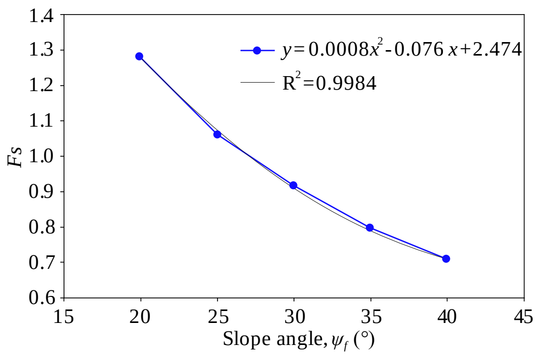

Figure 4. Stability factor influence rule due to variation in slope angle under the action of applied load

The analysis results shows a constant change rule as that described in Figure 2 as the factor of safety deceases with increase in slope angle. Considering, Figure 1b, when the slope isn't loaded by any external loading, the factor of safety $F_s = 1.14$ for $\psi_f = 25°$. However, under the action of a surcharge load, the factor of safety decreases from $F_s = 1.14$ to $F_s = 1.06$. This highlights the relative importance of considering the effect of surcharge such as that of a waste dump within stability analysis. Furthermore, it is seen that the application of an external load leads to further reduction in the stability factor and influences the mode of failure.

3.2. Effect of surface mines slope height on the stability of composite slope

In order to study the variation of surface mines slopes height on the stability of composite slope, a control variant technique was used to calculate the factor of safety of the slope by varying the slope heights. Two sets of analysis were done in order to analyze the slope height influence rule under the action of an external load and without an external load. These analyses were done in order to deduce the influence and interaction of the slope height under the action of loading within a composite slope system. In the first sets of analysis, only the foundation slope strength parameters were used to analyze the factor of safety. The slope height used in the two sets of models varied from $H = 100$ m to $H = 600$ m at an interval of 100 m while a constant slope angle $\psi_f = 25°$ and strength parameters were used in all models. The strength properties used in these analyses are those shown in Table 1 for foundation slope and bed rock. The importance of these analyses is to understand different mode of failure and how the factor of safety behaves without the application of a surcharge load. The results are then compared with slopes with a surcharge. Figure 5 shows the graphical output of the numerical analysis when the models are run without the application of a surcharge while Figure 6 depicts its influence rule. From Figure 6, it is seen, that with increase in the height of the slope, the factor of safety decreases indicating a negative logarithmic change rule. The results shows that the slope height influences not only the factor of safety but also the mode of failure. The results also shows that as the height H increases the relative contribution of the cohesion to the total resistance decreases, however for very high slopes, the stable slope angle approaches the friction angle ϕ.

For the slope with a surcharge such as that of a waste dump the basic geometrical parameters used in the analysis were such that $\Delta H = 20$ m, $\theta = 33°$, $d = 10$ m; and $\psi_f = 25°$. The strength parameters are those shown in Table 1, and only the height was interchange within all models. Figure 7 shows the graphical outputs from the numerical simulations while Figure 8 indicates the influence rule of the slope height on the factor of safety under the action of an applied load. The analysis results shows a constant change rule as that described in Figure 6 as the factor of safety deceases with increase in slope height. Considering, Figure 5, when the slope isn't loaded by any external loading, the factor of safety $F_s = 0.99$ for $H = 200$ m. However, under the action of a surcharge load, the factor of safety further decreases from $F_s = 0.99$ to $F_s = 0.96$. This highlights the relative importance of considering the effect of surcharge such as that of a waste dump within any stability analysis. Furthermore, it is seen that the application of an external load leads to further reduction in the stability factor and influences the mode of failure.

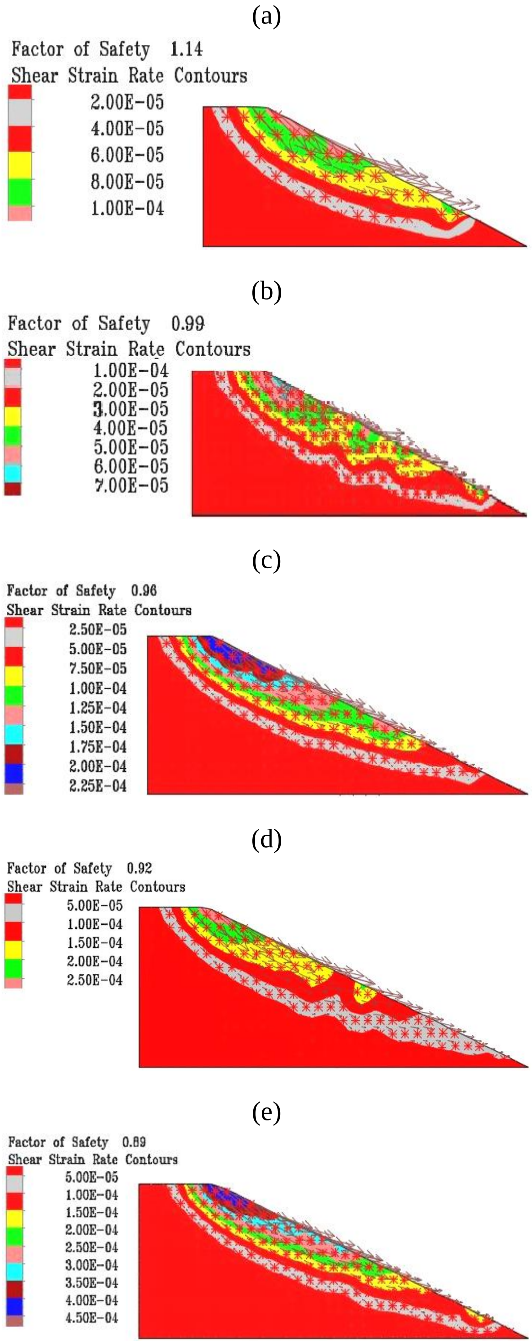

Figure 5. Graphical output of numerical results by variation in slope height: (a) H = 100; (b) H = 200; (c) H = 300; (d) H = 400; (e) H = 500

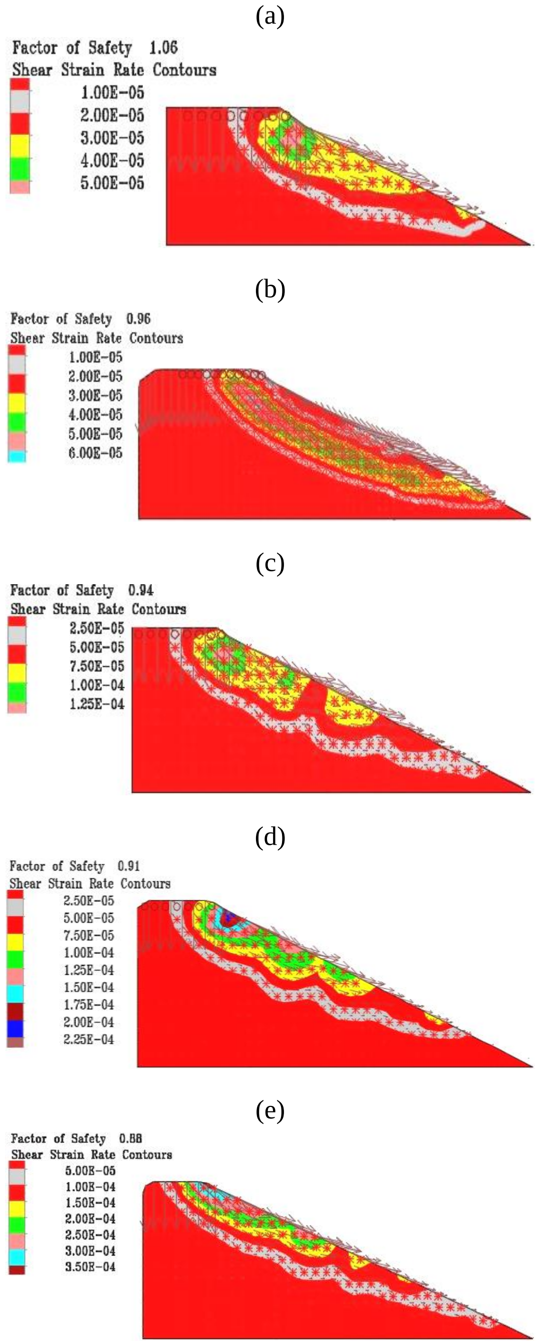

Figure 7. Graphical representation of variation in excavation depth under the action of applied load: (a) H = 100; (b) H = 200; (c) H = 300; (d) H = 400; (e) H = 500

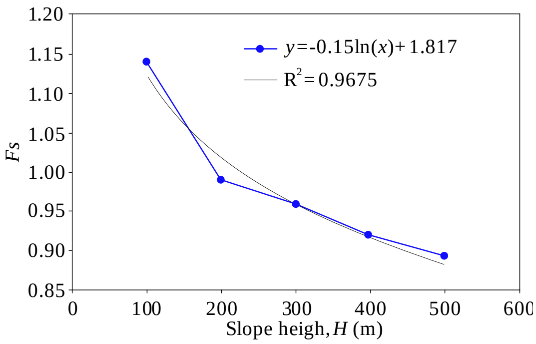

Figure 6. Stability factor influence rule due to slope height variation

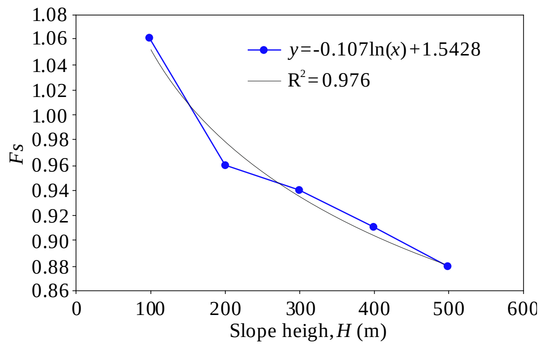

Figure 8. Variation pattern of excavation depth, under the action of applied load

3.3. Effect of a waste dump height on the stability of a composite slope

In order to obtain the influence of the variation of the loading condition especially the change in dumping height, a constant dump angle $\theta = 20°$, Excavation depth, $H = 150$ m, slope angle, $\psi_f = 20°$ and dump position $d = 50$ m was used in all models within this section (Fig. 9).

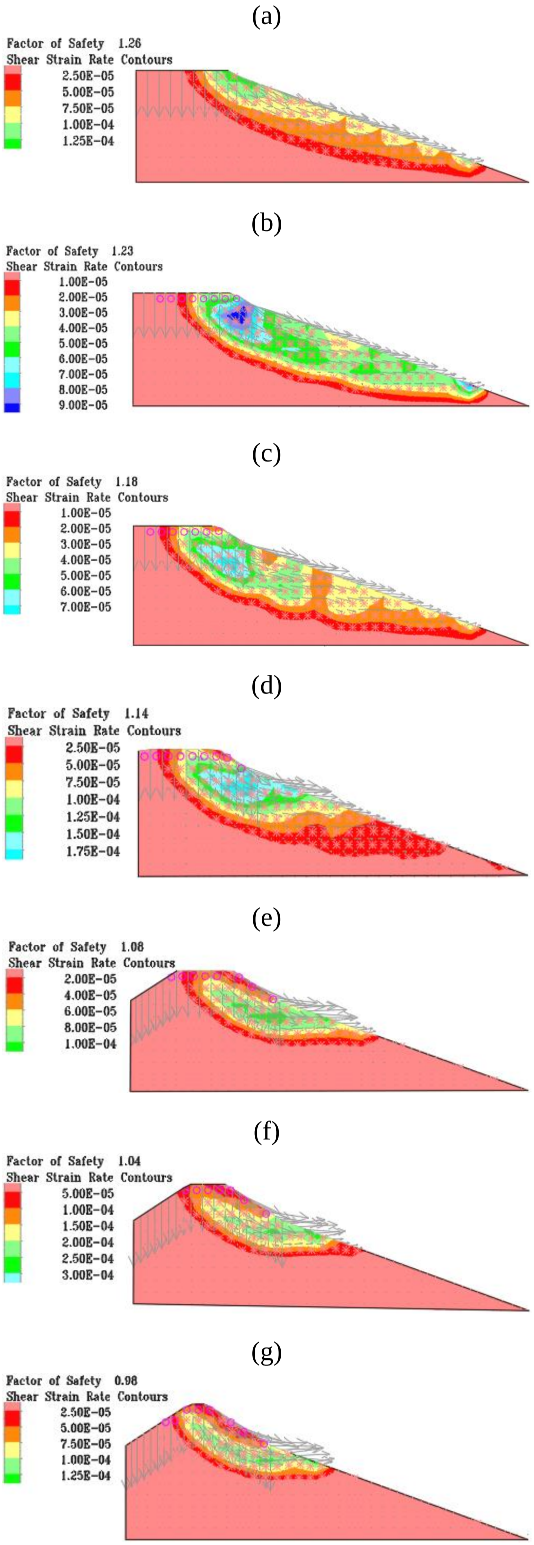

Figure 9. Graphical representation of variation in dumping height: (a) ΔH = 10 m; (b) ΔH = 20 m; (c) ΔH = 30 m; (d) ΔH = 40 m; (e) ΔH = 50 m; (f) ΔH = 60 m; (g) ΔH = 70 m

The slope stability is analyzed as a two-dimensional problem using FLAC/Slope. From the analysis, the relative influence of the dumping height on the factor of safety is obtained. Figure 9 shows the graphical outputs from the numerical analysis while Figure 10 depicts the influence rule of the dumping height.

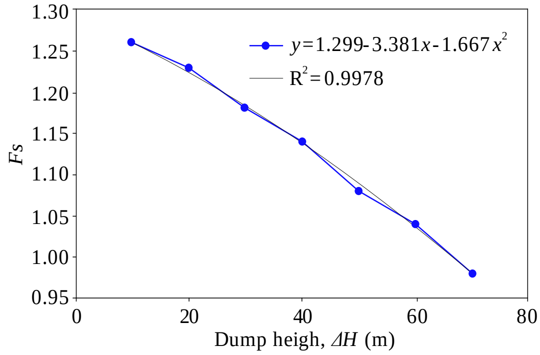

Figure 10. Stability factor influence rule due to dumping height variation

The analysis results shows, that following the increase in the dumping height the factor of safety decreases indicating a quadratic functional rule as the stability coefficient decreases to a minimum value.

3.4. Effect of surface mines waste dump position on composite slope stability

Open pit slopes exist with a factor of safety without the application of external loads. The surcharge is estimated as a distributed load caused by the weight of the waste dump. It has been seen that the waste dump placed on the surface mines slope induces additional stresses which lead to reduction in the factor of safety. In order to obtain the influence of the variation of the dumping position, the slope stability is analyzed using the 2-dimensional stress reduction method employed in FLAC/Slope.

The dump parameters and slope parameters were held constant in all models including the strength parameters described in Table 1. The dump position was interchanged in 12 different models ranging from $d = 10$ m to $d = 800$ m. Figure 11 shows the graphical outputs from the numerical modeling while Figure 12 shows the influence rule of the dump position on the factor of safety when all other parameters are held constant. The results shows an increase in the factor safety when the dump is moving away from the crest of the pit slope.

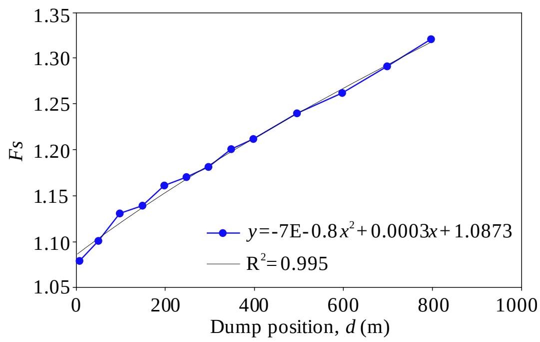

Figure 11. Influence rule of dump position on composite slope stability

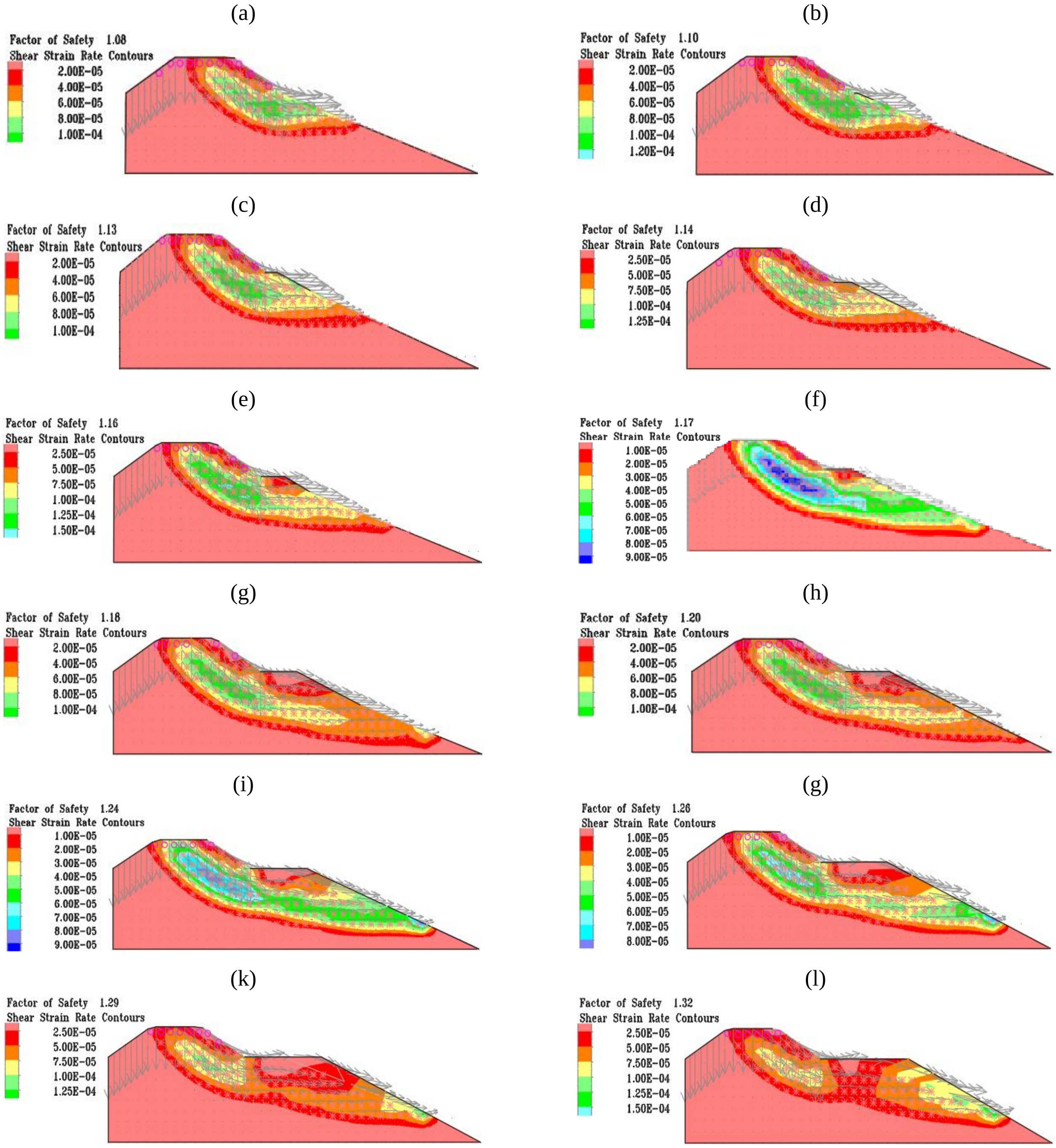

Figure 12. Graphical representation of variation in dump position, when $\Delta H = 50$ m, $\psi = 20°$: (a) d = 10 m; (b) d = 50 m; (c) d = 100 m; (d) d = 150 m; (e) d = 200 m; (f) d = 250 m; (g) d = 300 m; (h) d = 400 m; (i) d = 500 m; (g) d = 600 m; (k) d = 700 m; (l) d = 800 m

The results also shows a negative quadratic change rule, indicating a direct relationship with the factor of safety. Hence, the dumping position of the waste dump is a key factor that influences the stability and profitability of any surface mining operation.

3.5. Effect of surface mines waste dump angle on composite slope stability

The impact due to instability in surface mining cannot be overemphasized as there have been several literatures that discuss the adverse effect this may have on people and the environment. The waste dump angle is a key parameter that determines the volume of waste rock material and the maximum capacity of the dump. To find the relative influence of the dump angle in the formation of a composite slope, several analyses were performed. The use of parametric modeling was the best choice suitable for computing the factor of safety and understanding the influence of the waste dump angle on the stability of the slope.

The geometrical parameters used in the models were such that $\psi_f = 30°$, $\Delta H = 10$ m, $H = 100$ m, $d = 50$ m while the strength parameters used are shown in Table 1. Figure 13 shows the graphical outputs from the numerical analysis while Figure 14 shows the influence rule of the dumping angle when all other parameters are held constant. From the analysis results it can be seen that the factor of safety decreases with increase in the dumping angle indicating a negative quadratic change rule. Hence it can be said that the dumping angle is a key parameter that influences the stability of composite slopes.

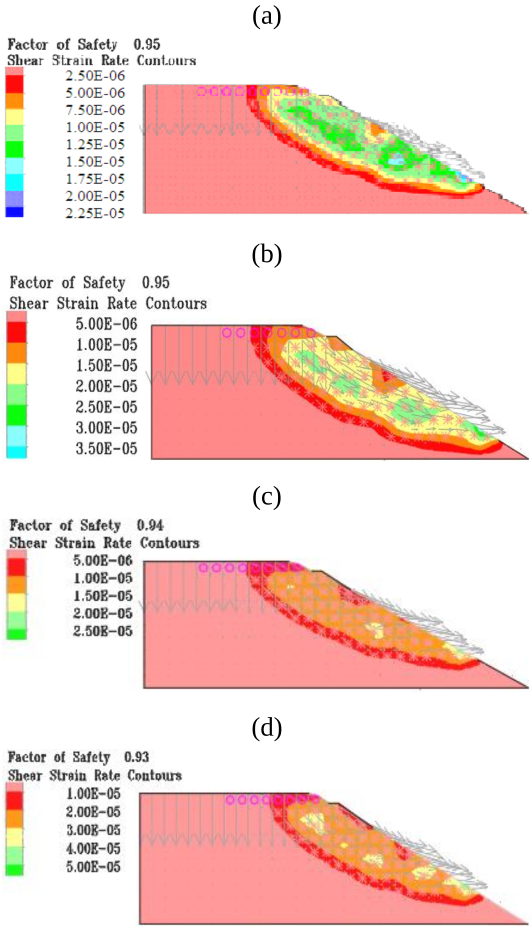

Figure 13. Graphical representation of variation in dumping angle: θ = 20°; θ = 25°; θ = 30°; θ = 33°

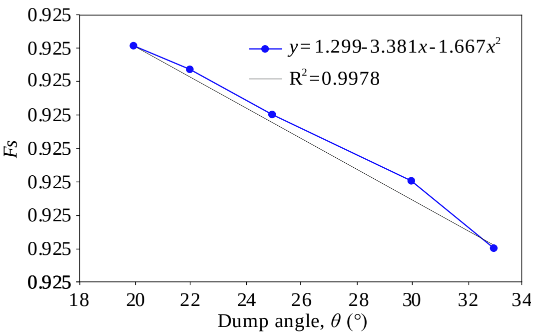

Figure 14. Change rule of dumping angle on the stability of composite slope

4. Conclusions

When the load is applied on the surface mines slope it induces additional stresses within the rock mass and the magnitude of the load reduces away from the point of application. However, it is seen that an increase in the other geometrical parameters results in a decrease in the factor of safety and the result is obvious. From the analysis, it is seen that the influence of the dumping position on the critical sliding surface to the factor of safety is defined by the area of a parallelogram whose base is equivalent to the distance moved and the height and angle of the parallelogram is determined by the waste dump.

With increase in the angle of the slope, the factor of safety decreases indicating a quadratic change rule. The results shows that the slope angle influences not only the factor of safety but also the mode of failure.

It is observed that the relative importance of considering the effect of surcharge such as that of a waste dump within stability analysis. It is seen that the application of an external load leads to further reduction in the stability factor and influences the mode of failure.

The slope height influences not only the factor of safety but also the mode of failure. The results also shows that as the height H increases the relative contribution of the cohesion to the total resistance decreases, however for very high slopes, the stable slope angle approaches the friction angle.

The relative importance of considering the effect of surcharge such as that of a waste dump within any stability analysis has been observed. It is observed that the application of an external load leads to further reduction in the stability factor and influences the mode of failure.

From the analysis, the relative influence of the dumping height on the factor of safety is obtained.

The analysis results shows, that following the increase in the dumping height the factor of safety decreases indicating a quadratic functional rule as the stability coefficient decreases to a minimum value.

The results also shows a negative quadratic change rule, indicating a direct relationship with the factor of safety. Hence, the dumping position of the waste dump is a key factor that influences the stability and profitability of any surface mining operation.

The dumping angle is a key parameter that influences the stability of composite slopes.

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Аналіз основних параметрів, що визначають стійкість укосу, складеного зі змішаних м'яких порід

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Мета. Обгрунтування параметрів, що визначають стійкість укосу, складених зі змішаних м'яких порід на основі проведення чисельного моделювання.

Методика. Застосовано чисельне моделювання для визначення базового впливу основних геометричних параметрів композитного борту на його стабільність без урахування таких зовнішніх факторів, як грунтові води, сейсмічний та вибуховий вплив. Схема впливу глибини виїмки, висоти розвантаження, кута нахилу, кута розвантаження і положення розвантаження на фактор безпеки композитного укосу була проаналізована за допомогою FLAC/Slope.

Результати. Доведено, що, чим більше відстань між відвалом і верхньої або нижньої бровкою уступу, тим вище фактор безпеки, а поліпшення фактору безпеки по критичній поверхні ковзання визначається площею паралелограма. Встановлено, що якщо відстань між відвалом і бровкою відвалу більше критичного і бічного тиску, що виникає за рахунок нашарування відвалу, то вона не впливає на критичну поверхню ковзання і на поверхні укосу виникають деформації, в той час як його стійкість знаходиться під відносним впливом механічної міцності й геометричних параметрів укосу. Визначено, що висота схилу впливає не тільки на фактор безпеки, але і на режим руйнування, зі збільшенням висоти відносний внесок зчеплення в загальний опір зменшується, однак для дуже високих ухилів стабільний кут нахилу наближається до кута тертя.

Наукова новизна. Виявлено новий характер взаємодії між основними геометричними параметрами композитного укосу та їх впливу на стабільність та фактор безпеки.

Практична значимість. Результати дослідження можуть бути використані для проектування та аналізу стабільності композитних укосів, складених з м'яких порід.

Ключові слова: *композитний укіс, кут відвалу, геометричні параметрами, бічній тиск*

Анализ основных параметров, определяющих устойчивость откоса, сложенного из смешанных мягких пород

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Цель. Обоснование параметров, определяющих устойчивость откоса, сложенного из смешанных мягких пород на основе проведения численного моделирования.

Методика. Применено численное моделирование для определения базового воздействия основных геометрических параметров композитного борта на его стабильность без учета таких внешних факторов, как грунтовые воды, сейсмическое и взрывное воздействие. Схема влияния глубины выемки, высоты разгрузки, угла наклона, угла разгрузки и положения разгрузки на фактор безопасности композитного откоса была проанализирована с помощью FLAC/Slope.

Результаты. Доказано, что, чем больше расстояние между отвалом и верхней или нижней бровкой уступа, тем выше фактор безопасности, а улучшение фактора безопасности по критической поверхности скольжения определяется площадью параллелограмма. Установлено, что если расстояние между отвалом и бровкой отвала больше критического и бокового давления, возникающего за счет напластования отвала, то не оказывается влияния на критическую поверхность скольжения и на поверхности откоса возникают деформации, в то время как его устойчивость находится под относительным влиянием механической прочности и геометрических параметров откоса. Определено, что высота склона влияет не только на фактор безопасности, но и на режим разрушения, с увеличением высоты относительный вклад сцепления в общее сопротивление уменьшается, однако для очень высоких уклонов стабильный угол наклона приближается к углу трения.

Научная новизна. Выявлен новый характер взаимодействия между основными геометрическими параметрами композитного откоса и их влияния на стабильность и фактор безопасности.

Практическая значимость. Результаты исследования могут быть использованы для проектирования и анализа стабильности композитных откосов, сложенных из мягких пород.

Ключевые слова: *Композитный откос, угол отвала, геометрические параметры, боковое давление*

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