Chapter 5

Analysis and Comparison the Slope Stability Analysis Methods

5.1 Introduction

In this chapter, the slope stability analyses by computer programs of slope models and landslides data previously mentioned in chapter 3 and 4 are described. The analytical results of the normal forces by each slope stability analysis method are compared with the normal forces from the slope model tests. Through the study on many slope failures in Northern Thailand, the applicability of various slope stability analysis methods are revealed. The factor of safety obtained by each slope stability analysis methods are considered and compared with the typical value of safety factor. Furthermore, a comparison of theory and applications in slope stability problem is also performed in the section 5.4.

5.2 Slope stability analysis of slope models

In the analysis process by computer programs, which are programmed and modified by Assoc. Prof. Kanji Kondo, the analysis condition of the slope is assigned to be the same condition as the model tests. Base on the basis of theory, at any point on the slip surface has the same value of safety factor (i.e. the factor of safety is taken to be the same for each slice). Since the separation of the slip plane of the slope model and the condition of the slip surface is not always in the plastic state, the factor of safety for each slice is also different. The mobilized shear strength parameters for each slice are considered in the slope stability analysis to make a comparison to the real condition. There are 5 methods adopted in the comparison; Fellenius method (1936), Simplified Janbu method (1955), Spencer method (1967), Slice spring method (1999), and Rigid bodies-spring method (1977).

5.2.1 Results of the stability analysis

From the analyses of model 1, model 2 and model 3 in both case (a) and (b), the results of the normal forces for each slice are shown in table D.1-D.3 for Fellenius method, table

D.4-D.6 for Simplified Janbu method, table D.7-D.9 for Spencer method, table D.10-D.12 for Slice spring method, and table D.13-D.15 for Rigid bodies-spring method. Fig. 5.1-5.5 show the graphs of the normal forces in each slice. The percentage of difference can calculate from equation 5.1.

$$\%difference = \frac{N_{analyzed} - N_{measured}}{N_{measured}} x100\% \qquad (5.1)$$

And the average percentages of difference obtained from various slope stability analysis methods are demonstrated in table 5.1.

From the results of these analyses and the comparison with the measured normal forces in the model test, this may conclude that:

Fellenius method, When the load at the top of the slope increases, the normal force increases in slice 4 only. But the force of slice 1, 2 and 3 are constant at any bearing load. Most of the results are highly undervalued from the measured normal forces in the model tests. Because the assumptions about the inter-slice force do not satisfy the static force equilibrium, the normal forces are calculated by equation 2.5 (see in chapter 2). So the self-weight of soil and the surface loading are separately transferred for each slice. Thus, the normal force of slice 1, 2 and 3 are not changed even the loads increase. The percentages of difference are valued in 5-36% which is very alterable. The error may be as large as 60% (Whitman and Bailey, 1967) which that of some slices illustrate much values. However, the average percentages of difference obtained by Fellenius method are 10.27% for case (a) and 22.91 % for case (b).

Simplified Janbu method, When the loads at the top of slope increase, the normal forces increase in slice 1 and 4 but those of slice 2 and 3 decrease a little. Because of the neglect of the inter-slice shear force in the assumption, the forces are rarely transferred to its slice. The normal forces of the inside slice (i.e. slice 2 and 3) are not increase, but that slightly increases in the lowest slice (i.e. slice 1). However, the normal force of slice 4 is still increased by the direct surface loading. The difference between the analyzed and measured normal forces are rather high, 5-30%, but not higher than that by Fellenius method. The average percentages of difference obtained by Simplified Janbu method are 9.01% for case (a) and 17.83% for case (b).

Spencer method, Since Spencer(1967) assumes the constant relationship between the magnitude of the inter-slice shear and normal forces, the results of the normal force by this method increase in every slices, especially in slice 4 which directly obtained the forces from the surface loading. Nevertheless, there is still much difference between the analyzed and measured normal forces about 5-28% which is slightly smaller than that by Simplified Janbu method. The average percentages of difference obtained by Spencer method are 8.89% for case (a) and 16.64% for case (b).

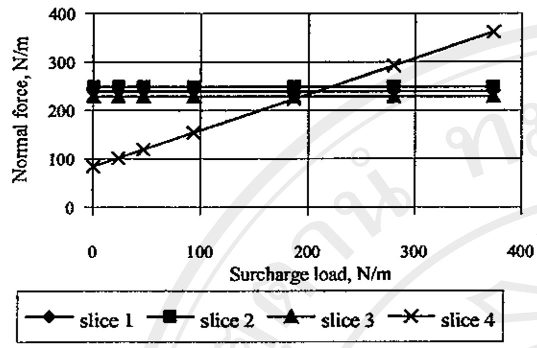
Slice spring method, When the loads at the top of slope increase, the normal forces increase in every slice which the trend of the normal force value is similar to that of the measured one. But at the small surface loading of case (b), the results of the analysis cannot be obtained. There is small error, 3-12%, of the results obtained from Slice spring method to the measured one. The average percentages of difference obtained by this method are 6.20% for case (a) and 8.23% for case (b).

Rigid bodies-spring method, As the concept of discrete element of soil continuum (e.g. Finite element method), the forces are transferred to all discrete units. The values of the normal forces are very close to those of Slice spring method and increase in the same direction as those of measured one when the surface loadings increase. The errors of the calculated to the measured normal forces are quite small, 3-14%. The average percentages of difference are 6.95% for case (a) and 9.44% for case (b)

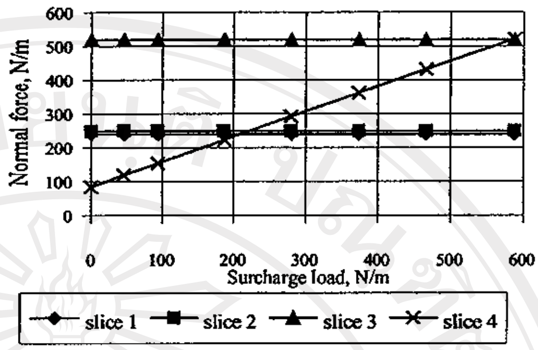
According to the results of the normal forces analyzed by various slope stability analysis methods and the percentage of error in the table D.1–D.15, the graph of the relationship between the surface loading and the percentage of difference are shown in fig. 5.6 and fig. 5.7. From fig. 5.6, for case (a) (i.e. slope without the anchoring force) the graphs are very different. It is shown that the failure plane, which has the lowest value of factor of safety, occurred inside the sliding mass. In case (b) (i.e. slope attached the anchoring force), the graph of 3 models in fig. 5.7 are shown in the same direction. When the surface loads increase, the graphs are gradually decreased to the stable level. At the point near to the failure time, the differences of difference of any methods are smaller than those at the stable time.

Model 1 (slope angle = 15.0 degrees)

case (a) slope without the anchoring force

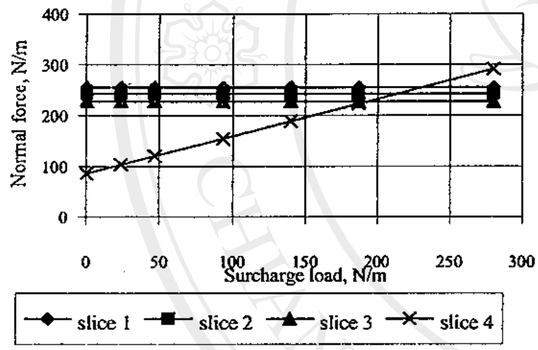


case (b) slope attached the anchoring force

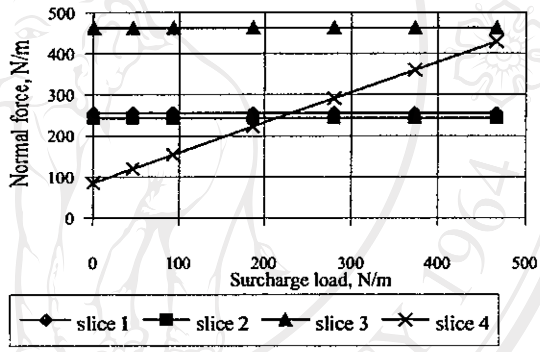


Model 2 (slope angle = 17.5 degrees)

case (a) slope without the anchoring force

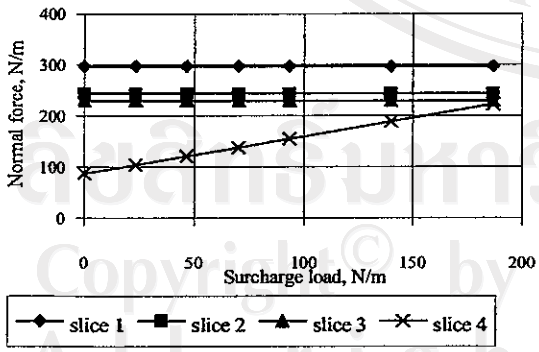


case (b) slope attached the anchoring force



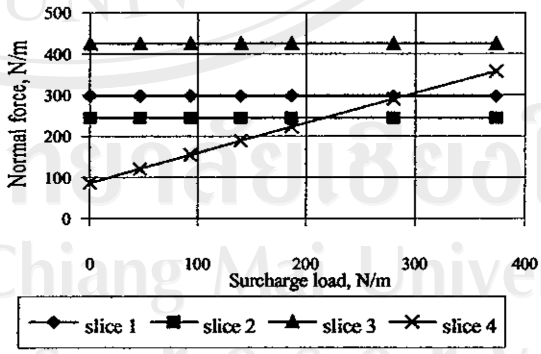
Model 3 (slope angle = 20.0 degrees)

case (a) slope without the anchoring force



B=20cm.

case (b) slope attached the anchoring force

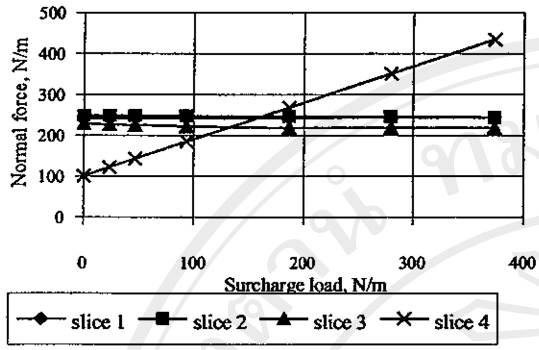


B=20cm.

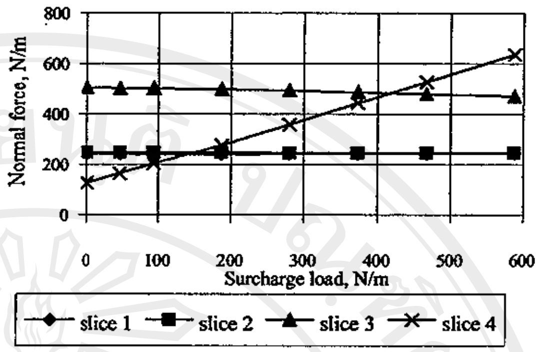
Fig. 5.1 The graphs of the normal forces obtained by Fellenius method in each slice

Model 1 (slope angle = 15.0 degrees)

case (a) slope without the anchoring force

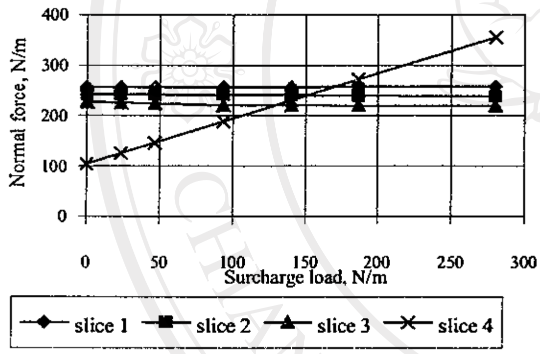


case (b) slope attached the anchoring force

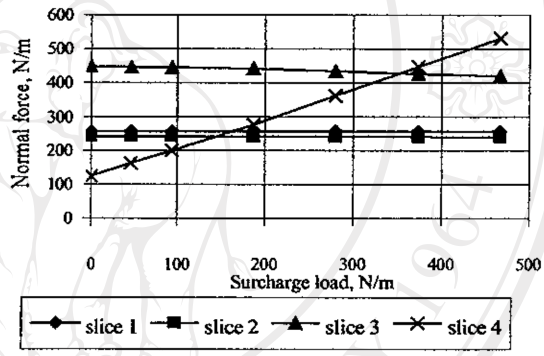


Model 2 (slope angle = 17.5 degrees)

case (a) slope without the anchoring force

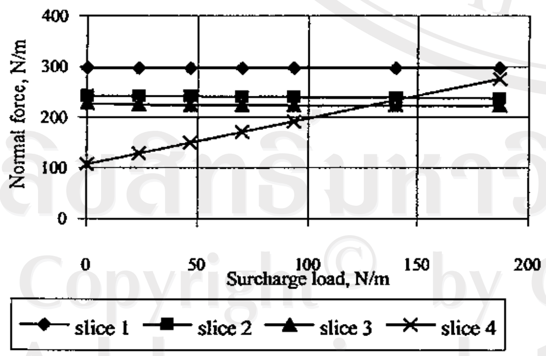


case (b) slope attached the anchoring force



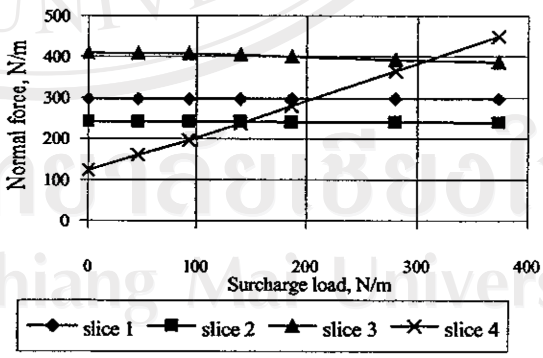
Model 3 (slope angle = 20.0 degrees)

case (a) slope without the anchoring force



B=20cm.

case (b) slope attached the anchoring force

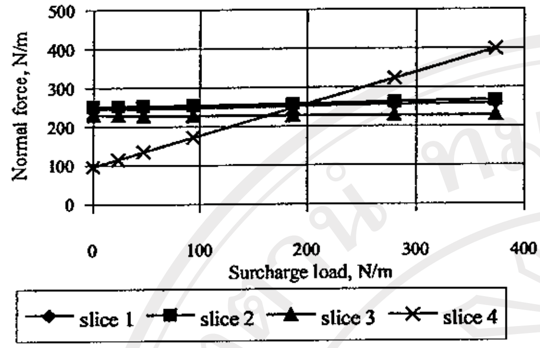


B=20cm.

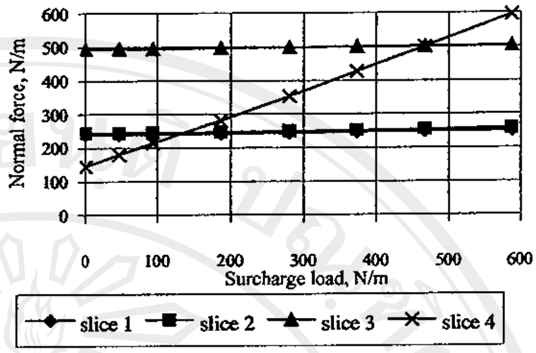
Fig. 5.2 The graphs of the normal forces obtained by Simplified Janbu method in each slice

Model 1 (slope angle = 15.0 degrees)

case (a) slope without the anchoring force

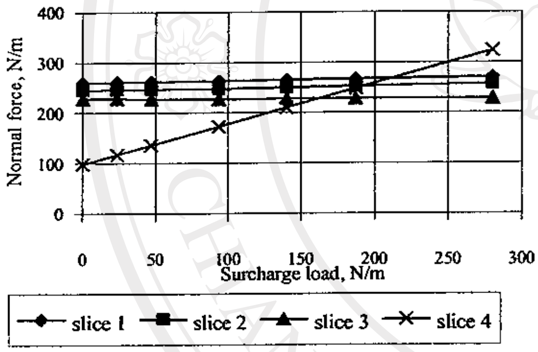


case (b) slope attached the anchoring force

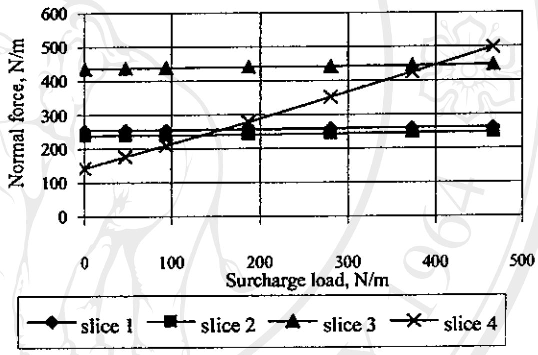


Model 2 (slope angle = 17.5 degrees)

case (a) slope without the anchoring force

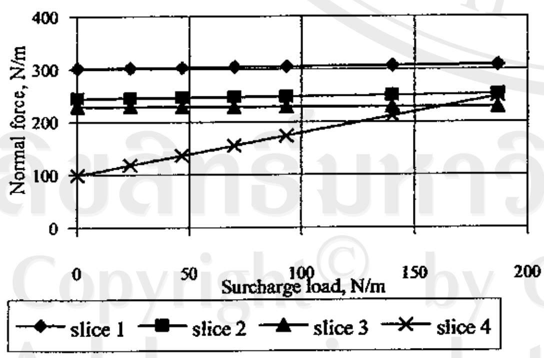


case (b) slope attached the anchoring force



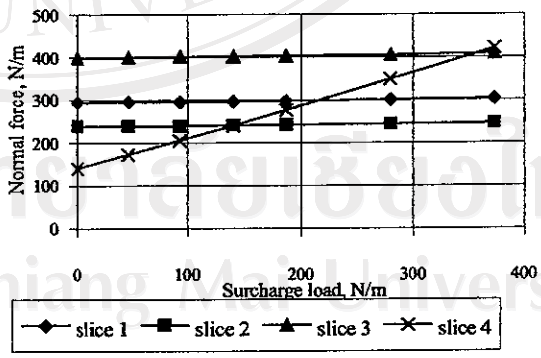
Model 3 (slope angle = 20.0 degrees)

case (a) slope without the anchoring force



B=20cm.

case (b) slope attached the anchoring force

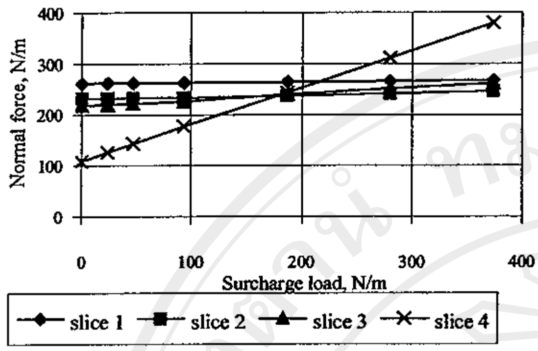


B=20cm.

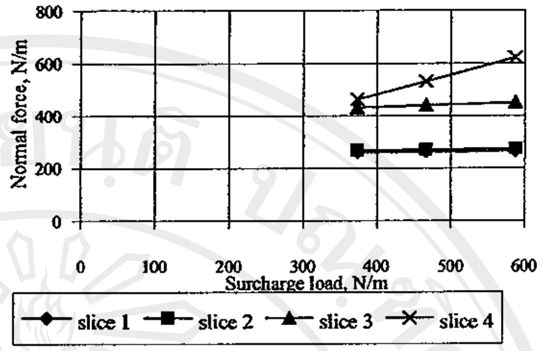
Fig. 5.3 The graphs of the normal forces obtained by Spencer method in each slice

Model 1 (slope angle = 15.0 degrees)

case (a) slope without the anchoring force

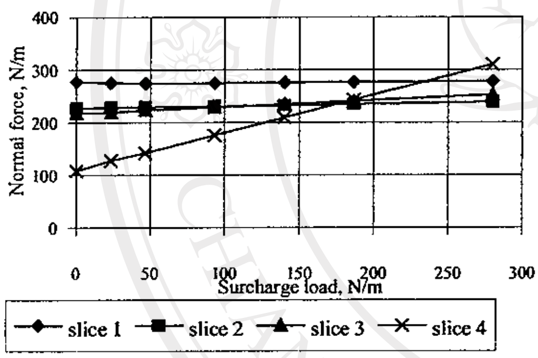


case (b) slope attached the anchoring force

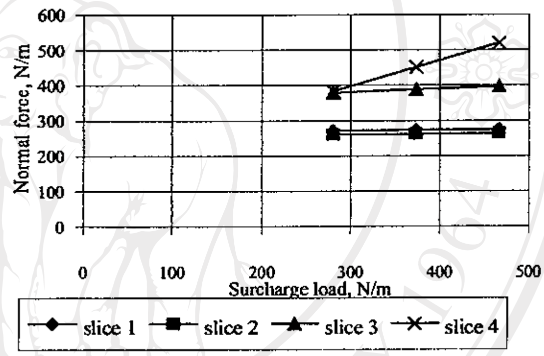


Model 2 (slope angle = 17.5 degrees)

case (a) slope without the anchoring force

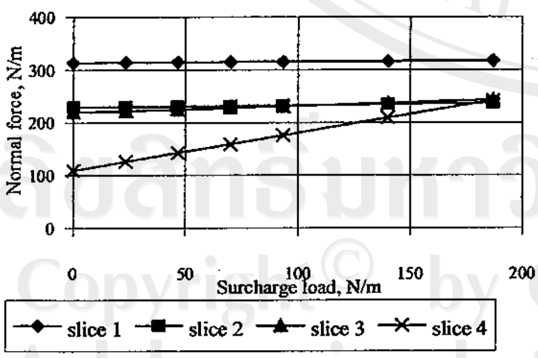


case (b) slope attached the anchoring force

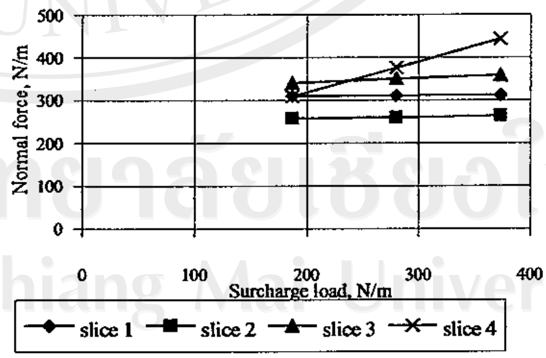


Model 3 (slope angle = 20.0 degrees)

case (a) slope without the anchoring force



case (b) slope attached the anchoring force

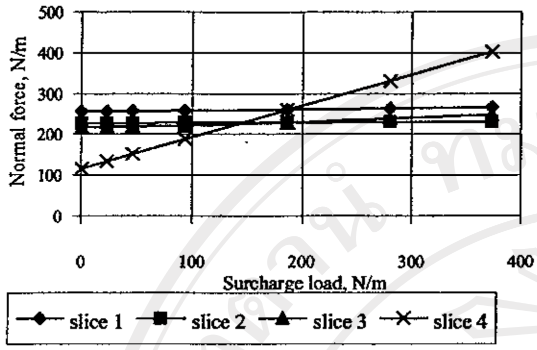


B=20cm. B=20cm.

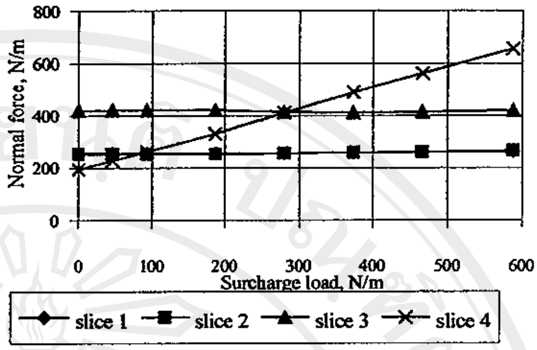
Fig. 5.4 The graphs of the normal forces obtained by Slice spring method in each slice

Model 1 (slope angle = 15.0 degrees)

case (a) slope without the anchoring force

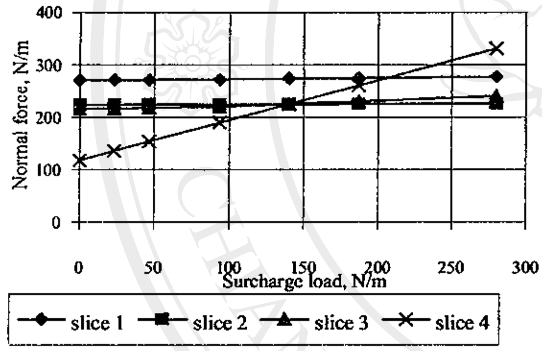


case (b) slope attached the anchoring force

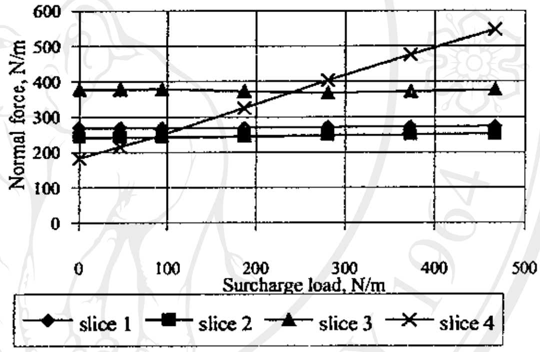


Model 2 (slope angle = 17.5 degrees)

case (a) slope without the anchoring force

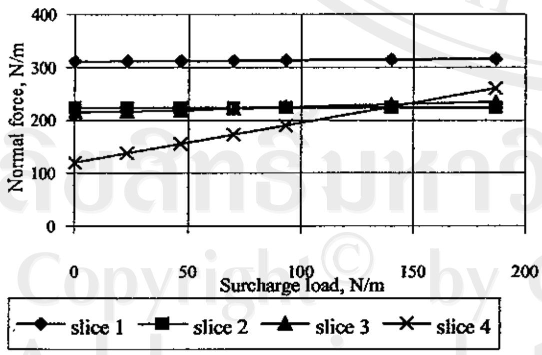


case (b) slope attached the anchoring force



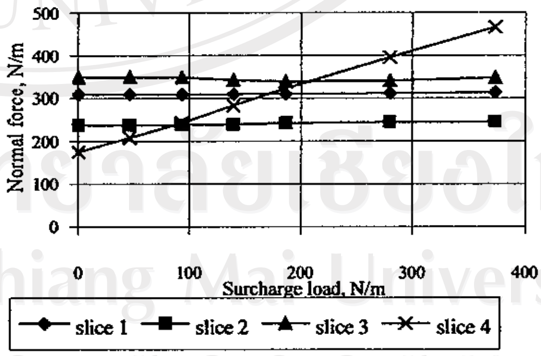
Model 3 (slope angle = 20.0 degrees)

case (a) slope without the anchoring force



B=20cm.

case (b) slope attached the anchoring force



B=20cm.

Fig. 5.5 The graphs of the normal forces obtained by Rigid bodies-spring method in each slice

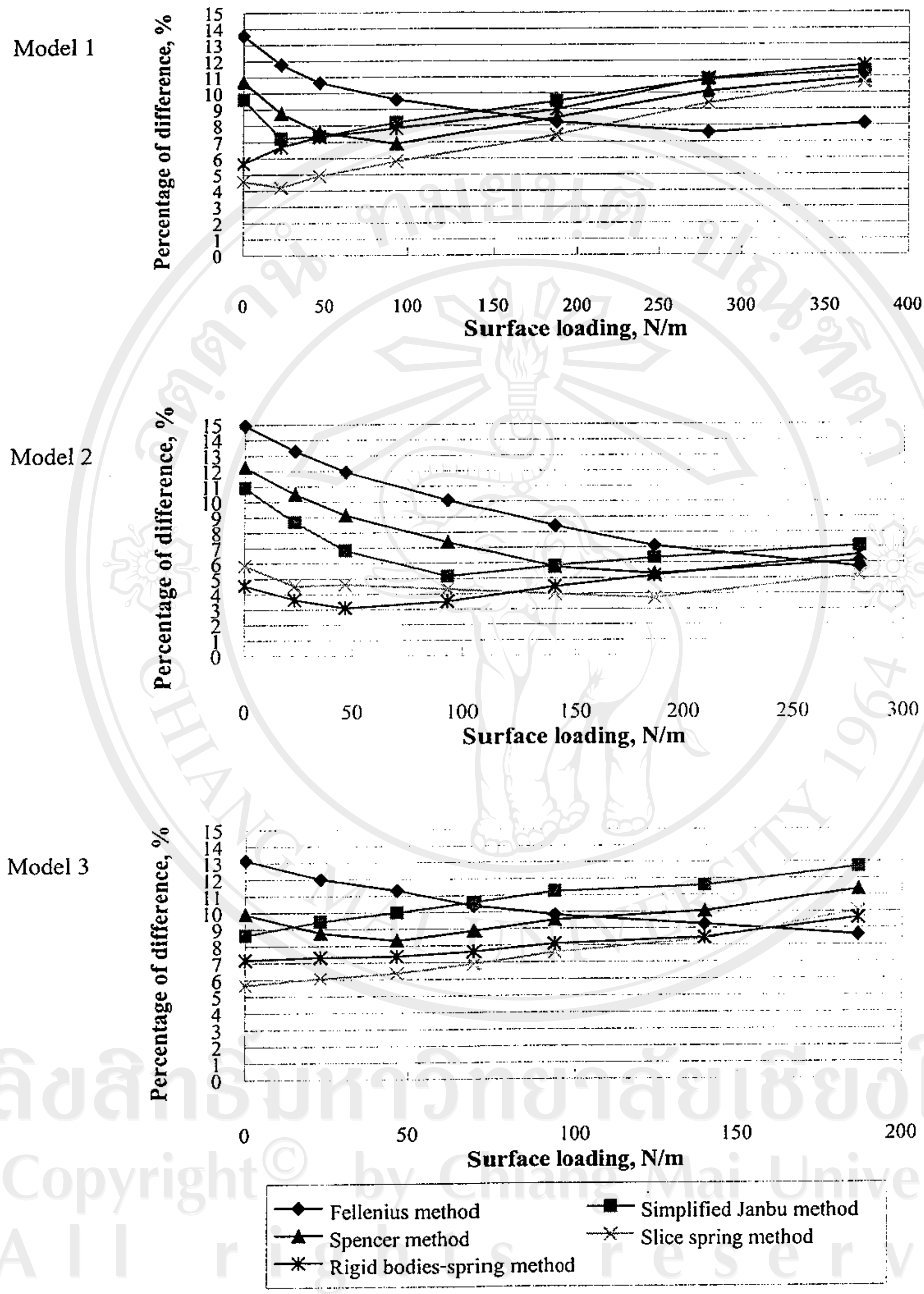


fig. 5.6 The relationship between the surface loading and the percentage of difference of all methods for case (a) : slope without the anchoring force

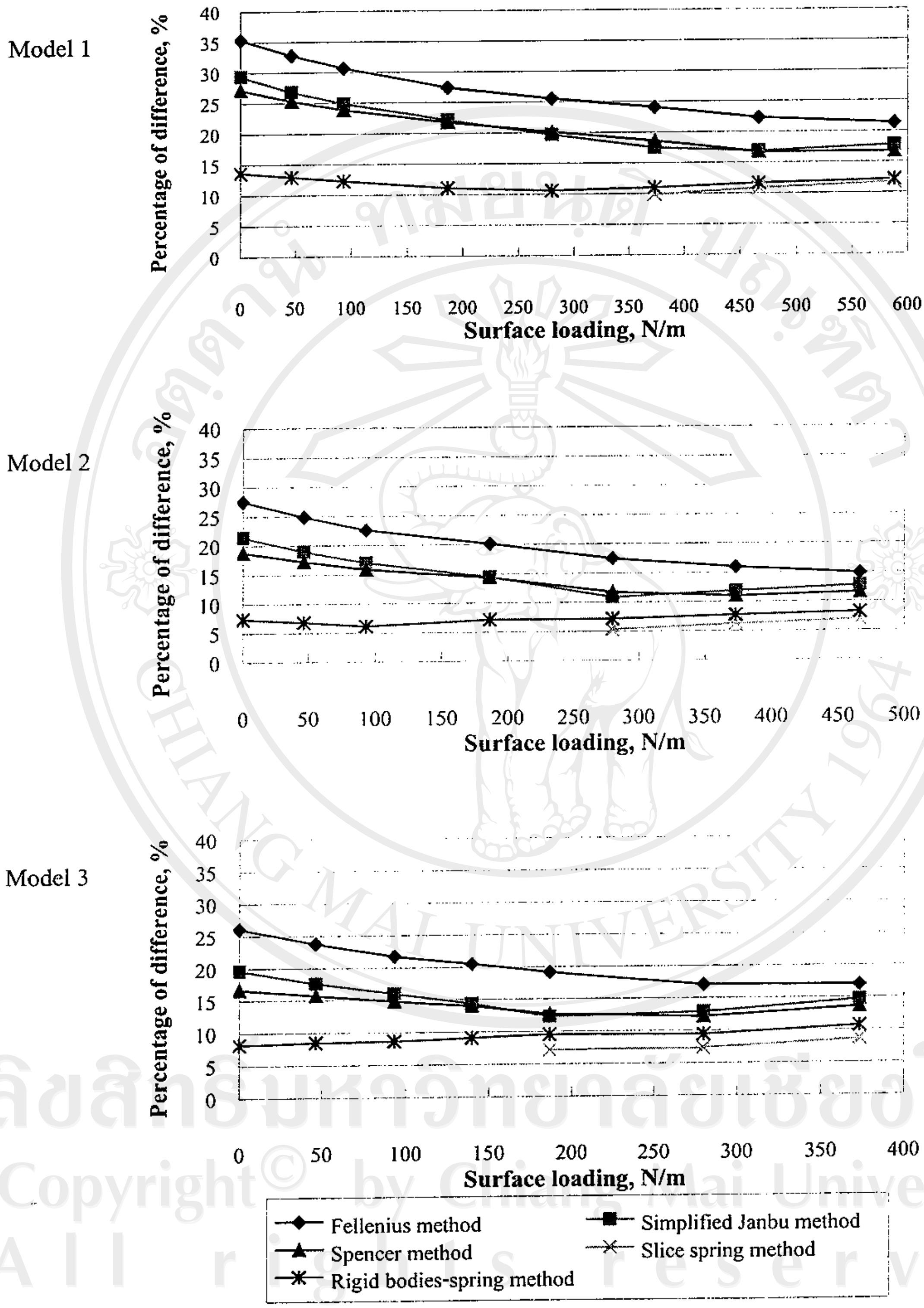


fig. 5.7 The relationship between the surface loading and the percentage of difference of all methods for case (b) : slope attached the anchoring force

Table 5.1 The average percentage of difference obtained by comparison between various slope stability analysis methods and the measured data

(a) Case a : Slope without the anchoring force

Slope model	Inclination angle of slope, β (degrees)	Percentage of difference obtained from slope stability analysis methods (%)				
		Fellenius method	Simplified Janbu method	Spencer method	Slice spring method	Rigid bodies-spring method
1	15.0	9.93	9.15	9.07	6.71	8.44
2	17.5	10.22	7.27	8.05	4.60	4.43
3	20.0	10.66	10.61	9.55	7.29	7.97
Average		10.27	9.01	8.89	6.20	6.95

(b) Case b : Slope attached the anchoring force

Slope model	Inclination angle of slope, β (degrees)	Percentage of difference obtained from slope stability analysis methods (%)				
		Fellenius method	Simplified Janbu method	Spencer method	Slice spring method	Rigid bodies-spring method
1	15.0	27.45	21.88	21.29	10.80	11.91
2	17.5	20.49	15.33	14.37	6.16	7.22
3	20.0	20.78	15.37	14.27	7.73	9.18
Average		22.91	17.53	16.64	8.23	9.44

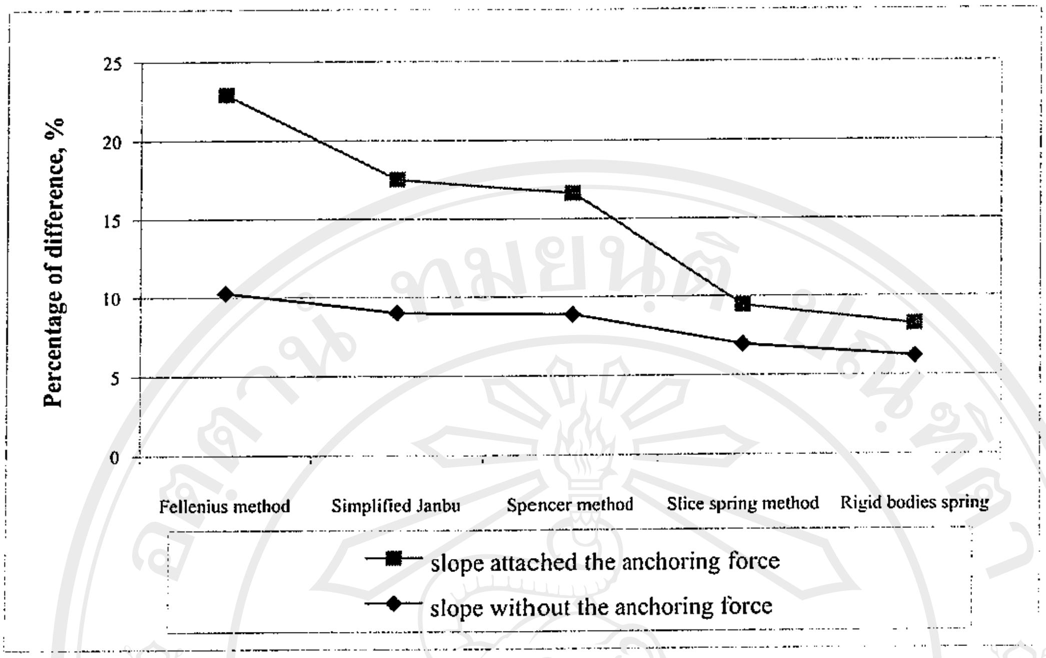


fig. 5.8 The graph of the average percentage of difference obtained by each methods

5.2.2 Discussion of the analytical results

From the study of the slope stability analysis methods by analyzing and verifying the calculated normal forces and the measured normal forces of the slope model, it is found that Slice spring method and Rigid bodies-spring method are more suitable for the slope with non-circular failure surface than Spencer method, Simplified Janbu method and Fellenius method. The ordinary method of slices shows very big difference from the actual values if comparing to other methods. As the results of the analysis, this could be divided various slope stability analysis methods into 3 groups.

i) Low accurate group (Fellenius method)

Since Fellenius ignores the inter-slice force, Fellenius method gives much difference in results from the actual values and sometimes this may be lead to an underestimate of the results of the normal forces by as much as 60% (Whitman and Bailey, 1967).

ii) Moderate accurate group (Simplified Janbu method and Spencer method)

Spencer method gives a little better accuracy than Simplified Janbu method, and both of them are more accurate than Fellenius method. Although the assumptions on the inter-slice force of Simplified Bishop method, Simplified Janbu method, Janbu's rigorous method, Spencer method and Morgenstern-Price method are different, but all of these methods have the similar form of the normal force equation (Fredlund and Krahn, 1977). These methods, therefore, can be classified in this group. However, the Simplified Bishop method is merely suitable for a homogeneous soil slope with circular shape of failure surface (Cheng, 1997).

iii) High accurate group (Slice spring method, Rigid bodies-spring method)

Even though, Slice spring method based on method of slices and limit equilibrium method, but this method utilizes the springs and sliders to represent the characteristic of elastic and plastic of soil, and determines the inclination angle of the inter-slice forces from the displacement of slices (Kondo et al., 1999). Slice spring method, then, gives a high accuracy than other methods of slices, as well as Rigid bodies-spring method or other Finite element methods which are based on the limit analysis and discrete element. These methods, nevertheless, need more sufficient detailed and accurate information to input data.

The differences of various slope stability analysis methods in the normal forces are quite small for the normal slope problems. But if applied with more complicated geotechnical problems such as; case (b) : slope attached the anchoring force, the difference will be greater as shown in fig 5.8.

All slope stability analysis methods with the exception of the ordinary method of slices can be applied for the slope with non-circular failure surface, because the differences are in the acceptable level. If there are enough and accurate information, Slice spring method and Rigid bodies-spring method which give high accuracy are the most suitable. Alternatively, in the case of inadequate data, the methods in the moderate accurate group are easier to apply whether the slope is general or complex. However, the ordinary method of slices gives the advantage of analysis time (i.e. can calculate within few minutes) which can be applied in the preliminary analysis of the problem for the approximately results.

5.3 Slope stability analysis of landslides in Northern Thailand

In this section, the analyses of 4 actual landslides in Northern Thailand which obtained the secondary data from the concerned organization are presented, as well as a special landslide case investigated in this study (see previously details in chapter 4). All 5 slope failure cases are studied and analyzed by the following methods:

i) Ordinary method of slices or Fellenius method

ii) Simplified Bishop method

iii) Simplified Janbu method

iv) Spencer method

v) Slice spring method

vi) Rigid bodies-spring method

At the start of the slope stability analysis, the slope geometry, loading condition, geological condition, groundwater condition and slip plane which are used as the basis for the stability analysis must be defined. For some cases, the necessary data such as: cross-section of slope, slope plan view, soil boring logs, slip plane, groundwater level at the failure time and etc. are shortage. These data will be assumed by typical values at the critical condition. Landslides are easily occurred under the worst condition. The procedure using submerged unit weight of the soil (i.e. fully-saturated soil) then is analyzed, although the condition of groundwater is generally, and particular in slopes, not fully-saturated.

For Slice spring method and Rigid bodies-spring method, these 2 methods need to define the Poisson's ratio, μ, and Modulus of elasticity, E in the analysis. These data can be assumed by the typical values in the table C.8 and C.9.

The analytical results in the factor of safety values predicted from various methods will be compared with the expected factor of safety (FS = 1)

5.3.1 Results of the stability analysis

Case 1 : Public Highway no. 1093, Chiangrai

The first case is a slope failure on the left way of public highway no. 1093 at Km. 35+400 in Chiangrai province. The slope with 10 meters height, 20 degrees inclination of slope angle. The soil slope compiles completely decomposed limestone overlaying a medium to dense limestone. Because the lack of data, only SPT values are available, so the soil is assumed to be cohesionless soil (e.g. c'=0). The soil parameters of the upper and lower strata used in the analysis are respectively $\phi' = 29^{\circ}$, $\gamma = 1.911$ t/m^3 and $\phi' = 35^{\circ}$, $\gamma = 2.039$ t/m^3 which obtained from the chart of the relationship between SPT value and ϕ. The slip plane is assumed to be non-circular and estimated from the data of soil boring logs and the sketch by department of public highway as shown in fig. 5.9. From table C.8 and C.9, μ=0.3 and E=25 MPa are used in the analysis which depend on type of soil. The 13 slices are divided and fully-saturated soil is assumed.

Case 2 : Mae Laeng Luang Dam, Chiangmai

The second case is a cut slope with an average slope angle at 45 degrees, 16 meters height on the left embankment of Mae Laeng Luang Dam, Chiangmai where the failure surface is assumed to be non-circular shape (fig. 5.10). The subsurface geology of this area consists of completely, moderate to slightly weathered rock of granite and basalt. The soil parameters are c' = 1.5 t/m^3, $\phi' = 25^{\circ}$, $\gamma = 1.800$ t/m^3 and c' = 5.0 t/m^3, $\phi' = 28^{\circ}$, $\gamma = 2.000$ t/m^3. The 9 divided slices and fully-saturated soil are used in the analysis. μ=0.3 and E=25 MPa are assumed which depend on type of soil in table C.8 and C.9.

Case 3 : Bhuping Palace, Chiangmai

The third case is an in-situ soil slope failure (i.e. landslide) behind the Bhuping Palace, Chiangmai. The height of slope is 39 meters and the inclination angle of slope is approximately 32 degrees. The slope comprises of loose-medium silty sand underlying a layer of dense silty sand and the bedrock. The soil parameters are c' = 1.900 t/m^3, $\phi' = 31.32^{\circ}$, $\gamma = 1.835$ t/m^3 and c' = 1.923 t/m^3, $\phi' = 42.60^{\circ}$, $\gamma = 1.937$ t/m^3. The slip plane is assumed from survey and site investigation by department of irrigation is shown in fig. 5.11. The divided 12 slices are used in the analysis with the assumption of submerged unit weight of soil. μ=0.35 and E=20 MPa of silty sand from table C.8 and C.9 are used in the analysis.

Case 4 : Mae Moh Mine, Lampang

The forth case is a cut-slope failure in Mae Moh Mine, Lampang. The soil slope is homogeneous decomposed lignite overlaying a lignite layer. The height of slope is about 13 meters and the inclination angle of slope is approximately 22 degrees. The slip plane and soil parameters are obtained from site investigation by the researcher in Mae Moh Mine. A typical section with assumed non-circular failure plane is shown in fig. 5.12. The soil parameters used in the analysis are and $c' = 0$ t/m^3, $\phi' = 38.37^\circ$, $\gamma = 1.800$ t/m^3. The actual sliding mass is divided into 7 slices and the worst condition of groundwater (i.e. fully-saturated soil) is determined in the analysis procedure. μ=0.3 and E=25 MPa are assumed which depend on type of soil in table C.8 and C.9.

Case 5 : Doi Suthep, Chiangmai (Case study)

This case is an in-situ soil slope failure located in Doi Suthep, Chiangmai (On the right way of the route from Chiangmai city to Doi Suthep – Bhuping Palace). The slope comprises of a layer of sandy clay varying from 0.5 meters to 3.5 meters in thickness underlying a moderate to slightly decomposed granite. The shear strength parameters of soil are obtained by the consolidated-undrained triaxial compression test in laboratory and Standard penetration test in the field. The soil parameters are $c' = 1.1$ t/m^3, $\phi' = 24.80^\circ$, $\gamma = 1.936$ t/m^3 for the upper layer, $c' = 0.5$ t/m^3, $\phi' = 31.00^\circ$, $\gamma = 1.974$ t/m^3 for the intermediate layer, and $c' = 0$ t/m^3, $\phi' = 38.00^\circ$, $\gamma = 2.100$ t/m^3 for the moderate decomposed granite layer.

The original ground surface is estimated by overlapping the adjacent cross-sections. When compared the ground surface of each section and the present ground surface of a slope, it is found that the ground surface of Km. 13+862.50 is possible to be the original ground surface, because the ground surface is related to the actual sliding mass. But when used the ground surface of Km. 13+837.50 to be the original ground surface of a slope and analyzed under fully-saturated, partly-saturated and dry conditions, the factors of safety given by Spencer method are 0.9006, 1.1817 and 1.2992 respectively. It is implied that the actual ground water level of this section is not fully-saturated. If it is under fully-saturated condition, the failure of slope will be happened. Nevertheless, the failure of slope depends on shear strength parameter of soil and other factors at that section.

The approximate location of the failure plane is assumed by site investigation and standard penetration test along the center of the slope. The typical section is shown in fig. 5.13. As an actual failure occurred during the final heavy rainfall in the year 2002, the groundwater condition at the failure time may assume to be fully-saturated, and the 12 divided slices are determined in the calculation. μ=0.4 from table C.8 and E=12.1MPa calculated from stress-strain relationship are used in the analysis

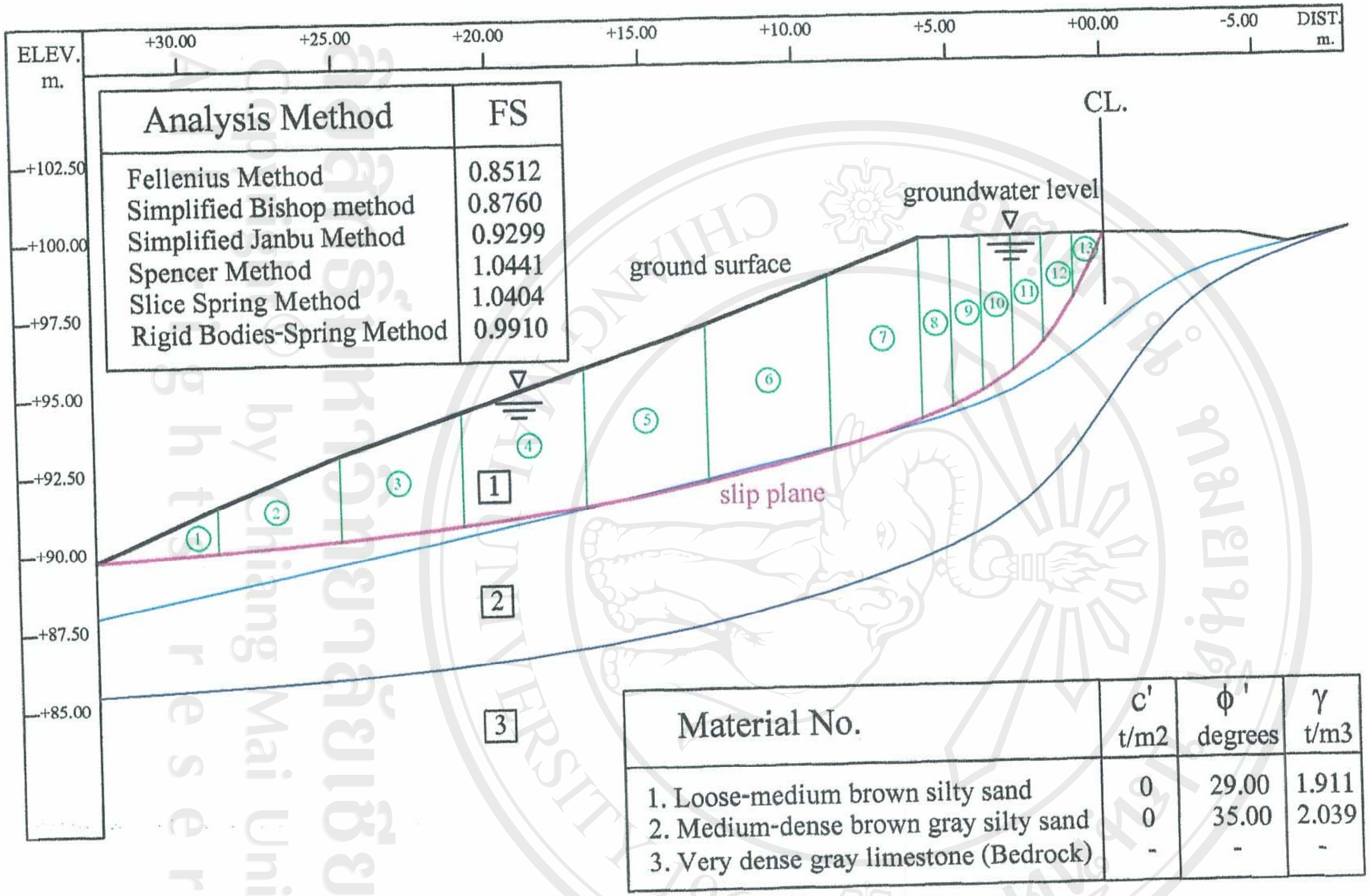
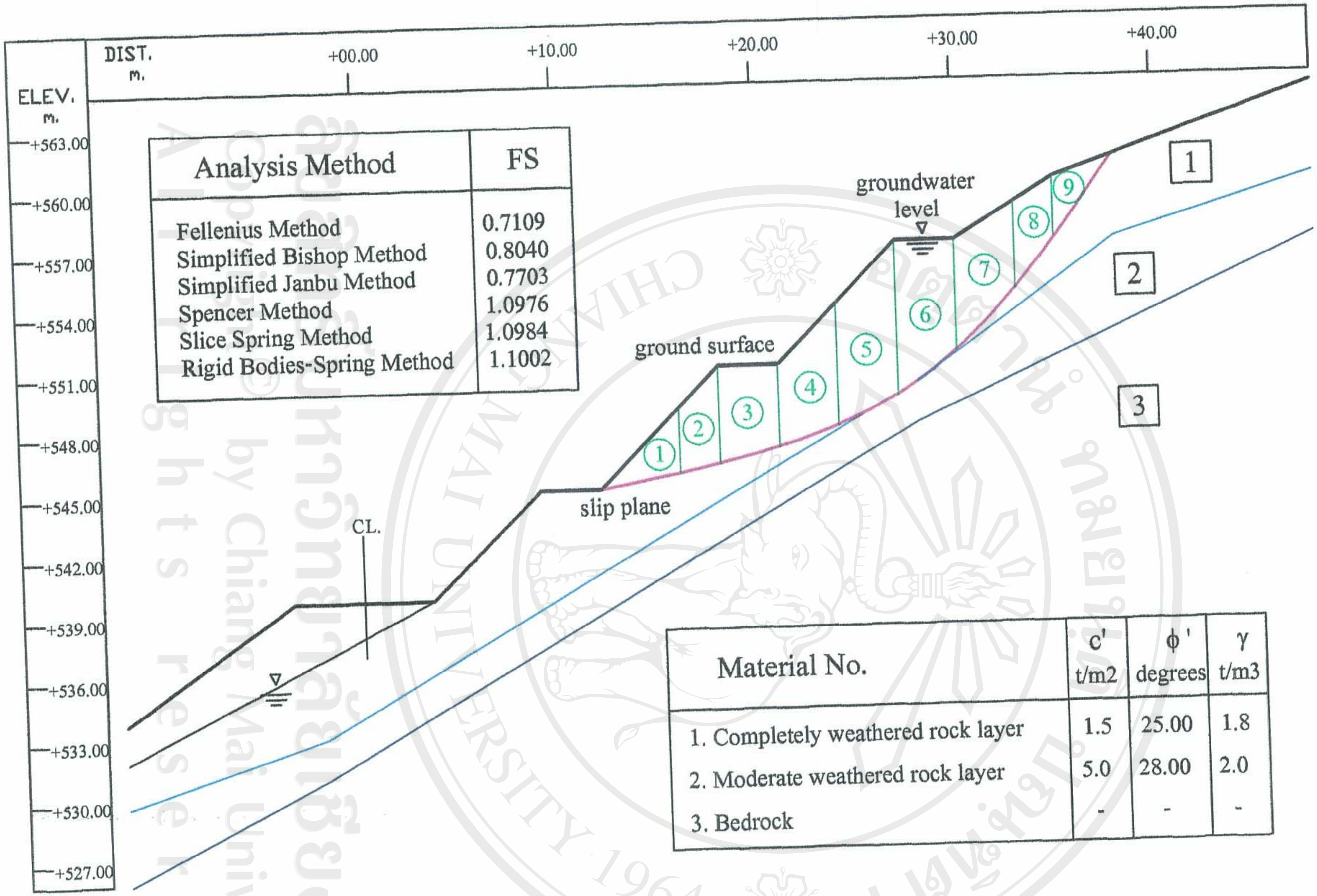


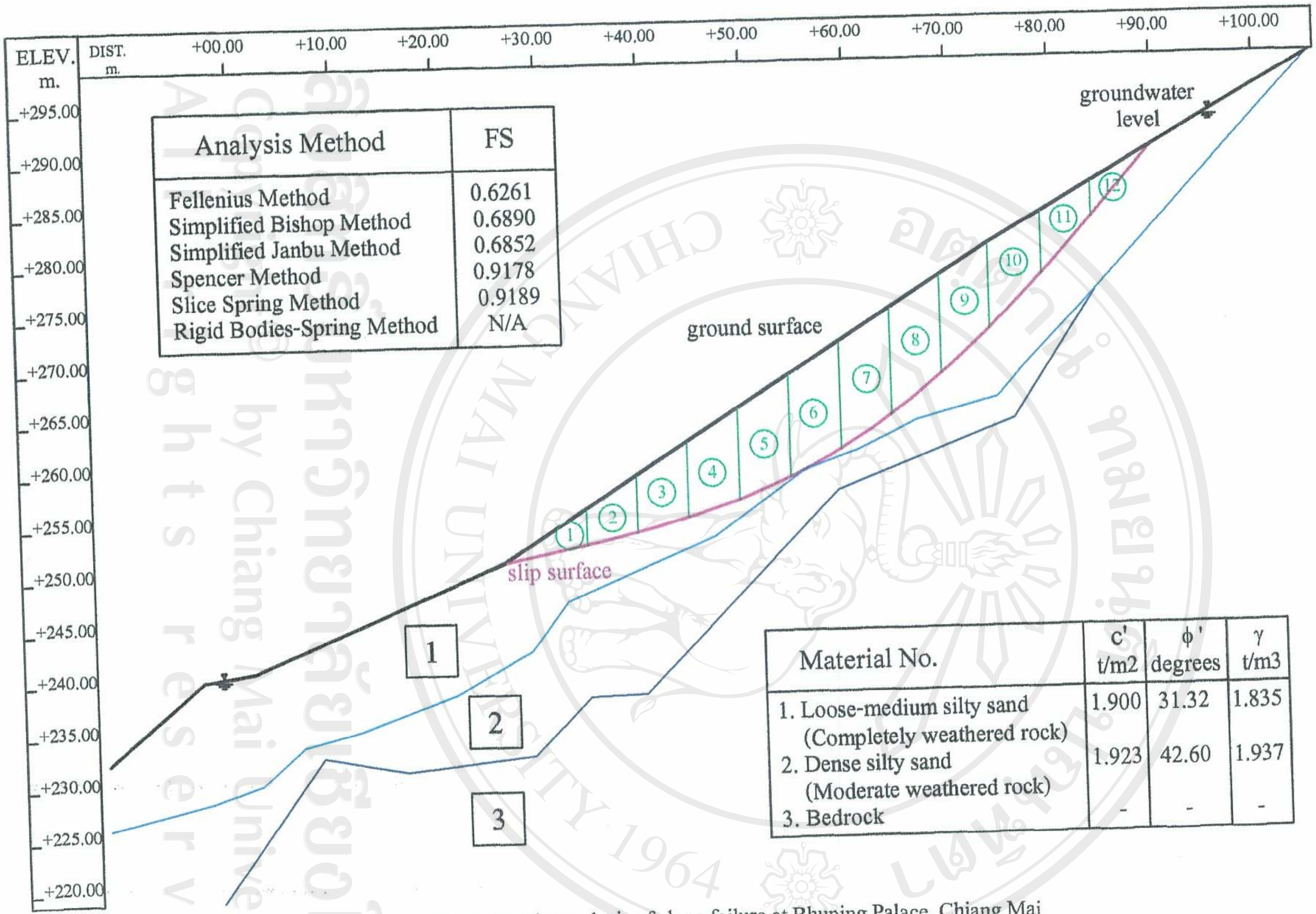
Fig. 5.9 The analysis of slope failure on public highway no. 1093 at km. 35+400, Chiang Rai



Analysis Method	FS
Fellenius Method	0.7109
Simplified Bishop Method	0.8040
Simplified Janbu Method	0.7703
Spencer Method	1.0976
Slice Spring Method	1.0984
Rigid Bodies-Spring Method	1.1002

Material No.	c' t/m2	ϕ ' degrees	γ t/m3
1. Completely weathered rock layer	1.5	25.00	1.8
2. Moderate weathered rock layer	5.0	28.00	2.0
3. Bedrock	-	-	-

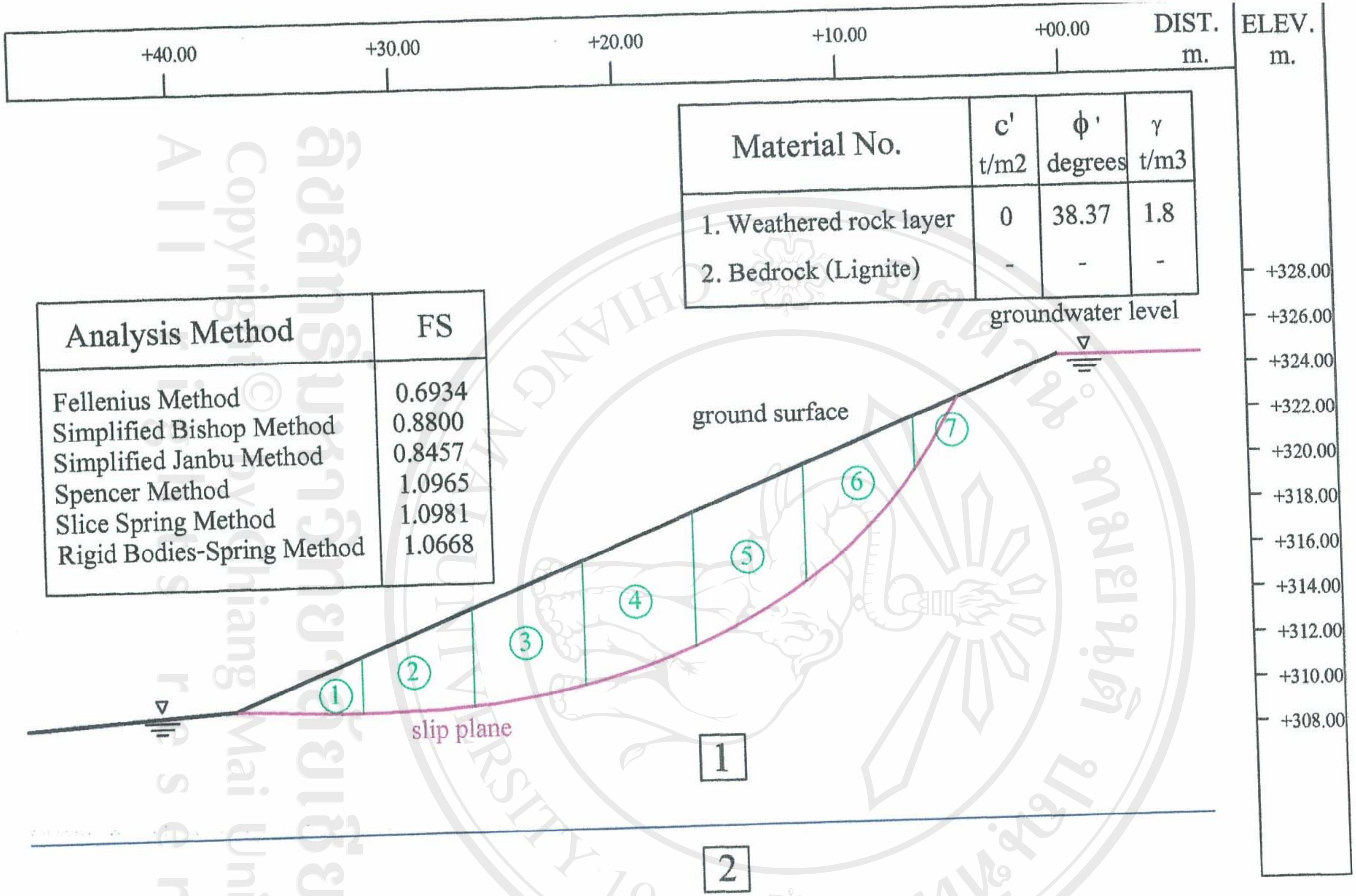
Fig. 5.10 The analysis of slope failure at Mae Laeng Luang Dam, Chiang Mai



Analysis Method	FS
Fellenius Method	0.6261
Simplified Bishop Method	0.6890
Simplified Janbu Method	0.6852
Spencer Method	0.9178
Slice Spring Method	0.9189
Rigid Bodies-Spring Method	N/A

Material No.	c' t/m2	φ' degrees	γ t/m3
1. Loose-medium silty sand (Completely weathered rock)	1.900	31.32	1.835
2. Dense silty sand (Moderate weathered rock)	1.923	42.60	1.937
3. Bedrock	-	-	-

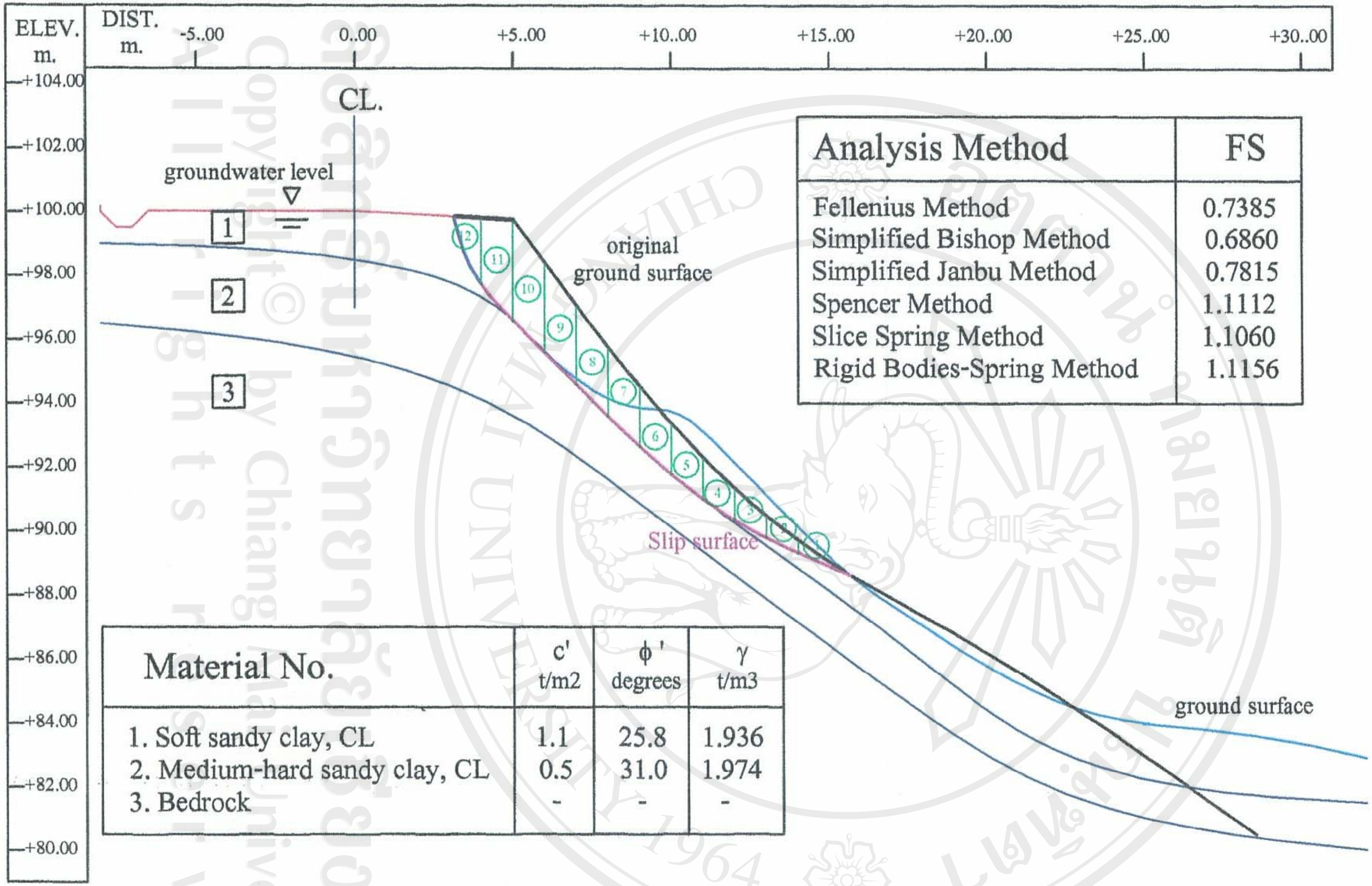
Fig. 5.11 The analysis of slope failure at Bhuping Palace, Chiang Mai



Material No.	c' t/m2	φ' degrees	γ t/m3
1. Weathered rock layer	0	38.37	1.8
2. Bedrock (Lignite)	-	-	-

Analysis Method	FS
Fellenius Method	0.6934
Simplified Bishop Method	0.8800
Simplified Janbu Method	0.8457
Spencer Method	1.0965
Slice Spring Method	1.0981
Rigid Bodies-Spring Method	1.0668

Fig. 5.12 The analysis of failure slope in Mae Moh Mine, Lampang



Analysis Method	FS
Fellenius Method	0.7385
Simplified Bishop Method	0.6860
Simplified Janbu Method	0.7815
Spencer Method	1.1112
Slice Spring Method	1.1060
Rigid Bodies-Spring Method	1.1156

Material No.	c' t/m2	φ' degrees	γ t/m3
1. Soft sandy clay, CL	1.1	25.8	1.936
2. Medium-hard sandy clay, CL	0.5	31.0	1.974
3. Bedrock	-	-	-

Fig. 5.13 The analysis of failure slope in Doi Suthep, Chiang Mai

The results of the analysis of all slope failure cases based on the actual failure surface are summarized as shown in table 5.2. And fig. 5.14 shows the safety factors obtained from each analysis methods. The percentage of difference to the expected factor of safety (FS=1) are also shown in table 5.2.

From fig. 5.14 and the values of safety factors in table 5.2, the factor of safety for most cased given by the Spencer method are very similar to Slice spring method and Rigid bodies-spring method and all of them are slightly above the expected factor of safety (i.e. slightly over FS=1). The discrepancies between the factor of safety given by these 3 methods, Spencer method, Slice spring method, and Rigid bodies-spring method and the expected factor of safety are 8.63%, 8.48% and 7.29% respectively by mean. The other methods, Fellenius method, Simplified Bishop method and Simplified Janbu method, give the value of factor of safety less than the expected factor of safety about 27.60%, 24.70%, and 17.89% respectively.

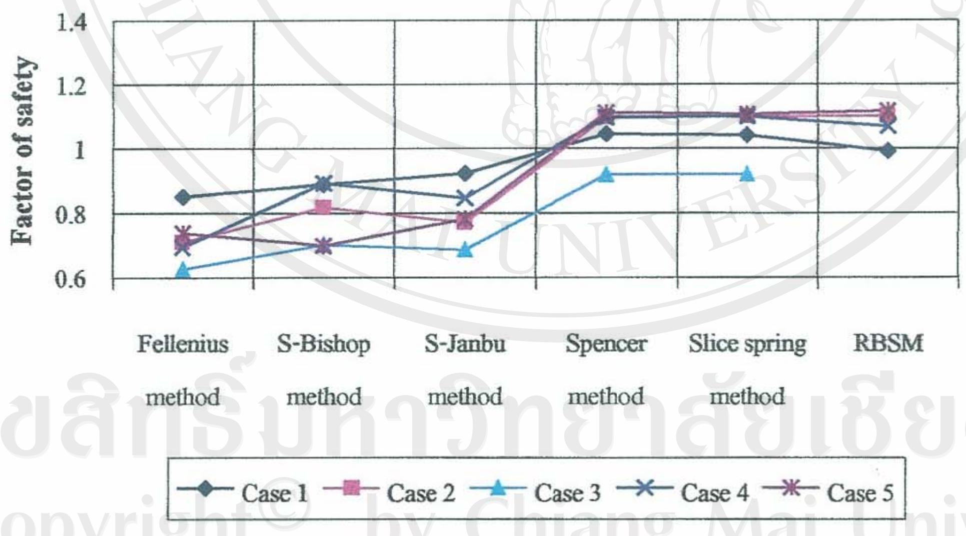


Fig. 5.14 Factor of safety obtained from each analysis methods

Table 5.2 Safety factor of landslides obtained by various slope stability analysis methods and the percentage of difference from FS=1

	Factor of safety					% Difference from FS=1.0000					
	Case 01	Case 02	Case 03	Case 04	Case 05	Case 01	Case 02	Case 03	Case 04	Case 05	**Average**
Fellenius method	0.8512	0.7109	0.6261	0.6934	0.7385	-14.88	-28.91	-37.39	-30.66	-26.15	**27.60**
Simplified Bishop method	0.8760	0.8040	0.6890	0.8800	0.6860	-12.40	-19.60	-31.10	-12.00	-31.40	**21.30**
Simplified Janbu method	0.9229	0.7703	0.6852	0.8457	0.7815	-7.71	-22.97	-31.48	-15.43	-21.85	**19.89**
Spencer method	1.0441	1.0976	0.9178	1.0965	1.1112	4.41	9.76	-8.22	9.65	11.12	**8.63**
Slice spring method	1.0404	1.0984	0.9189	1.0981	1.1060	4.04	9.84	-8.11	9.81	10.60	**8.48**
Rigid bodies-spring method	0.9910	1.1002	N/A	1.0668	1.1156	-0.90	10.02	N/A	6.68	11.56	**7.29**

5.3.2 Discussion of the analytical results

For most landslides cases in this study which the shape of failure surface is non-circular, Fellenius method and Simplified Bishop method rather highly underestimate the value of the factor of the safety more than 20%. The apartness of these results may be explained by the fact that the wrong assumptions are made in these 2 methods (i.e. Fellenius method assumed the resultant of the inter-slice force to be zero and Bishop's simplified method assumed the inter-slice shear force to be zero) and these can adopt only in circular slip surface problems. Therefore, they are not suitable foe the analysis of slope failures in Northern Thailand which have non-circular shape of slip failure. Fore purely cohesive soils both Fellenius method and Bishop's simplified method however can give very accurate factor of safety if the failure mechanism is a simple rotation mechanism (Jiang and Magnan, 1997).

Although the Bishop's simplified method and Janbu's simplified method have the same assumption about inter-slice force and same general formulation of the normal force (Fredlung and Krahn, 1977), but Simplified Janbu method is suitable for non-circular slip surface which is in agreement with the slope failure in the northern area of Thailand. It can be seen that the estimation of the factor of safety given by Simplified Janbu method is better than Simplified Bishop method. However, Simplified Janbu method gives a moderate value of the percentage of difference to the expected factor of safety. Because Simplified Janbu method satisfies the overall force equilibrium alone. , but it is not satisfy the overall moment equilibrium.

The factor of safety given by Spencer method agrees very well with the factor of safety given by Slice spring method and Rigid bodies-spring method, and they are close to the expected factor of safety if compare with the other methods. These results however obtained by these two methods did not coincide with the actual failure slip surface. This may be due to the assumption of fully-saturated soil in the analysis procedure which the groundwater conditions are generally not fully saturated in the actual situation.

Nevertheless, it has been pointed out by De Mello (1977) that a factor of safety of 1.0 does not indicate the correct value of safety factor under the failure condition of a slope. The real factor of safety may be slightly less or more than 1.0, which is strongly influenced by minor geological details, stress-strain characteristics of the soil, actual pore-pressure distribution, initial stress, progressive failure and numerous other factors.

5.4 Comparison of the results of model tests and actual landslides

Based on the previous studies in the section 5.2 and 5.3, the summary of the suitable methods of slope stability analysis between the model tests and the actual cases are compared. The comparison classified in the accuracy level is given in table 5.3.

Table 5.3 Comparison of theory and application parts

Accuracy level	% Difference from actual condition	Methods of slope stability analysis	
		Model tests	Actual cases
Low	> 20%	Fellenius method	Fellenius method Simplified Bishop method
Moderate	10 – 20 %	Simplified Bishop method Simplified Janbu method Spencer method	Simplified Janbu method
High	< 10%	Slice spring method Rigid bodies-spring method	Spencer method Slice spring method Rigid bodies-spring method

In the model test, Fellenius method gives the lowest accuracy which the differences in some cases may be as large as 60% (Whitman and Bailey, 1967). The methods which make the assumptions on the inter-slice force (Bishop's simplified method, Janbu's simplified method and Spencer method), all give moderately accurate results for the analysis of the slopes. Slice spring method which utilized springs and sliders to represent the characteristic of elastic and plastic of soil, and Rigid bodies-spring method which based on the discrete element and limit analysis, are more accurate than others. However, the summations of the normal forces obtained by analysis, with the exception of Fellenius method, are higher than the measured normal forces. It is implied that the factor of safety obtained from these methods might be higher than the actual condition.

In the actual cases, various slope stability analysis methods are applied in several examples slope failure cased in Northern Thailand. For practical slope failure problems with non-circular shape of failure surface and relatively steep slope (i.e. slope angle more than 20 degrees), Spencer method, Slice spring method and Rigid bodies-spring method give high accuracy. Spencer method is suitable for earth slope in Northern Thailand, because it can apply easier than others. However, under the circumstances of a big surcharge load acting on a slope and the gentle or mild slope (i.e. slope angle is about 5-20 degrees), it is not appropriate to use Spencer method because of highly inaccuracy (Kondo, 2000). Spencer method, Simplified Bishop method, Simplified Janbu method and Fellenius method give much error in the analysis of the bearing capacity (Hansen, 1996, Kondo, 2000). On the other hand, in the preliminary analysis of slope or in the field, Fellenius can apply because of the advantage of the calculation. (i.e. it is amenable and easy to hand calculation).