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Slope stability evaluation by limit equilibrium and Finite Element Methods

Evaluation de la stabilité de versants par des méthodes d'équilibre limite et éléments finis

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ABSTRACT

A case study is presented for a natural slope situated in Nepal, where a hydropower project is being constructed. A 40 m high concrete dam is situated close to a 65 m high slope, consisting of river and glacier deposits. The long-term safety of the slope is evaluated by the software codes PLAXIS and GeoSlope, mainly changing the groundwater conditions in the slope. Variations of these conditions have also been studied by Janbu's Direct method. The computed factors of safety from PLAXIS are based on Mohr-Coulomb model, whereas the results from GeoSlope utilize the limit equilibrium methods. Safety factors obtained from these methods for a number of water level variations are discussed and compared. The groundwater variation is studied both for dry and wet seasonal conditions. Apart from this, conditions with pseudo-static earthquake loading in GeoSlope and dynamic loading in PLAXIS have been presented. The dynamic analyses have been performed based on prescribed displacements at the base of the model and selected acceleration-time series. The output results from the dynamic analyses are discussed in terms of displacements, acceleration and generated pore pressure in the slope. The authors have concluded that potentially unstable slope conditions exist due to combined groundwater variations and earthquake impact.

RÉSUMÉ

Notre étude traite de la stabilité d'une pente naturelle située au Népal, sur le site de construction d'une centrale hydroélectrique. Un barrage en béton de 40 m de hauteur est construit à proximité d'un massif de 65 m de hauteur, composée d'alluvions et de dépôts issus de la fonte des glaciers. La stabilité à long terme de la pente est évaluée à l'aide des logiciels PLAXIS et GeoSlope, les simulations portant essentiellement sur la modification du niveau de la nappe souterraine au sein du massif. Cette évolution est aussi étudiée à l'aide de la méthode de Jambu. Les coefficients de sécurités déterminés sous PLAXIS sont basés sur le modèle de Mohr-Coulomb, alors que les résultats obtenus à l'aide de GeoSlope s'appuient sur la méthode de l'équilibre limite. Les coefficients de sécurités obtenus par diverses méthodes sont étudiés et comparés pour plusieurs niveaux de la nappe, ceux-ci étant choisis de manière à simuler aussi bien les saisons sèches que les saisons humides. Nous présentons aussi des simulations effectuées sous chargement dynamique sous PLAXIS, et en conditions de tremblement de terre pseudo-statique sous GeoSlope. Ces analyses dynamiques sont effectuées à déplacements imposés à la base du modèle de massif, avec une accélération déterminée. Les résultats de ces simulations sont analysés en termes de champs de déplacements, d'accélération et de pression interstitielle résultante au sein du massif. La conclusion des auteurs est que la pente du massif peut devenir instable, sous l'action combinée d'un tremblement de terre et des variations du niveau de la nappe souterraine.

1 INTRODUCTION

The case study described herein is taken from a slope situated at the Middle Marsyangi hydropower project in Nepal. A forty meter high concrete dam is planned, next to a 65 m high slope composed by fluvial and glacial deposits. This natural slope is situated on the left bank of the river and downstream of the dam. The investigated slope is shown in Fig. 1.

As seen in the figure, this slope has been designed, reshaped and vegetated, and no significant instability problems have been experienced for the last two years. However, long-term as well as short-term stability has been evaluated in this paper, based on the input parameters obtained from drained and undrained triaxial tests. The analyses have been performed using an advanced finite element program (PLAXIS) and simple limit equilibrium methods (GeoSlope). Finite element automatically identifies the most critical sliding mechanism and its factor of safety, having an advantage over limit equilibrium (Nordal & Glaamen 2004).

Even though the slope does not exhibit distinct soil layering by visual observation, three soil layers are used in PLAXIS and GeoSlope models. This is because of the different shear strength

Fig. 1 View of the slope from June 2003

parameters found for the samples taken from the two upper layers. The bottom layer is harder, compacted by overburden and mostly lies below the water level in the river. The test specimens were reconstituted close to the Standard Proctor maximum dry density. The authors would like to point out that a reconstituted sample can not attain its aging effect in the laboratory, and hence the obtained strength parameter values may probably somewhat on the lower side.

Similarly, the maximum grain size of the test samples was limited to 8 mm for the 54 mm diameter and 100 mm height specimen. This may yield a reduction in the strength as well. On the other hand, the strength parameters depend on large number of factors such as the void ratio, density and structure of soil, the effective stress level and the method of loading (Janbu 1973). The results from stability analyses presented herein are based on these investigated parameters, and they should be understood as qualitative parameters, where the aim has been to point out relative differences between the analysed slope conditions by limit and finite equilibrium methods.

2 UTILIZED METHODS FOR STABILITY ANALYSES

The stability evaluations in this paper are carried out by the software codes PLAXIS and GeoSlope, but also the simpler Direct method proposed by Janbu (1968). PLAXIS computes the factor of safety by a c-ϕ numerical reduction procedure. The GeoSlope software uses several methods, which are all based on limit equilibrium formulations, except for one method utilizing the finite element approach (Krahn 2004). Computation of the safety factor in GeoSlope is very fast and efficient, and the safety factors from various methods can be compared easily. Janbu's Direct method uses a set of stability charts to evaluate the stability of an idealized unit slope.

2.1 Analyses performed with PLAXIS

PLAXIS geotechnical software computes the factor of safety based on various models mostly related to stress-strain relationship. Both long-term and short-term safety evaluations, including earthquake effects on the slope, have been carried out using separate input parameters. The plane-strain Mohr-Coulomb model with 15 noded elements is used, based on both drained and undrained soil parameters.

The c-ϕ reduction method is applied for conventional stability evaluations, whereas a more advanced dynamic analysis has been performed to simulate the earthquake conditions. Since an earthquake is sudden and instantaneous, undrained soil parameters are used in the dynamic study. Two different groundwater level recordings, one representing dry, the other wet season conditions are defining the in situ pore pressures.

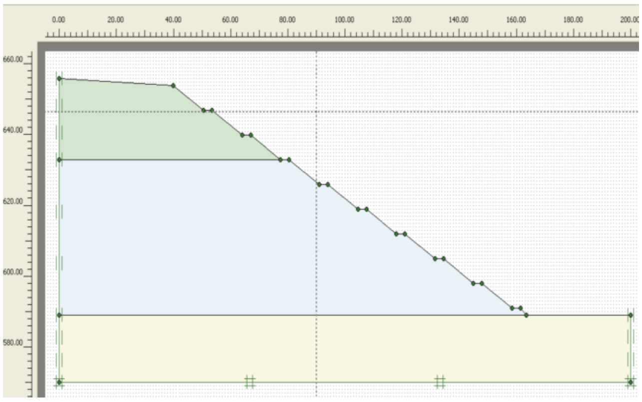

Fig. 2 Geometrical model used in PLAXIS simulation

The geometrical model in PLAXIS is made as shown in Fig. 2. This model is made with three soil layers D1, D2 and D3. The profile consists of 3m intermediate berm after 7 m vertical drop, the berm to berm slope being 1:1.5. The average slope inclination is 28^{o} and the total slope height is 65 m from the toe.

All the input parameters are given in Tables 1, 2 and 3. Some general soil parameters, partly used for classification and identification of the soils, and partly as input to PLAXIS, are listed in Table 1. The first two parameters in table 1 are from the Standard Proctor test.

Table 1 General soil parameters for PLAXIS

Soil	γ_d	γ	ν	E	k
D1	20.6	22.4	0.3	6	1.50
D2	20.6	22.4	0.3	6	0.86
D3	20.6	22.4	0.3	6	0.86

Units: γ & γ_d (kN/m^3) E (MPa) k (cm/day)

The key parameters in the slope stability analyses, the cohesion c and friction ϕ, are given in Table 2. The strength properties of soil layers D1 and D2 were determined from triaxial test, whereas the properties for D3 are assumed based on those for D1 and D2. The drained and undrained triaxial tests have generated different parameters, particularly regarding the cohesion.

Table 2 Effective strength properties of the soils

Soil	Drained (D)		Undrained (U)	
layers	c (kPa)	ϕ (^{o})	c (kPa)	ϕ (^{o})
D1	13.0	33	5.8	30
D2	13.5	34	6.2	32
D3	14.0	35	6.5	34

Extreme groundwater readings from piezometer recordings for year 2004 are presented in Table 3 (MMHEP 2004). The ground surface elevation (GSE) (see the table) relates to the slope profile where the piezometers are installed. These groundwater levels, corresponding to the dry and wet seasons, are defined in the PLAXIS calculations. in Stage construction.

Table 3 Groundwater recordings from 2004

GSE (m)	HGWL (m)	LGWL (m)
647	627	623
633	615	605
619	605	596

The calculation stages used for the analysis are given in Table 4. In calculation of the initial conditions, the groundwater level was located at the base and the initial stresses were run with $\sum$M-weight = 0 in the K$_o$-procedure in PLAXIS.

The tension cut-off defined in the Mohr-Coulomb model (*Advanced parameters*) has been deactivated for all the analyses presented in this paper. However, the safety factors obtained respectively from a 10 kPa activated and deactivated tension cut-off was compared, and no significant differences were found.

Table 4 Calculation stages in PLAXIS

Identification	Phase no.	Start from	Calculation	Loading input
Initial phase	0	0	N/A	N/A
✓ M-weight	1	0	Plastic	Total multipliers
✓ c-fi_no GW	2	1	Phi/c reduction	Incremental multipliers
✓ Low _GWL	3	1	Plastic	Staged construction
✓ c-fi _low_GWL	4	3	Phi/c reduction	Incremental multipliers
✓ High_ GWL	5	1	Plastic	Staged construction
✓ c-fi _high_GWL	6	5	Phi/c reduction	Incremental multipliers

As seen from the table 4, the M-weight = 1 is applied in the first calculation phase, and thereafter c-ϕ reduction stage follows for evaluation of the safety factor without groundwater in the slope. In the next stage, the groundwater level is raised to the dry season level, and again c-ϕ reduction is run to calculate the safety level for dry season conditions. Similarly, the last two stages are used to define high groundwater surface in wet season, and there after to determine the factor of safety for this situation.

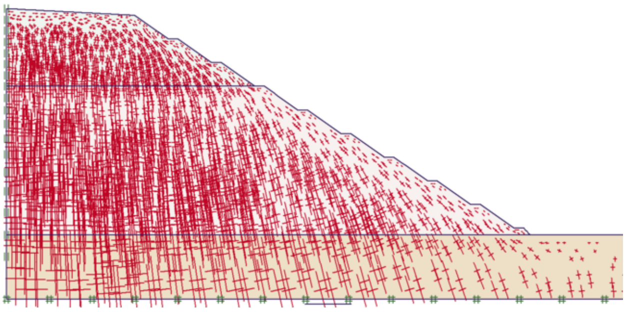

Fig. 3 Total stresses due to gravity (M-weight)

The total stresses generated by PLAXIS after the M-weight calculation phase is given in Fig. 3. The major principal stresses are oriented parallel to the inclined surface, illustrating a realistic stress situation in the sloping ground.

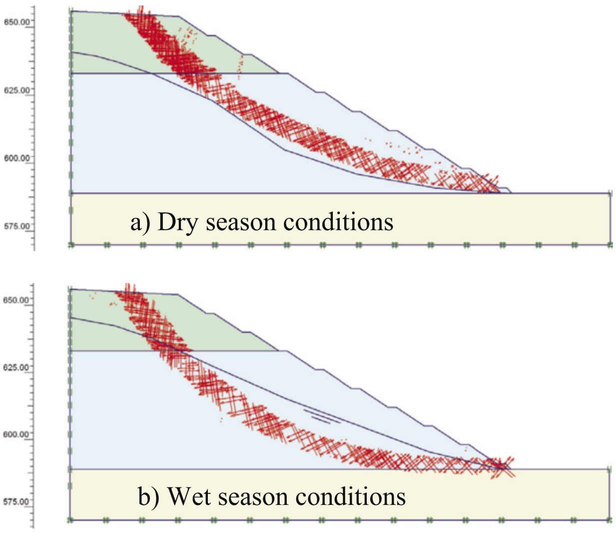

Fig. 4 Failure surfaces in PLAXIS (D)

The failure surfaces generated from the analyses, using drained (D) parameters, are given in Fig. 4 a) and b). The failure in a) is flatter with a larger radius of the slip circle, and occurs above the groundwater surface, In analysis b), the slip circle is almost in its entity below the water surface, being deeper with a smaller radius. The common feature of both cases is that both slip surfaces hit the toe of the slope. The rise of the water surface apparently moves the slip surface further inside the slope.

A somewhat different failure surface is obtained from the analyses using undrained (U) soil parameters as shown in Fig. 5 a). The failure representing dry season conditions is even flatter and does not reach up to the toe of the slope. This may be explained by the difference in cohesion between the two cases, (U) and (D). The failure geometry in Fig. 5 b) is similar in shape to the failure zone seen in Fig. 4 b). Both surfaces move into the slope as the groundwater rises during the wet season. This causes reduction in the safety level and is discussed below.

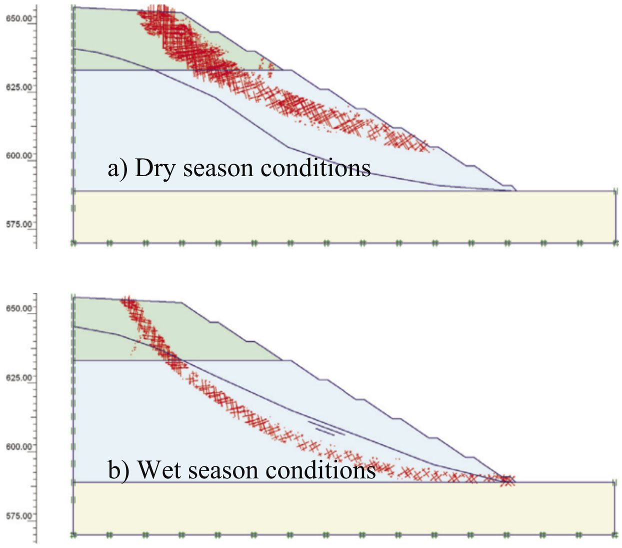

Fig. 5 Failure surfaces from PLAXIS computations (U)

The safety factors obtained from drained and undrained parameters are plotted in Fig. 6. The influence of the groundwater is obvious from both analyses. In the analyses with drained parameters, the safety factor drops from 1.45 to 1.27, when the conditions shift from dry to wet season groundwater levels. Using undrained material parameters, the factor of safety even drops as low as 1.12 for wet season conditions.

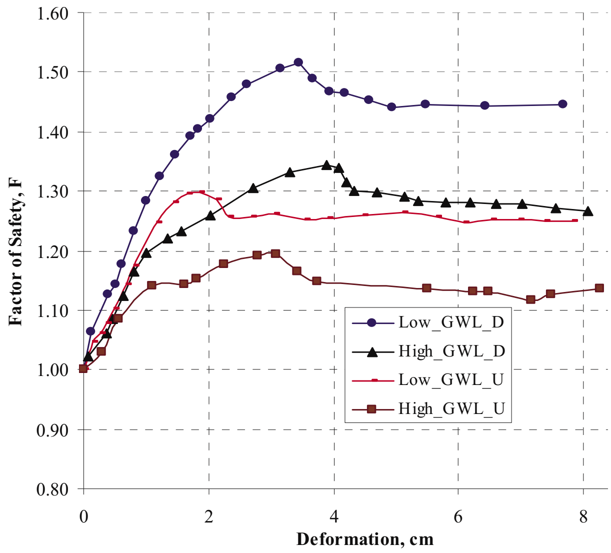

Fig. 6 Factors of safety using drained and undrained material parameters

Since the permeability of this soil is very low ($1–2.10^{-5}$ cm/s), rapid load impacts, as those from earthquakes, can create undrained conditions in the soil. Such instantaneous loading may be best represented by the conditions simulated in an undrained triaxial test. If such situations happen to exist in this slope on the unfavourable direction, it will be potentially unstable since the safety margin obtained from the undrained parameters is very low. The pseudo-static analyses carried out in PLAXIS (not presented here) showed that the slope attains equilibrium condition for an earthquake coefficient α <0.1g which is lower than the limiting design value of 0.25g for this area. However, the minimum safety factor, obtained from PLAXIS for drained material parameters, is close to 1.3, which is the minimum value accepted for effective stress analysis in Scandinavian countries. This analysis shows a stable slope.

2.2 Dynamic analyses with PLAXIS

The slope has also been studied by introducing dynamic loads due to earthquakes by means of prescribed horizontal displacements that are imposed at the base of the model. Absorbent boundary conditions are applied at the far vertical boundaries to absorb outgoing waves. Standard earthquake boundaries can directly be applied from the loads menu (PLAXIS 2004). The model used for dynamic analysis is shown in Fig. 7. The acceleration profile which shows the data provided from PRAXIS is given in Fig. 8. This accelerogram has been used in the dynamic analyses. Among other outputs from dynamic analyses, the time-displacement and time-acceleration curves can be obtained for any point in the slope.

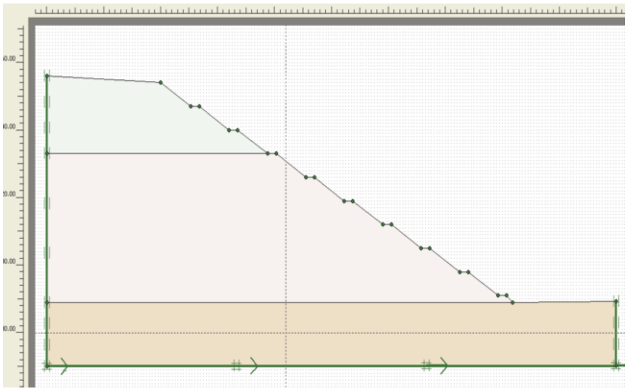

Fig. 7 Geometric model for dynamic analysis with PLAXIS

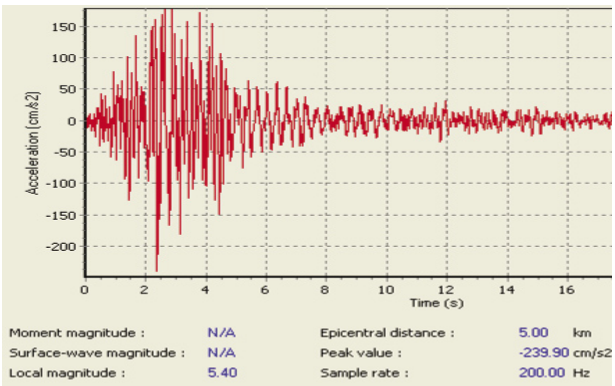

Fig. 8 Accelerogram for dynamic analyses (PLAXIS 2004)

Two cases are considered in dynamic analysis: One with 50 mm and another with 100 mm prescribed displacements. Since the action of earthquake is instantaneous, the undrained soil properties are best suited for such analysis. The physical damping in the soil is simulated by means of Rayliegh damping factors ($\alpha = \beta = 0.01$) and stiffer and constant Young's modulus (30 MPa) have been used in dynamic calculations. The calculation stages for the 50 mm option are illustrated in Table 5.

Table 5 Calculation stages in PLAXIS dynamic analysis

Identification	Phase no.	Start from	Calculation	Loading input
Initial phase	0	0	N/A	N/A
✓ M-weight	1	0	Plastic	Total multipliers
✓ GW_dry season	5	1	Plastic	Staged construction
✓ pres displ 5 cm	2	5	Dynamic analysis	Total multipliers
✓ GW_wet season	3	1	Plastic	Staged construction
✓ pre disp 5cm	4	3	Dynamic analysis	Total multipliers

Fig. 9 shows the horizontal deformation versus the dynamic time for a 10 sec interval. In this figure, a permanent deformation of nearly 600 mm is observed at the middle of the slope during the wet season. This deformation is due to the prescribed (induced) displacement of 100 mm. The graph in the middle refers to the deformation occurring in the dry season for 100 mm induced displacement. This overlaps the curve representing the 50 mm induced displacement for the wet season.

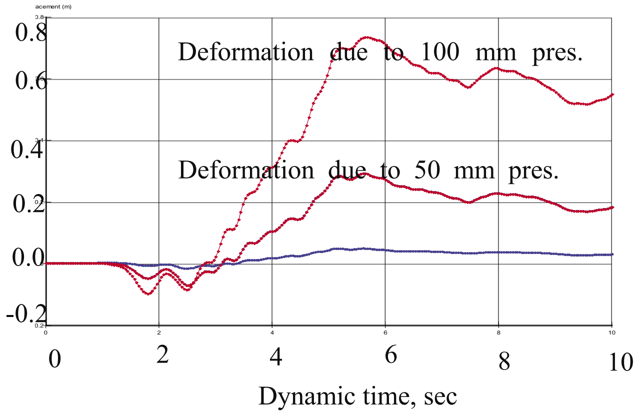

Fig. 9 Horizontal deformation, Ux (m) from PLAXIS

Dynamic shaking from an earthquake will cause permanent deformations in the slope. A moderate input to base displacement amplifies to large deformations in the slope. The calculations are performed with undrained parameters and zero dilatancy angle. During shaking, large pore pressure in the order of 1000 kPa is computed by PLAXIS. Certainly suction in the porewater develops during earthquakes and large values could be realistic for fine grained, homogeneous soils. However, cavitations will occur in fissures in the clay and in coarser soils and limit the allowable suction to a level of about 100 kPa. If this restriction is introduced into PLAXIS, the soil will fail and unlimited deformations will occur. It is strongly believed that the given earthquake would cause failure if the direction of waves is outside the slope profile, i.e. towards the river valley.

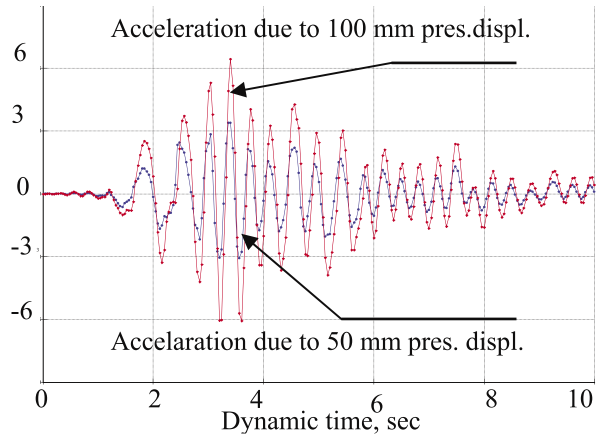

Fig. 10 Horizontal acceleration, a_x (m/s^2) from PLAXIS

From the dynamic analysis it is seen that the induced displacement of 100 mm and a wet season groundwater conditions together have produced a maximum acceleration of 6 m/s^2 after 3 sec of ground excitation. However, this two third of gravity lasts for very short time and damps out gradually as shown in Fig. 10.

2.3 Analyses with GeoSlope

GeoSlope is a modern limit equilibrium based software which includes several components. Among them is SLOPE/W, which is used for stability calculations. The SLOPE/W algorithm solves two equations: One with respect to moment equilibrium; the other with respect to horizontal force equilibrium. This routine computes the factor of safety for many available equilibrium methods (Krahn 2004). Some of these methods are briefly described below.

The *Ordinary method (OM, 1)* satisfies moment equilibrium and neglects the interslice forces. The force polygon does not close in this method, and thus gives the factor of safety on lower side (GeoStudio 2004). *Bishop's simplified method (BM, 2)*, satisfies only moment equilibrium. This method considers the normal forces and neglects the shear forces between the slices. The factor of safety in this method is computed by the equilibrium Equation (1), which iterates solution for factor of safety, consistently on a trial and error approach (Aryal, et al. 2004).

$$F = \frac{R.\sum \dfrac{(c' + (p-u)\tan\phi').b}{m_\alpha}}{\sum pb.x} \qquad (1)$$

where $m_\alpha = \cos\alpha + \dfrac{\tan\phi'}{F}.\sin\alpha$

Here, R is the radius of the slip surface, c' and ϕ' are cohesion and soil friction, p is the total normal stress, u is the pore pressure, b is the slice width, x is the moment arm for each slice and α is the slope angle at the base of the slice.

Janbu's simplified method (JM, 3) is identical to Bishop's method, but it satisfies horizontal force equilibrium. Like Bishop's method, Janbu's simplified method includes the interslice normal forces and neglects the shear forces. The horizontal force equilibrium Equation (2) includes Janbu's correction factor f_o, which takes account of the interstice shear forces and gives high precision of safety depending on slip surface (Aryal, et al. 2004). It looks like that GeoSlope utilizes the equilibrium relation without considering this correction factor.

$$F = f_o.\frac{\sum \dfrac{(c' + (p-u)\tan\phi').b}{n_\alpha}}{\sum p.b} \qquad (2)$$

where $n_\alpha = m_\alpha \cos\alpha$

The Morgenstern-Price method (M-P, 4) considers both normal and shear interslice forces, and satisfies both force and moment equilibrium. This method allows for a variable relationship between the interslice shear and normal forces (Krahn, 2004).

Limit equilibrium methods are used to determine factor of safety by the ratio of average shear strength along a critical shear surface to the average equilibrium shear stress mobilised along the same surface. The accuracy depends on the assumptions made and upto ± 6% variations may result among the well established limit equilibrium methods (Nordal & Glaamen 2004). The safety factors obtained from SLOPE/W by use of the same drained material properties as in PLAXIS are presented in Fig. 11 a) and b) for the given analyses conditions. The safety factors found from some of the methods in GeoSlope and PLAXIS are similar. Even though, the results from Bishop method, 2) and Morgenstern-Prince method, 4) in GeoSlope are identical to each other, these methods slightly overestimate the safety factor compared to PLAXIS. Moreover, Janbu's simplified method gives closer results compared with the PLAXIS.

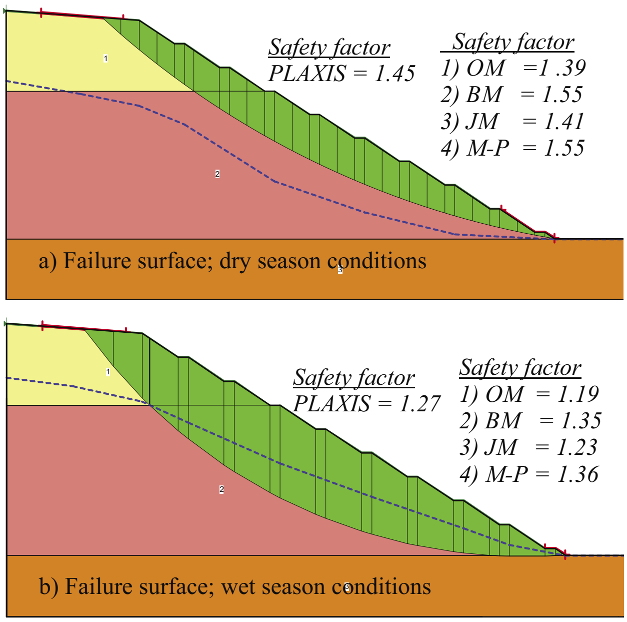

Fig. 11 Failure surfaces and safety factors (PLAXIS and GeoSlope)

Free body diagrams and force polygons for slice no 12 are presented in Fig. 12 a) and b) for the Jambu's simplified and Morgenstern-Price methods to compare the forces. Both methods seem to have good closing of the force polygons.

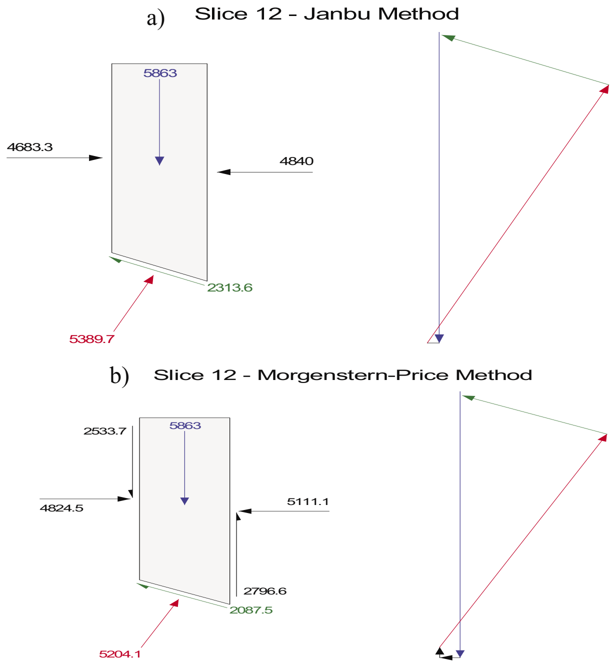

Fig. 12 Free body diagram and force polygons from methods 3) and 4) (wet season conditions, no earthquake)

As in PLAXIS, the undrained soil parameters and an equivalent horizontal acceleration component of α = 0.25g are used to model the seismic conditions in GeoSlope. The results and the failure surfaces are presented in Fig. 13. The safety factors given in Fig. 13 a) and b) relate to the dry and wet seasonal conditions. The slope seems to be unstable in both conditions while considering the acceleration due to earthquake shakings. These figures further indicate that the degree of instability of the slope becomes higher in wet conditions than in dry ones.

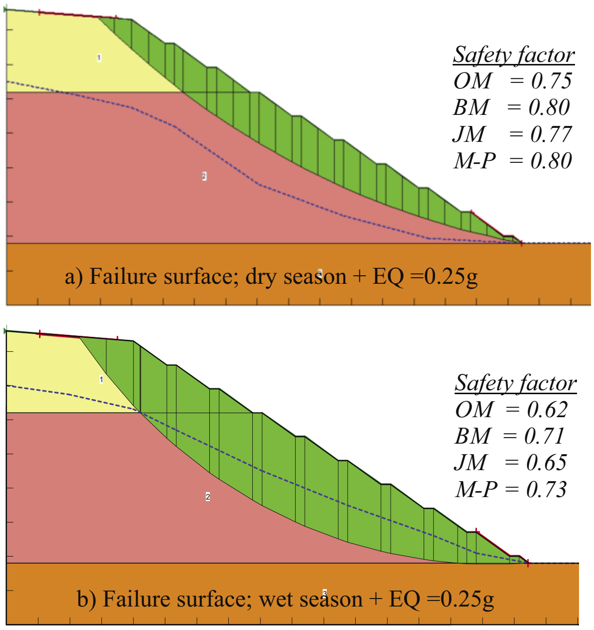

Fig. 13 Failure surfaces and safety factors (seismic conditions)

2.4 Analyses with Janbu's Direct method

Janbu's Direct method is quite convenient for checking the stability of an idealised slope. The analysis can be carried out quickly, using the stability charts and derived relations by Janbu (1968). This method is applied here to evaluate the safety of the same slope of 65m height and 1:1.87 (β= 28^0) inclination. Since the failure surface mostly lies in the D2 layer, drained shear strength parameters for this layer (c = 13.5 kPa and $\phi = 34^0$) and soil densities obtained from the Standard Proctor test (γ_d = 20.6 kN/m^3 and γ = 22.4 kN/m^3) are used in the computations. A sensitivity study has been carried out with changing the average pore pressure ratio, ($r_u = u/\gamma H$, where H is the slope height), on the slope and the computed safety factors against to the average r_u-values are presented in Fig. 14

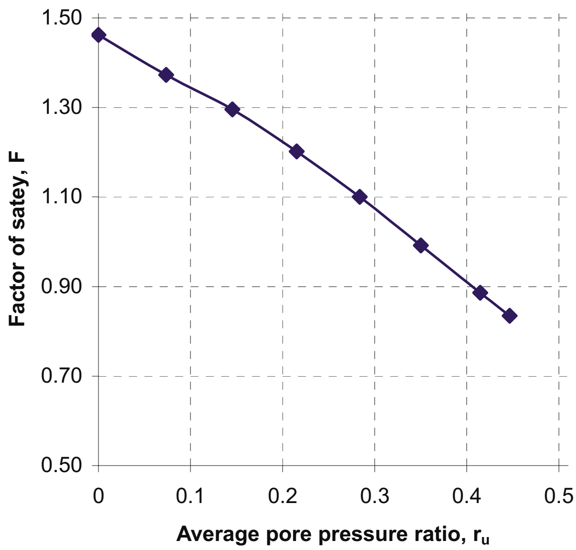

Fig. 14 Influence on safety factor from groundwater variations

In this analysis, a significant variation in the safety factor has been found with the increasing average pore pressure ratio in the slope. The computed factor of safety based on an average pore pressure on the sliding surface convergences the results close to the other presented methods. A full groundwater conditions drops the safety factor below the equilibrium state and a dry condition gives the safety factor of 1.45 same as in PLAXIS.

3 CONCLUSIONS

The safety factors obtained from various methods reveal that the slope is stable in long-term conditions, except for the sudden instantaneous loads caused by an earthquake impact. The analyses carried out by PLAXIS, GeoSlope and Janbu's Direct method, using drained strength parameters show a significant reduction of the safety against failure when the groundwater level increases, eventually corresponding to wet season conditions. Monitoring the proper function of drainage systems is hence very important to limit the groundwater rise in the slope.

The safety margin obtained from the analyses with undrained soil parameters indicates that the slope is at the verge of failure if en earthquake would occur. The results obtained from the GeoSlope analyses are far below the equilibrium requirement for the earthquake conditions, equivalent to 0.25g horizontal acceleration. This instability will be the case only if an earthquake generates vibrations in the most unfavourable direction in the slope, i.e. the vibrations towards the river side. PLAXIS analyses also show unstable situation in pseudo-static loading conditions using α = 0.1g and large permanent deformations have been found from the dynamic analyses. The wet season groundwater levels combined with an earthquake will be the most critical situation which indicates a potential risk for slope instability.

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