"As closer a man gets to his targets, the greater become the difficulties."

– Goethe

SLOPE STABILITY MODELING MANGTI LANDSLIDE 7

BACKGROUND AND HISTORY

Stability analysis of earth structures constitutes a most important numerical solution in geotechnical engineering. This is in part because stability is obviously a key issue in any project – will the structure remain stable or collapse? The idea of discretizing a potential sliding mass into slices was introduced as early as in 1916. Petterson (1955) presented the stability analysis of the Stigberg Quay in Gothenberg, Sweden where the slip surface was taken to be circular and the sliding mass was divided into slices, which is commonly known as the Limit Equilibrium Method. In the mid-1950s Janbu (1954) and Bishop (1955) developed advances in the method. The advent of electronic computers in the 1960's made it possible to more readily handle the iterative procedures inherent in the method which led to mathematically more rigorous formulations such as those developed by Morgenstern and Price (1965) and by Spencer (1967).

Modern limit equilibrium software (in the present case GEO-SLOPE/W, 2004) is making it possible to handle ever-increasing complexity within an analysis. It is now possible to deal with complex stratigraphy, highly irregular pore-water pressure conditions, various linear and nonlinear shear strength models, almost any kind of slip surface shape, concentrated loads, and structural reinforcement. Limit equilibrium formulations based on the method of slices are also being applied more and more to the stability analysis of structures such as tie-back walls, nail or fabric reinforced slopes, and even the sliding stability of structures subjected to high horizontal loading arising, for example, from ice flows (Krahn, 2004).

SOLUTION TECHNIQUES

Different solution techniques adopting Slices' method have been developed over the years. However, these differ on: a) what equations of statics are involved and satisfied; b) which interslice forces are included and; c) what is the assumed relationship between the interslice shear and normal forces? A schematic cross section (Figure 7.1) illustrates a typical sliding mass discretized into slices and the possible forces on the slice. Normal and shear forces act on the slice base and on the slice sides.

A gist of prevailing software added analysis methods signifying equations of statics satisfied and interslice forces and their relationships is given in Table 7.1A&B.

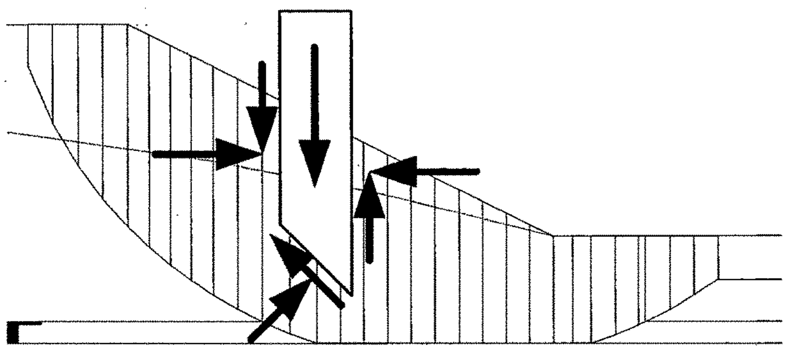


Figure 7.1 – Slice Discretization and Slice Forces in a Sliding Mass

Table 7.1A - Equations of Statics Satisfied

Method	Moment Equilibrium	Force Equilibrium
Ordinary or Fellenius	Yes	No
Bishop's Simplified	Yes	No
Janbu's Simplified	No	Yes
Spencer	Yes	Yes
Morgenstern-Price	Yes	Yes
Corps of Engineers– 1	No	Yes
Corps of Engineers – 2	No	Yes
Lowe-Karafiath	No	Yes
Janbu Generalized	Yes (by slice)	Yes
Sarma – vertical slices	Yes	Yes

Table 7.1B - Interslice Force Characteristics and Relationships

Method	Interslice Normal (E)	Interslice Shear (X)	Inclination of X/E Resultant, and X-E Relationship
Ordinary or Fellenius	No	No	No interslice forces
Bishop's Simplified	Yes	No	Horizontal
Janbu's Simplified	Yes	No	Horizontal
Spencer	Yes	Yes	Constant
Morgenstern-Price	Yes	Yes	Variable; user function
Corps of Engineers– 1	Yes	Yes	Inclination of a line from crest to toe
Corps of Engineers – 2	Yes	Yes	Inclination of ground surface at top of slice
Lowe-Karafiath	Yes	Yes	Average of ground surface and slice base inclination
Janbu Generalized	Yes	Yes	Applied line of thrust and moment equilibrium of slice
Sarma – vertical slices	Yes	Yes	$X = C + E \tan \Phi$

(After Krahn, 2004)

GENERAL LIMIT EQUILIBRIUM METHOD

A General Limit Equilibrium (GLE) formulation was developed by Fredlund (Fredlund and Krahn 1977; Fredlund et al. 1981). The GLE method is most useful tool for explaining the differences between – the various methods and for determining interslice force functions that are influencing the computed factor of safety. The GLE formulation is based on two factor of safety equations and allows for a range of interslice shear-normal force assumptions. One equation gives the factor of safety with respect to moment equilibrium (F_m), while the other equation gives the factor of safety with respect to horizontal force equilibrium (F_f). The interslice shear forces in the GLE method are handled with an equation (Morgenstern and Price 1965):

$$X = E\lambda f(x) \qquad \textbf{(14)}$$

Where, ***f(x)*** is a function, ***λ*** is the percentage (in decimal form) of the function used, ***E*** is the interslice normal force and ***X*** is the interslice shear force. The GLE factor of safety equation with respect to moment equilibrium is given by Equation 15-

$$F_m = \frac{\sum (c'\beta R + (N - u\beta) R \ \tan\phi')}{\sum Wx - \sum Nf \pm \sum Dd} \qquad \textbf{(15)}$$

The factor of safety equation with respect to horizontal force equilibrium is given by Equation 16-

$$F_f = \frac{\sum (c'\beta \cos\alpha + (N - u\beta) \tan\phi' \cos\alpha)}{\sum N \sin\alpha - \sum D \cos\omega} \qquad \textbf{(16)}$$

The terms in the equations are:

c'	= effective cohesion
ϕ'	= effective angle of friction
U	= pore-water pressure
N	= slice base normal force
W	= slice weight
D	= concentrated point load
β, R, x, f, d, ω	= geometric parameters
α	= inclination of slice base

The key variable **'N'** in both equations is the normal at the base of each slice, which is obtained by the summation of vertical forces and may be defined as –

$$N = \frac{W + (X_R - X_L) - \dfrac{c'\beta \sin\alpha + u\beta \sin\alpha \ \tan\phi'}{F}}{\cos\alpha + \dfrac{\sin\alpha \tan\phi'}{F}} \qquad \textbf{(17)}$$

F is F_m when N is substituted into the moment factor of safety equation and *F* is F_f when *N* is substituted into the force factor of safety equation. Further, the slice base normal is dependent on the interslice shear forces X_R and X_L on either side of a slice, hence, it varies with each method. The GLE method computes F_m and F_f for a range of lambda (λ) values, therefore, this method can be applied to any kinematically admissible slip surface shape.

The stability analysis of Mangti Landslide has been carried out using GeoStudio's GEOSLOPE/W, 2004 software and using following approaches.

A. BISHOP'S SIMPLIFIED APPROACH

Bishop developed an equation for the normal at the slice base by summing slice forces in the vertical direction. The consequence of this is that the base normal becomes a function of the factor of safety. A simple form of the Bishop's Simplified factor of safety equation in the absence of any pore-water pressure is represented by Equation 18:

$$FS = \frac{1}{\sum W \sin\alpha} \sum \left[\frac{c\beta + W\tan\phi - \frac{c\beta}{FS}\sin\alpha\tan\phi}{m_\alpha} \right] \quad \textbf{(18)}$$

FS as seen on both sides of the above equation is not unlike the ordinary factor of safety equation except for the m_α term, which is defined by Equation 19:

$$m_\alpha = \cos\alpha + \frac{\sin\alpha\tan\phi}{FS} \quad \textbf{(19)}$$

To solve for the Bishop's Simplified factor of safety, it is necessary to start with a guess for FS. In SLOPE/W software package, the initial guess is taken as the Ordinary factor of safety. The initial guess for FS is used to compute m_α and then a new FS is computed. Next the new FS is used to compute m_α and then another new FS is computed. This procedure is repeated until the last computed FS is within a specified tolerance of the previous FS. This Bishop's simplified approach envisages no interslice shear forces, as originally assumed by Bishop, but the interslice normal forces are included. Therefore, in this case the moment factor of safety (F_m) is insensitive to the interslice forces. Thus the force factor of safety (F_f) is sensitive to the interslice shear.

In summary, the Bishop's Simplified method, (1) considers normal interslice forces, but ignores interslice shear forces, and (2) satisfies over all moment equilibrium, but not overall horizontal force equilibrium.

B. JANBU'S SIMPLIFIED APPROACH

The Janbu's Simplified approach is similar to the Bishop's Simplified one except that this approach satisfies only overall horizontal force equilibrium, but not overall moment equilibrium. In this factor of safety is usually low, even though the slices are in force equilibrium. As with the Bishop's Simplified method, lambda (λ) is zero, whereas, in the Janbu's Simplified approach the interslice shear is ignored. Since force equilibrium is sensitive to the assumed interslice shear. Therefore, ignoring the interslice shear, makes the resulting factor of safety too low for circular slip surfaces.
In summary, the Janbu's Simplified method, (1) considers normal interslice forces, but ignores interslice shear forces, and (2) satisfies over all horizontal force equilibrium, but not over all moment equilibrium.

C. MORGENSTERN-PRICE APPROACH

Morgenstern and Price (1965) approach is similar to that proposed by the Spencer, with the provision for various user-specified interslice force functions. The interslice functions available in SLOPE/W for use with the Morgenstern-Price (M-P) method are: Constant, Half-sine, Clipped-sine, Trapezoidal and Data-point specified.
As with the Spencer approach, the force polygon closure is very good with the M-P approach, since both shear and normal interslice forces are included. A significant observation in the M-P Factor of Safety is that it is lower than the Bishop's Simplified Factor of Safety. This is because the moment equilibrium curve has a negative slope.
In summary, the Morgenstern-Price method:

- Considers both shear and normal interslice forces,
- Satisfies both moment and force equilibrium, and
- Allows for a variety of user-selected interslice force function.

SLOPE STABILITY MODELING WITH GEOSTUDIO-GEOSLOPE STANDARD SOFTWARE

FUNCTIONAL MODALITIES

The slope stability modeling of Mangti Landslide was carried out on GeoStudio-GeoSlope Standard 2004 software package. The modeling is done on SLOPE/W, which is one component in a complete suite of geotechnical product called GeoStudio. The entire procedure can be summarized in five below mentioned stages (Krahn, 2004) –

1. Geometry – description of the stratigraphy and shapes of potential slip surfaces.
2. Soil strength – parameters used to describe the soil (material) strength.
3. Pore-water pressure – means of defining the pore-water pressure conditions.
4. Imposed loading – surcharges or dynamic earthquake loads.
5. Reinforcement or soil-structure interaction – fabric, nails, anchors, piles, walls and so forth.

GEOMETRY

SLOPE/W uses the concept of regions to define the geometry signifying drawing a line around a soil unit or stratigraphic layer to form a closed polygon. Regions are in essence n-sided polygons and a typical slope stability case of studied Mangti Landslide defined with regions is shown in Figure 7.2. All regions need to be connected to form a continuum. This is done with the use of Points. The small black squares at the region corners in Figure 7.2 are the points. The regions are connected by sharing the points. In Figure 7.2, Points 1, 2, 3, 4, 6, 7, 8, 9, 17, 18, 19, 20, 21 and 22 are common to regions 1, 2, 3, 4 and 5 marked with bold letters on Figure 7.2 and thus these regions consequently behave as a continuum.

A special geometric object in GeoStudio is the ground surface line. In SLOPE/W, the ground surface line is used to control and filter trial slip surfaces. All trial slip surfaces must enter and exit along the ground surface. Triangular markers indicating the extents of ground surface line can be moved along the ground surface as illustrated

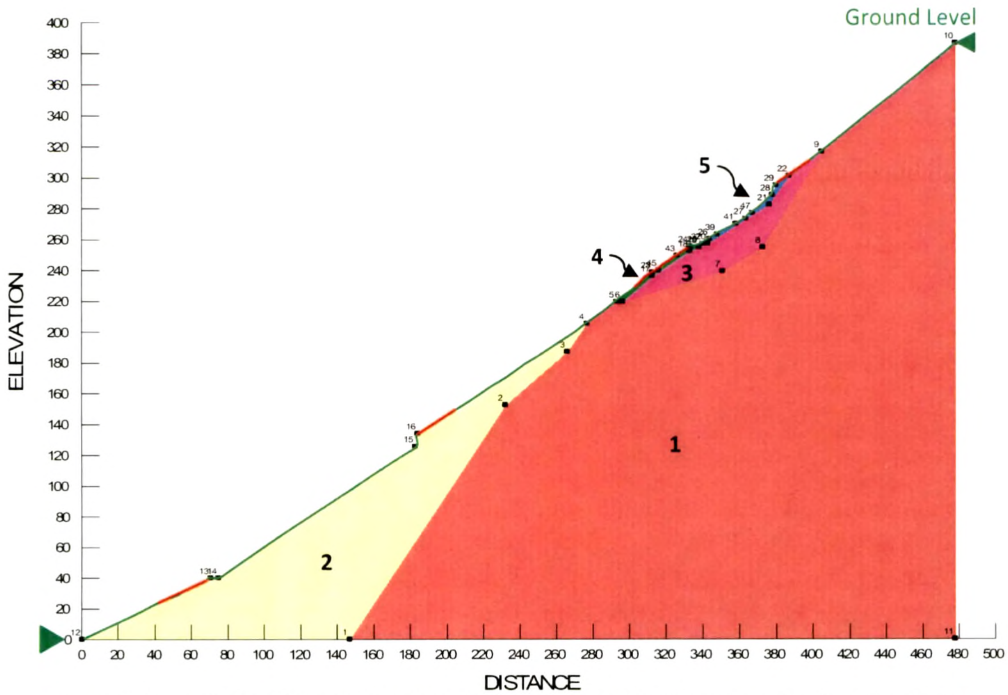


Figure 7.2 – 2-D GeoSlope Model of Mangti Landslide Showing Typical Regions for Slope Stability Analysis

through a green line on Figure 7.2. The smallest and largest x-coordinates in the problem are used to identify the ends of the intended ground surface line.

SLOPE/W has a particular technique for specifying trial slip surfaces called "Entry-Exit". Line segments can be specified which designate specific locations where all trial slip surfaces must enter and exit. These line segments are attached to the ground surface line.

Entry and Exit Specification

One of the difficulties in actually ascertaining the depth of the slip surface was due to unavailability of sub-surface data. This limitation was effectively overcome by specifying the location where the trial slip surfaces will likely enter the ground surface and where they will exit. The technique is called the Entry and Exit method in SLOPE/W. In the Figure 7.2 there are two heavy (red) lines along the ground surface. These are the areas where the slip surfaces will enter and exit. The software has provision for specifying number of entries and exits depending on the number of increments along these two lines. Behind the scenes, SLOPE/W connects a point along the entry area with a point along the exit area to form a line. At the mid-point of this connecting line, SLOPE/W creates a perpendicular line. Radius points along the perpendicular line are created to form the required third point of a circle. This radius point together with the entry and exit points are used to form the equation of a circle. SLOPE/W controls the locations of these radius points so that the circle will not be a straight line (infinite radius), and the entry angle of the slip circle on the crest will not be larger than 90 degrees (undercutting slip circle). The equation of a circle gives the center and radius of the circle, the trial slip surface is then handled in the same manner as the conventional Grid and Radius method. The number of radius increments is also a specified variable. The radius specification in the Entry and Exit method can be useful in situations where the slip surfaces are controlled by beddings of weaker materials, or an impenetrable material layer (bedrock). Although SLOPE/W posts no restriction to the location of the Entry and Exit zones, it has been taken care to define the Entry and Exit zones on locations where the critical slip surface is expected to daylight, with a view to avoid impossible and unreal slip surfaces.

Effect of Soil Strength

The fact that the position of the critical slip surface is dependent on the soil strength parameters is one of the most misunderstood and perplexing issues in slope stability analyses.

Purely frictional case

When the cohesion of a soil is specified as zero, as is the case with Mangti Landslide's lower level reactivated debris mass, the minimum factor of safety will always tend towards the infinite slope case where the factor of safety is given by Equation 20,

$$F.S. = \frac{\tan \phi}{\tan \alpha} \qquad (20)$$

Where:

ϕ = the soil friction angle

α = the inclination of the slope.

MATERIAL STRENGTH

There are many different ways of describing the strength of the materials (soil or rock) in a stability analysis. However, for this analysis ***Mohr*-Coulomb**, which is most commonly used method, has been adopted to describe the shear strength of geotechnical materials. The final adopted soil strength parameters from various laboratory investigations carried out on a number of disturbed and undisturbed Piezometer pit samples is shown in Table 7.2 below –

Table 7.2 – Adopted Material Properties in Slope Stability Analysis; Mangti Landslide

Regions	Material Type	Dry Unit Weight KN/m³	Cohesion in kPa 'c'	Angle of Friction 'ϕ'	Horizontal Seismicity Coefficient (k_h)	Vertical Seismicity Coefficient (k_v)
1	Impenetrable Layer/ Bed Rock	-	-	-	0.24	0.16
2	Boulder-Cobble Mix Soil	16.793	0	30°		
3	Silty Sand	21.015	12	29°		
4	Poorly Graded Sand	21.541	17	28°		
5	Poorly Graded Sand	14.092	13	29°		

PORE-WATER PRESSURE

Effective strength parameters, however, are only meaningful when they are used in conjunction with pore-water pressures. In this sense, the pore-water pressures are as important in establishing the correct shear strength as that the shear strength parameters. Due to the importance of pore-water pressures in a stability analysis, SLOPE/W has various ways of specifying the pore-water pressure conditions. The most common way of defining pore-water pressure conditions is with a piezometric line. With this option, SLOPE/W simply computes the vertical distance from the slice base mid-point up to the piezometric line, and multiplies this distance times the unit weight of water to get the pore-water pressure at the slice base. When the slice base mid-point is located above the piezometric line, the negative pore-water pressures are presented in CONTOUR, but additional strength due to the matric suction is assumed to be zero unless ϕ_b (Phi B) has been assigned a value. To ascertain the piezometric surface in Mangti Landslide Piezometers were installed at seven critical locations along crown, scarp, body, shoulder region and toe portion. As the landslide comprises predominantly of sand matrix supported boulder/cobbles debris mass, hence, the pore-water pressure is seen speedily dissipating. It was observed that the Mangti Landslide debris mass showed movement only on complete saturation and water table reaching ground surface. During such times the soil and embedded boulders attained semi-viscous fluid state and flowed down the slope. Thus, to analyze and evaluate the factor of safety value at times of complete saturation for devising remedial measure plan and prevent water to enter the vulnerable slopes, the pore-water pressure line was drawn at the ground surface and the factor of safety was evaluated.

SEISMIC LOAD

Seismic forces are usually oscillatory, multidirectional, and act only for moments in time. In spite of this complex response, static forces are sometimes used to represent the effect of the dynamic loading. The second concern is that the slope may not completely collapse during the shaking, but there may be some unacceptable permanent deformation. In the present slope stability analysis with SLOPE/W a pseudostatic type of analysis is used to evaluate the effect of seismic loading on the factor of safety of the slope mass.

Pseudostatic Analysis

A pseudostatic analysis represents the effects of earthquake shaking by accelerations that create inertial forces. These forces act in the horizontal and vertical directions at the centroid of each slice. The forces are defined as Equation 21:

$$F_h = \frac{a_h W}{g} = k_h W$$

$$F_v = \frac{a_v W}{g} = k_v W \qquad (21)$$

Where, a_h and a_v = horizontal and vertical pseudostatic accelerations,

g = the gravitational acceleration constant, and

W = the slice weight.

The ratio of a/g is a dimensionless coefficient k. In SLOPE/W, the inertial effect is specified as k_h and k_v coefficients. These coefficients can be considered as a percentage of g. A k_h coefficient of 0.2, for example, means the horizontal pseudostatic acceleration is 0.2g.

In SLOPE/W, the horizontal inertial forces are applied as a horizontal force on each slice and Vertical inertial forces in are added to the slice weight. It should be noted that the horizontal force is based on the actual gravitational weight of the slice and not on the altered weight. Vertical coefficients can be positive or negative. A positive coefficient means downward in the direction of gravity; a negative coefficient means upward against gravity.

The application of vertical seismic coefficients often has little impact on the safety factor. The reason for this is that the vertical inertial forces alter the slice weight. This alters the slice base normal, which in turn alters the base shear resistance. If, for example, the inertial force has the effect of increasing the slice weight, the base normal increases and then the base shear resistance increases. The added mobilized shear arising from the added weight tends to be offset by the increase in shear strength, particularly with specific relation to frictional strength components. Horizontal inertial seismic forces can have a dramatic effect on the stability of a slope. Even relatively small seismic coefficients can lower the factor of safety greatly, and if the coefficients are too large, it becomes impossible to obtain a converged solution (Krahn, 2004).

The difficulty with the pseudostatic approach is that the seismic acceleration only acts for a very short moment in time during the earthquake shaking. Therefore, the factor of safety in reality varies dramatically both above and below static factor of safety.

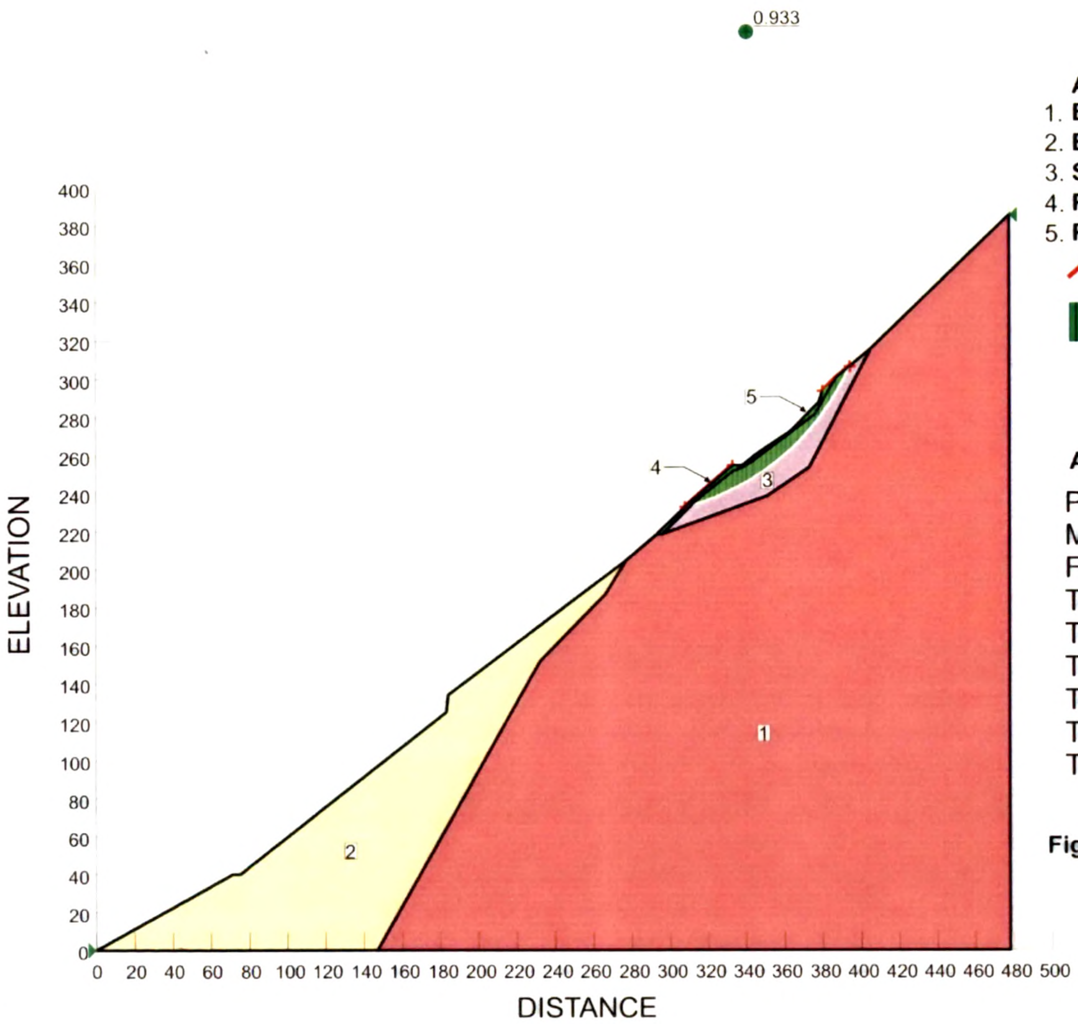
Mangti Landslide region falls in Zone V of Seismic Zones of India and accordingly the horizontal and vertical seismic load values (Table 7.2) are incorporated as per Indian Standard Codes [IS 1893 (Part 1): 2002].

SLOPE STABILITY ANALYSIS

In the case of Mangti landslide slope stability analysis, following four conditions have been applied and the factor of safety is compared for the cases;

1. Taking Material Properties in Natural Condition
2. Considering Fully Saturated Condition
3. Applying Seismic Load as per Zone – V of Seismic Zones of India
4. Considering Full saturation with the Seismic Loading

The Mangti Landslide in its present state is showing movement at two levels – The lower level is reactivation of the palaeo slumped mass due to removal of confinement at the base on account of road construction and the upper level is the current third phase of sliding. Within the SLOPE/W it is not possible to carry out the slope stability analysis simultaneously for two different mass movements so each case was analyzed independently and is presented in preceding Figure 7.3 – 7.4 and Table 7.3 – 7.4 respectively.



ADOPTED MATERIAL PROPERTIES

1. **Bed Rock** - Impenetrable layer
2. **Boulder-Cobble Mix Soil** - γ= 16.793 kN/m^3,c = 0, ϕ = 30
3. **Silty Sand** - γ= 21.015 kN/m^3,c = 12, ϕ = 29
4. **Poorly Graded Sand** - γ= 21.541 kN/m^3,c = 17, ϕ = 28
5. **Poorly Graded Sand** - γ= 14.092 kN/m^3,c = 13, ϕ = 29

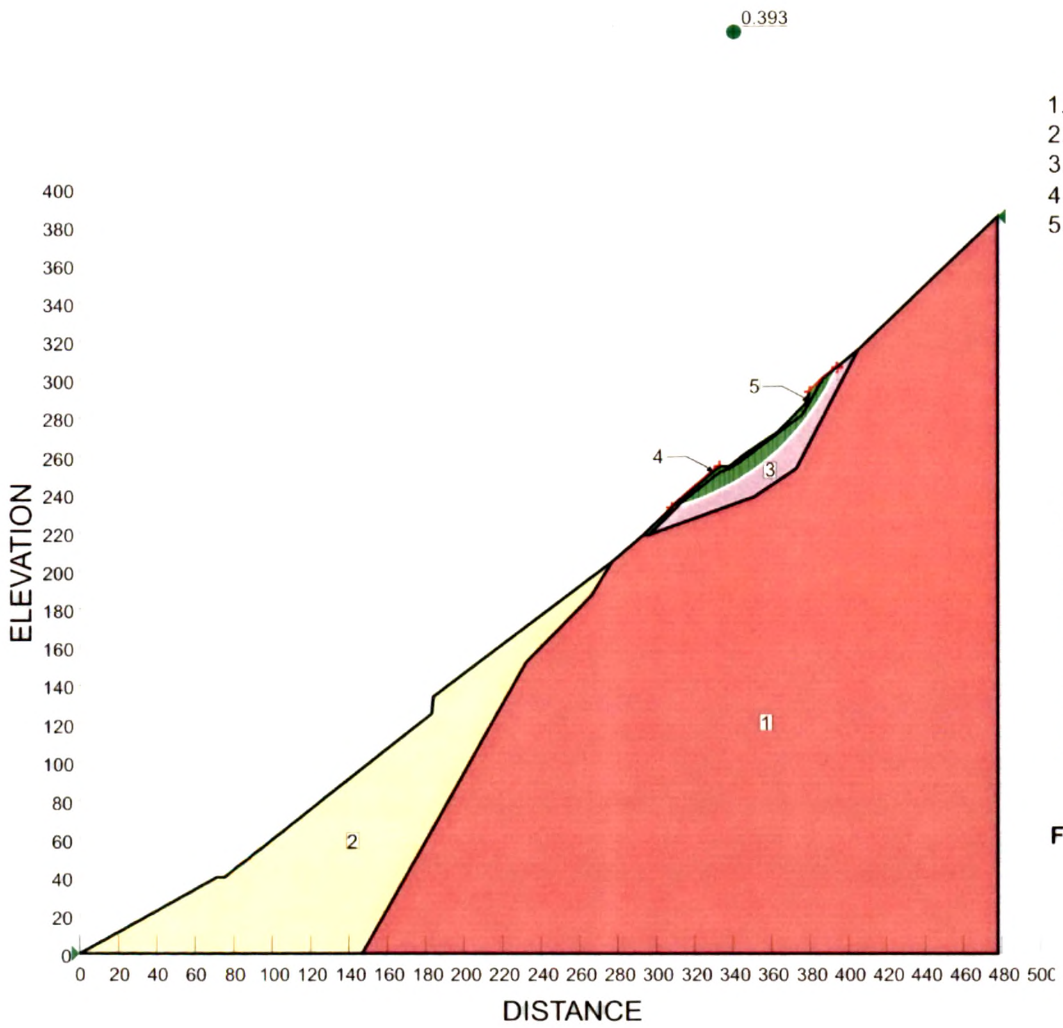
Entry-Exit Line for Slip Surface

Critical Slip Surface

ANALYSIS RESULT OF CRITICAL SLIP CIRCLE

Parameter	
Method	GLE
Factor of Safety	0.9328
Total Volume	766.67 m³
Total Weight	15501 kN
Total Resisting Moment	1.1076e+006 kN-m
Total Activating Moment	1.1874e+006 kN-m
Total Resisting Force	6718.1 kN
Total Activating Force	7202.5 kN

Figure 7.3a - Estimated Critical Slip Surface and Factor of Safety Under Natural Condition for Upper Level-Mangti Landslide



ADOPTED MATERIAL PROPERTIES

1. **Bed Rock -** Impenetrable layer
2. **Boulder-Cobble Mix Soil -** γ= 16.793 kN/m^3,c = 0, ϕ = 30
3. **Silty Sand -** γ= 21.015 kN/m^3,c = 12, ϕ = 29
4. **Poorly Graded Sand -** γ= 21.541 kN/m^3,c = 17, ϕ = 28
5. **Poorly Graded Sand -** γ= 14.092 kN/m^3,c = 13, ϕ = 29

Entry-Exit Line for Slip Surface

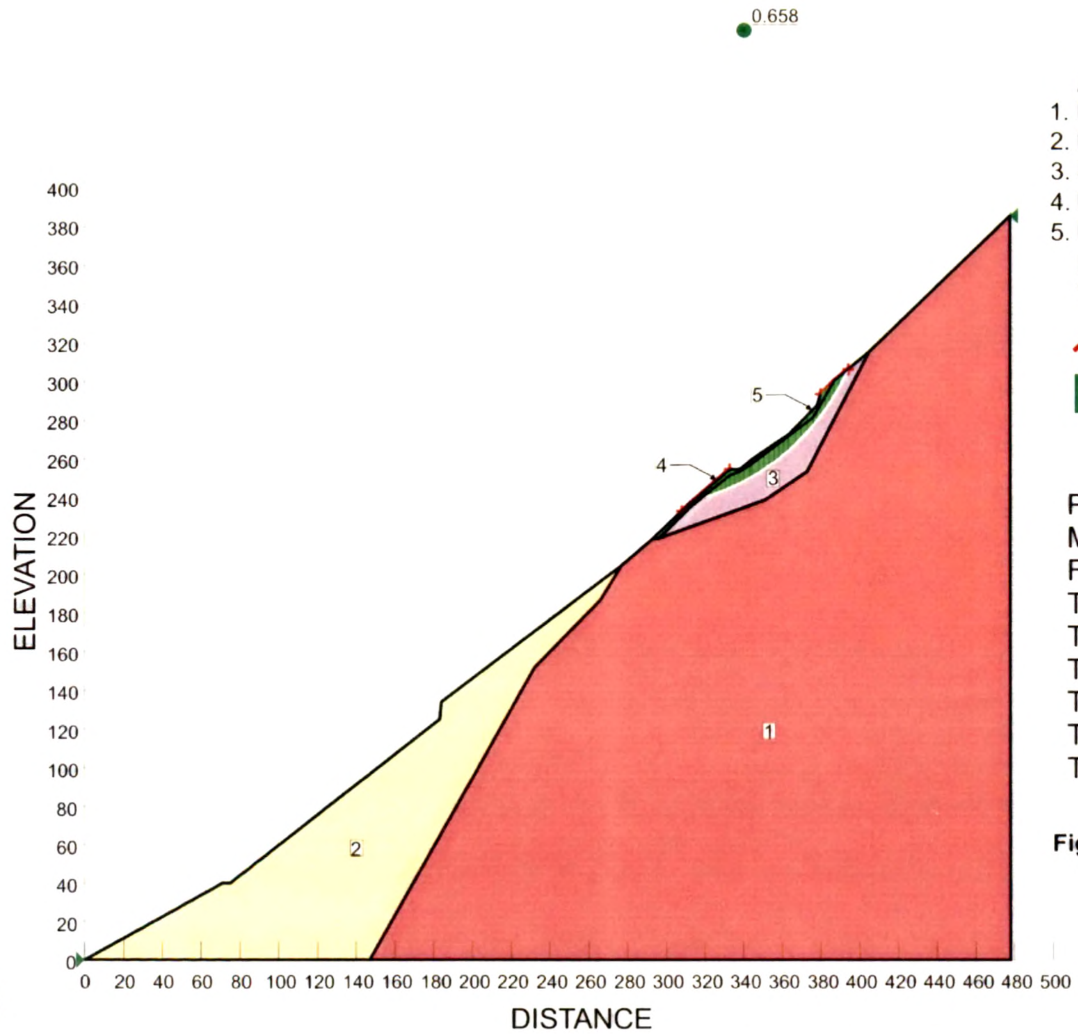
Piezometric Line

Critical Slip Surface

ANALYSIS RESULT OF CRITICAL SLIP CIRCLE

Parameter	
Method	GLE
Factor of Safety	0.3933
Total Volume	766.58 m^3
Total Weight	15499 kN
Total Resisting Moment	4.6689e+005 kN-m
Total Activating Moment	1.187e+006 kN-m
Total Resisting Force	3061.8 kN
Total Activating Force	7784.5 kN

Figure 7.3b - Estimated Critical Slip Surface and Factor of Safety Under Complete Saturation for Upper Level-Mangti Landslide



ADOPTED MATERIAL PROPERTIES

1. **Bed Rock -** Impenetrable layer
2. **Boulder-Cobble Mix Soil -** γ= 16.793 kN/m^3,c = 0, ϕ = 30
3. **Silty Sand -** γ= 21.015 kN/m^3,c = 12, ϕ = 29
4. **Poorly Graded Sand -** γ= 21.541 kN/m^3,c = 17, ϕ = 28
5. **Poorly Graded Sand -** γ= 14.092 kN/m^3,c = 13, ϕ = 29

Horizontal Seismicity Coefficient (k_h) = 0.24
Vertical Seismicity Coefficient (k_v) = 0.16

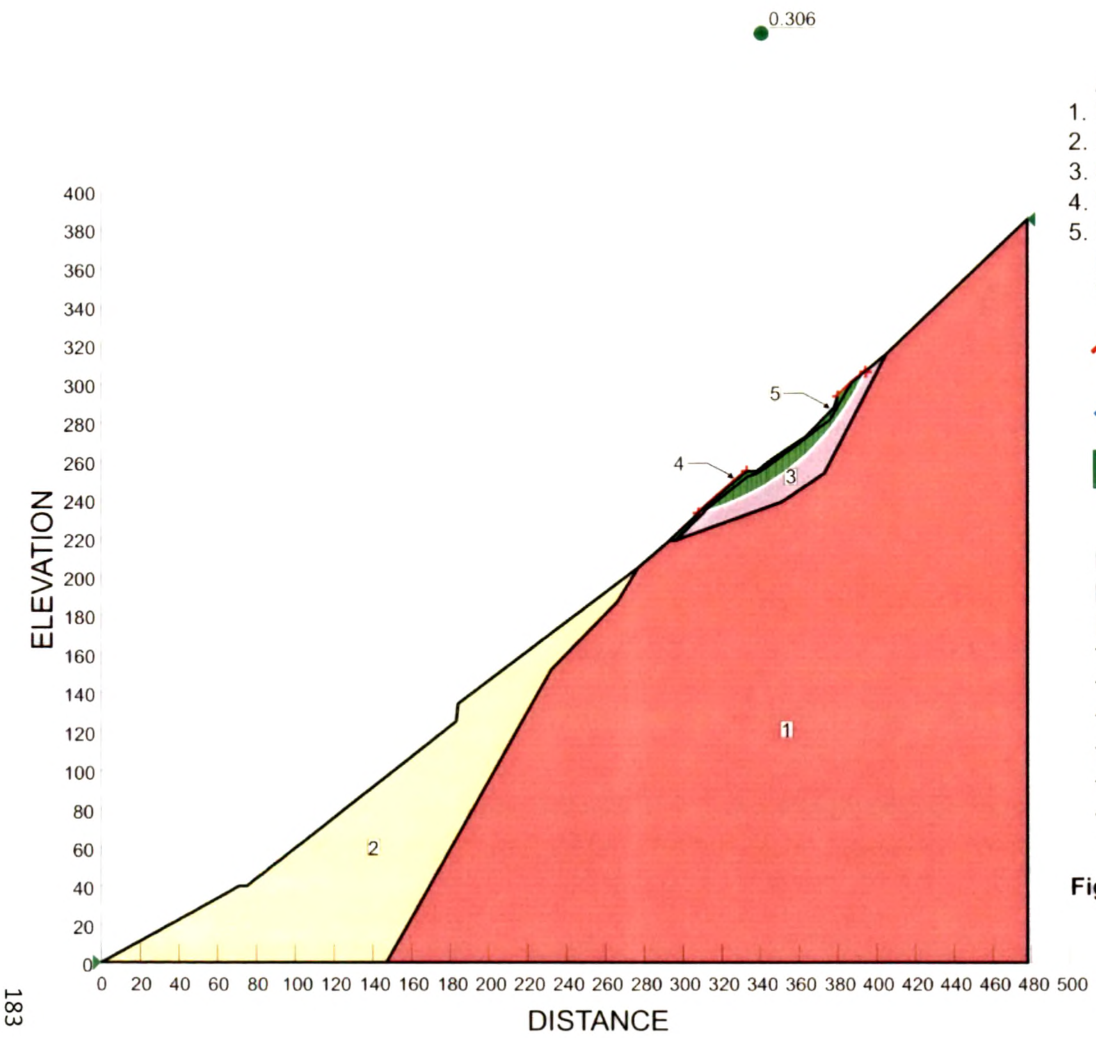
Entry-Exit Line for Slip Surface

Critical Slip Surface

ANALYSIS RESULT OF CRITICAL SLIP CIRCLE

Parameter	
Method	GLE
Factor of Safety	0.6575
Total Volume	608.71 m³
Total Weight	12174 kN
Total Resisting Moment	8.3568e+005 kN-m
Total Activating Moment	1.266e+006 kN-m
Total Resisting Force	5527 kN
Total Activating Force	8380.6 kN

Figure 7.3c - Estimated Critical Slip Surface and Factor of Safety Applying Seismic Loading Factor for Upper Level-Mangti Landslide



ADOPTED MATERIAL PROPERTIES

1. **Bed Rock -** Impenetrable layer
2. **Boulder-Cobble Mix Soil -** γ= 16.793 kN/m^3,c = 0, ϕ = 30
3. **Silty Sand -** γ= 21.015 kN/m^3,c = 12, ϕ = 29
4. **Poorly Graded Sand -** γ= 21.541 kN/m^3,c = 17, ϕ = 28
5. **Poorly Graded Sand -** γ= 14.092 kN/m^3,c = 13, ϕ = 29

Horizontal Seismicity Coefficient (k_h) = 0.24
Vertical Seismicity Coefficient (k_v) = 0.16

Entry-Exit Line for Slip Surface

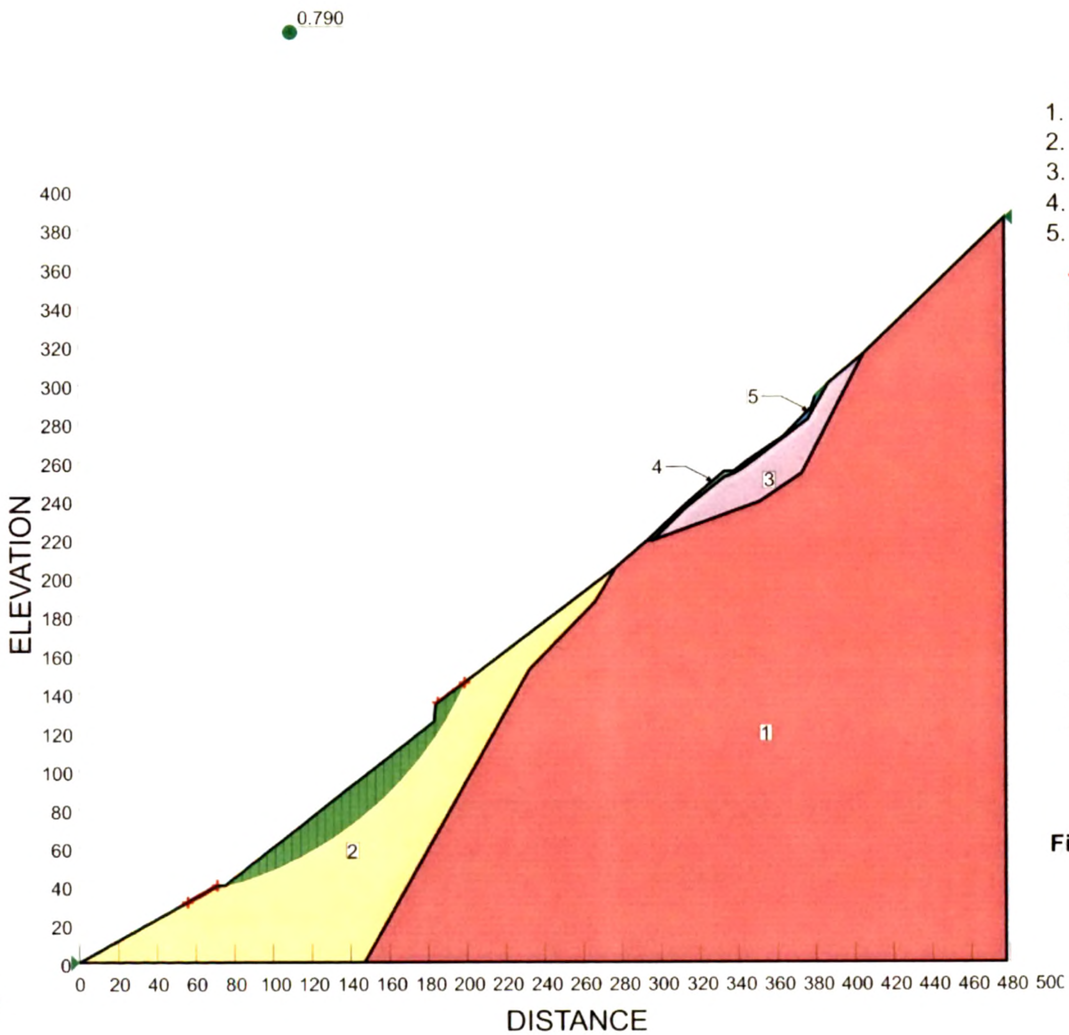
Piezometric Line

Critical Slip Surface

ANALYSIS RESULT OF CRITICAL SLIP CIRCLE

Parameter	
Method	GLE
Factor of Safety	0.3062
Total Volume	766.58 m^3
Total Weight	15499 kN
Total Resisting Moment	5.2805e+005 kN-m
Total Activating Moment	1.7342e+006 kN-m
Total Resisting Force	3584.1 kN
Total Activating Force	11651 kN

Figure 7.3d - Estimated Critical Slip Surface and Factor of Safety Under Complete Saturation and Applying Seismic Loading Factor for Upper Level-Mangti Landslide



ADOPTED MATERIAL PROPERTIES

1. **Bed Rock** - Impenetrable layer
2. **Boulder-Cobble Mix Soil** - γ= 16.793 kN/m^3,c = 0, ϕ = 30
3. **Silty Sand** - γ= 21.015 kN/m^3,c = 12, ϕ = 29
4. **Poorly Graded Sand** - γ= 21.541 kN/m^3,c = 17, ϕ = 28
5. **Poorly Graded Sand** - γ= 14.092 kN/m^3,c = 13, ϕ = 29

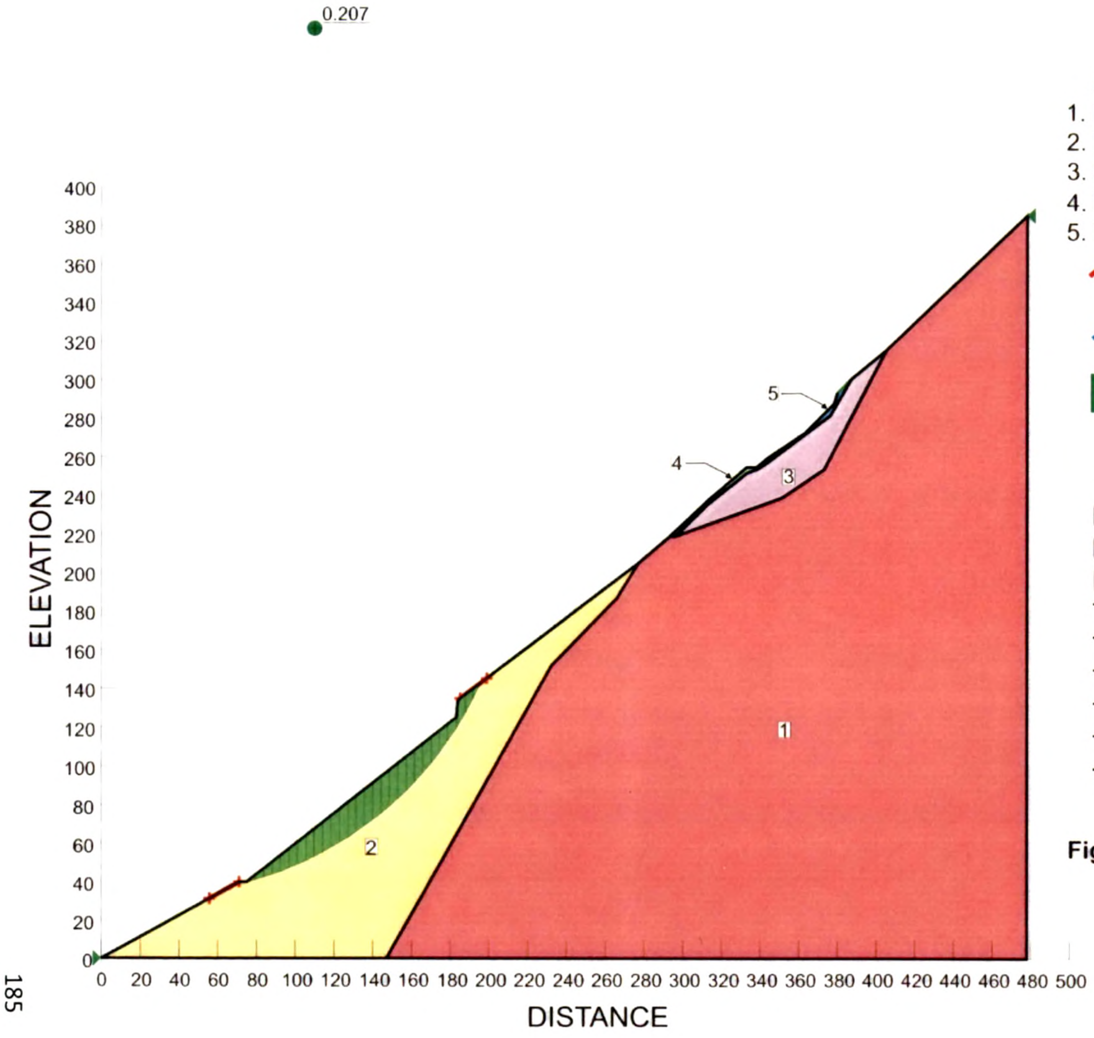
Entry-Exit Line for Slip Surface

Critical Slip Surface

ANALYSIS RESULT OF CRITICAL SLIP CIRCLE

Parameter	
Method	GLE
Factor of Safety	0.79
Total Volume	1672.2 m^3
Total Weight	28081 kN
Total Resisting Moment	2.5321e+006 kN-m
Total Activating Moment	3.205e+006 kN-m
Total Resisting Force	10536 kN
Total Activating Force	13336 kN

Figure 7.4a - Estimated Critical Slip Surface and Factor of Safety Under Natural Condition for Lower Level-Mangti Landslide



ADOPTED MATERIAL PROPERTIES

1. **Bed Rock** - Impenetrable layer
2. **Boulder-Cobble Mix Soil** - γ= 16.793 kN/m^3,c = 0, ϕ = 30
3. **Silty Sand** - γ= 21.015 kN/m^3,c = 12, ϕ = 29
4. **Poorly Graded Sand** - γ= 21.541 kN/m^3,c = 17, ϕ = 28
5. **Poorly Graded Sand** - γ= 14.092 kN/m^3,c = 13, ϕ = 29

Entry-Exit Line for Slip Surface

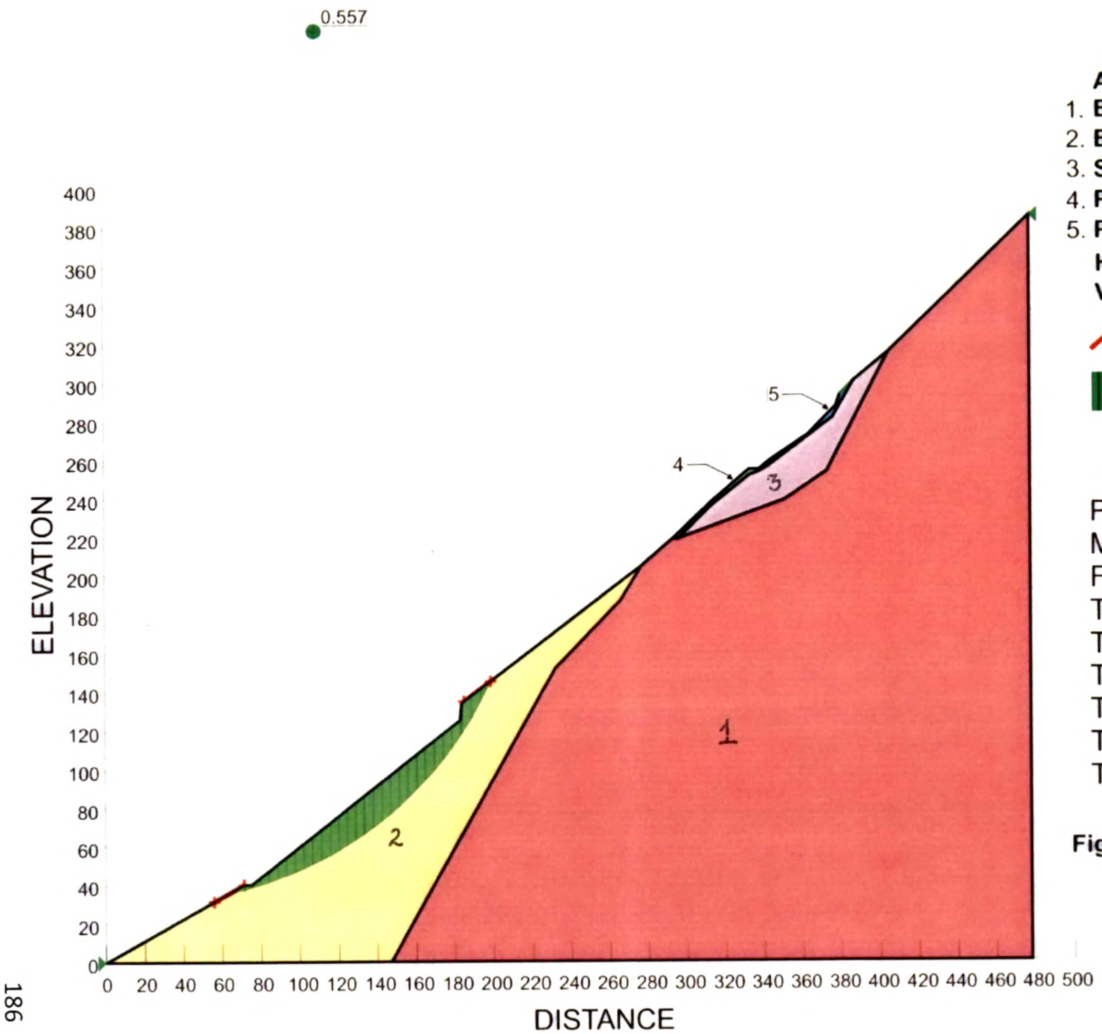
Piezometric Line

Critical Slip Surface

ANALYSIS RESULT OF CRITICAL SLIP CIRCLE

Parameter	
Method	GLE
Factor of Safety	0.207
Total Volume	1542.2 m³
Total Weight	25899 kN
Total Resisting Moment	5.8966e+005 kN-m
Total Activating Moment	2.8698e+006 kN-m
Total Resisting Force	2974.7 kN
Total Activating Force	14488 kN

Figure 7.4b - Estimated Critical Slip Surface and Factor of Safety Under Complete Saturation for Lower Level-Mangti Landslide



ADOPTED MATERIAL PROPERTIES

1. **Bed Rock** - Impenetrable layer
2. **Boulder-Cobble Mix Soil** - γ= 16.793 kN/m^3,c = 0, ϕ = 30
3. **Silty Sand** - γ= 21.015 kN/m^3,c = 12, ϕ = 29
4. **Poorly Graded Sand** - γ= 21.541 kN/m^3,c = 17, ϕ = 28
5. **Poorly Graded Sand** - γ= 14.092 kN/m^3,c = 13, ϕ = 29

Horizontal Seismicity Coefficient (k_h) = 0.24
Vertical Seismicity Coefficient (k_v) = 0.16

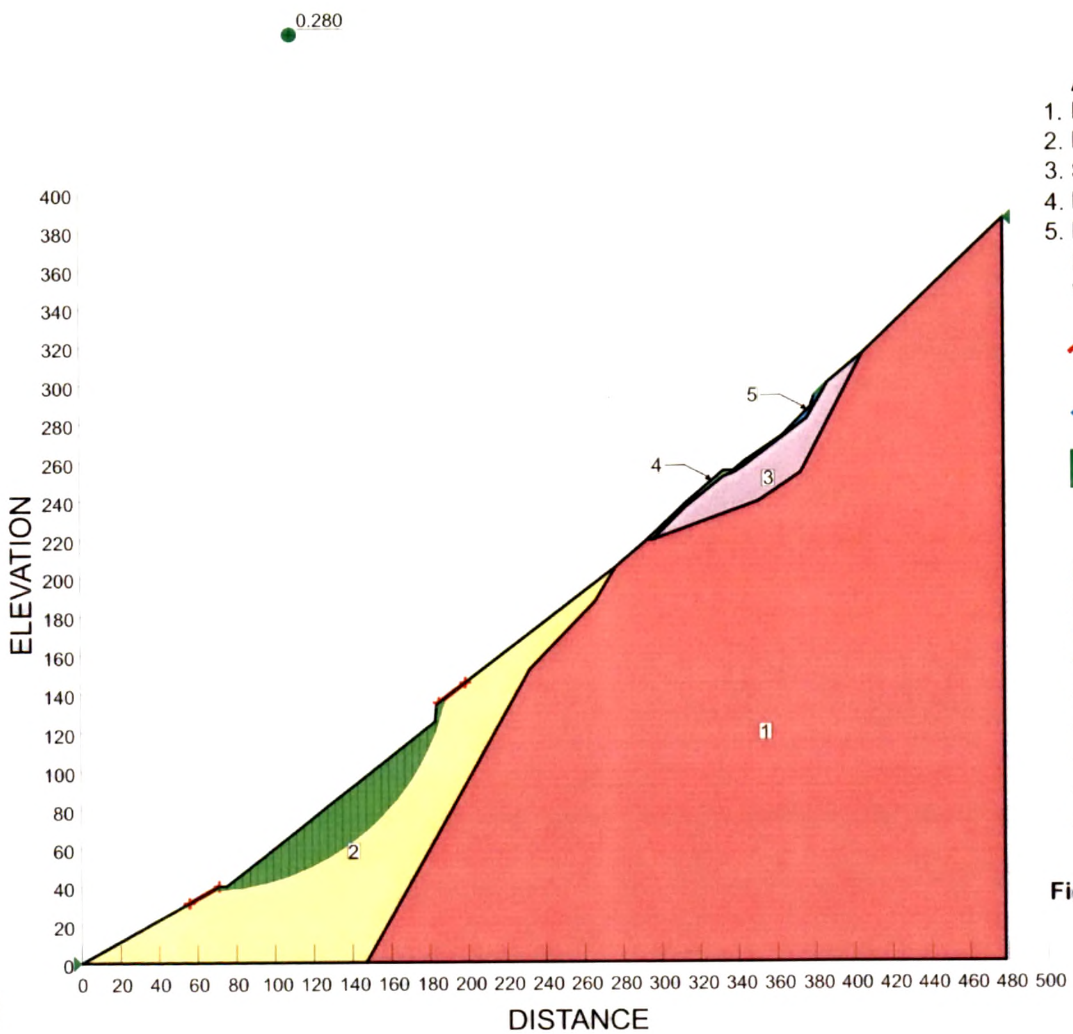
Entry-Exit Line for Slip Surface

Critical Slip Surface

ANALYSIS RESULT OF CRITICAL SLIP CIRCLE

Parameter	
Method	GLE
Factor of Safety	0.557
Total Volume	1741.6 m^3
Total Weight	29247 kN
Total Resisting Moment	2.7442e+006 kN-m
Total Activating Moment	4.9272e+006 kN-m
Total Resisting Force	11461 kN
Total Activating Force	20579 kN

Figure 7.4c - Estimated Critical Slip Surface and Factor of Safety Applying Seismic Loading Factor for Lower Level-Mangti Landslide



ADOPTED MATERIAL PROPERTIES

1. **Bed Rock** - Impenetrable layer
2. **Boulder-Cobble Mix Soil** - γ= 16.793 kN/m^3,c = 0, ϕ = 30
3. **Silty Sand** - γ= 21.015 kN/m^3,c = 12, ϕ = 29
4. **Poorly Graded Sand** - γ= 21.541 kN/m^3,c = 17, ϕ = 28
5. **Poorly Graded Sand** - γ= 14.092 kN/m^3,c = 13, ϕ = 29

Horizontal Seismicity Coefficient (k_h) = 0.24
Vertical Seismicity Coefficient (k_v) = 0.16

Entry-Exit Line for Slip Surface

Piezometric Line

Critical Slip Surface

ANALYSIS RESULT OF CRITICAL SLIP CIRCLE

Parameter	
Method	GLE
Factor of Safety	0.28
Total Volume	2211.8 m^3
Total Weight	37143 kN
Total Resisting Moment	1.089e+006 kN-m
Total Activating Moment	3.875e+006 kN-m
Total Resisting Force	8430.8 kN
Total Activating Force	30004 kN

Figure 7.4d - Estimated Critical Slip Surface and Factor of Safety Under Complete Saturation and Applying Seismic Loading Factor for Lower Level-Mangti Landslide

Table 7.3 – Estimated Factor of Safety Using Various Approaches
Upper Level-Mangti Landslide

Approaches Analyzed Case		Bishop	Janbu	Morgenstern-Price	GLE
Natural Condition	Moment Equilibrium	0.939	-	0.933	0.933
	Force Equilibrium	-	0.822	0.926	0.933
Complete Saturation	Moment Equilibrium	0.353	-	0.386	0.393
	Force Equilibrium	-	0.244	0.384	0.393
Applying Seismic Loading	Moment Equilibrium	0.642	-	0.642	0.658
	Force Equilibrium	-	0.572	0.638	0.658
Complete Saturation and Applying Seismic Loading	Moment Equilibrium	0.241	-	0.304	0.306
	Force Equilibrium	-	0.187	0.301	0.306

Table 7.4 – Estimated Factor of Safety Using Various Approaches
Lower Level-Mangti Landslide

Approaches Analyzed Case		Bishop	Janbu	Morgenstern-Price	GLE
Natural Condition	Moment Equilibrium	0.791	-	0.787	0.790
	Force Equilibrium	-	0.737	0.783	0.790
Complete Saturation	Moment Equilibrium	0.248	-	0.400	0.207
	Force Equilibrium	-	0.133	0.393	0.207
Applying Seismic Loading	Moment Equilibrium	0.546	-	0.548	0.557
	Force Equilibrium	-	0.498	0.544	0.557
Complete Saturation and Applying Seismic Loading	Moment Equilibrium	0.224	-	0.402	0.280
	Force Equilibrium	-	0.135	0.404	0.280

SLOPE STABILITY MODELING INCORPORATING REINFORCEMENT AND STRUCTURAL COMPONENTS

The limit equilibrium method of slices was initially developed for conventional slope stability analyses. The early developers of the method recognized some of the inherent potential difficulties of determining realistic stress distributions. For example, Lambe & Whitman (1969), in their textbook *Soil Mechanics* pointed out that the normal stress at a point acting on the slip surface should be mainly influenced by the weight of the soil lying above that point. It seems like they were concerned that other factors could influence the base normal stress and that this may not be appropriate. In spite of the early developers' concerns, over the years concentrated loads were incorporated into the method mainly to simulate equipment or other surcharge loading on the slope crest. Later, thoughts on the subject migrated to the idea that if concentrated point loads can be included in the method, then why not include lateral concentrated point loads to represent reinforcement. Conceptually, there seemed to be no reason for not doing this, and consequently the simulation of reinforcement with lateral concentrated loads has become common in limit equilibrium stability analyses.

In this presented case study of Mangti Landslide, an attempt has been made to apply lateral concentrated loads to simulate reinforcement in a limit equilibrium analysis to achieve the desired Factor of Safety, thereby, facilitating the development of Landslide Hazard Mitigation Plan. For this techno-economic viability has been chiefly considered towards choosing the type and quantum of a particular reinforcement for curtailing the costs. Three types of reinforcement viz. Uniform Pressure Lines (To imitate the load exerted by a Gabbion, normal to the sliding surface), Anchors and Soil Nails (Lazarte et al. 2003) have been conservatively used in simulation so as to achieve the desired Factor of Safety with minimal structural elements.

UNIFORM PRESSURE LINES

Surface surcharge pressures can be simulated with what is known as a surcharge load. The surcharge at the toe of the slope represents a Gabion or a Masonry Retaining Wall. The surcharge load must be defined above or on the ground surface line. The loading can be applied in a vertical direction or in a direction normal to the ground surface line. The vertical option is useful when modeling a berm, gabion or a masonry retaining wall. The normal direction can be used when modeling water or other fluid type of material when the loading is hydrostatic. As illustrated in the Figure 7.5a & b, the surcharge load regions are crosshatched. SLOPE/W creates slices so that slice edges fall at the ends of the surcharge load. A force representing the surcharge is added to the top of each slice as a point load. The force is equal to the vertical distance at mid-slice from the ground surface to the top of the surcharge load times the slice width times the specified surcharge (or unit weight).

In case of Mangti Landslide for Lower Level and Upper Level slides, a Uniform Pressure Line is drawn for a height of 5m and 4m respectively, while applied load is keyed in as Normal. As per the type of availability of rocks in this region the unit weight for the material was chosen to be 25 KN/m^3 in the limit equilibrium analysis.

ANCHORS

An anchor in SLOPE/W is reinforcement that consists of a bar that has a free length and a bonded length (Cheney, 1990). The capacity of the anchor is controlled either by the strength of the bar itself or by the shear resistance between the bonding grout and the soil. The bond pull-out skin friction is dependent on the ground conditions and the installation procedure and is therefore a site-specific parameter. All SLOPE/W analyses are per unit width perpendicular to the section. The re-inforcing therefore also has to be resolved into a per unit width force. Anchors are by default assumed to be tensioned or very rigid relative to the soil, and the load is assumed to be active immediately. SLOPE/W allows us to specify the ultimate breaking capacity of the bar together with a bar safety factor and an anchor spacing. The maximum reinforcement load for a tensioned anchor is computed as suggested by Krahn (2004):

Maximum Reinforcement Load = Bar Capacity ÷ Bar Safety Factor ÷ Spacing

The Bond Resistance is the design pullout resistance per unit length of the bonded zone. The Bond Resistance is a computed value based on the borehole diameter, the unit bond skin friction, a specified bond safety factor and the anchor spacing.

In equation form it can be represented as:

Bond Resistance = Unit bond Skin friction x π x Bond Diameter

The Bond Resistance is in units of force per unit length (F/L) of bond. The maximum pullout resistance available is the Bond Resistance times the total Bonded Length. In equation form this too can be represented as:

Maximum Pullout Resistance = Bond Resistance ÷ Bond Safety Factor ÷ Spacing

In SLOPE/W, the applied load is defined as the load that must be mobilized to achieve an acceptable factor of safety against potential failure of the retained soil wedge.

In all 08 rows of Anchors have been proposed for acquiring stability of the Mangti Landslide (Figure 7.5a & b). 03 rows for the Upper Level slide and 05 rows for the Lower Level slide. The specifications for each anchor applied in limit equilibrium analysis are shown in snapshots below (Plate VII.1 & VII.2). Plate VII.1, depicts the specifications proposed for Anchors and Soil Nails to be incorporated for Lower Level-Mangti Landslide and Plate VII.2, depicts the specifications proposed for Anchors to be incorporated for Upper Level Mangti-Landslide.

SOIL NAILS

Nails in SLOPE/W behave similar to anchors, except that the bond length is equal to the nail length (Figure 7.5b), the working load is always variable and the nails by default are considered as being active immediately; the specified parameters for nails are:

- Borehole diameter or effective diameter for driven nails
- Bond safety factor
- Bond unit skin friction
- Nail spacing horizontally along the wall
- Bar (reinforcement) ultimate capacity
- Bar (reinforcement) safety factor
- Shear capacity
- Shear safety factor
- Direction of shear-Parallel to slip surface base or Perpendicular to reinforcement

Identical to an anchor, the Bond Resistance, the Maximum Pullout Resistance and the Maximum Reinforcement Load are computed (Krahn, 2004) as follows:

Bond Resistance = Unit bond Skin friction x π x Bond Diameter

Maximum Pullout Resistance = Bond Resistance ÷ Bond Safety Factor ÷ Spacing

Maximum Reinforcement Load = Bar Capacity ÷ Bar Safety Factor ÷ Spacing

In Mangti Landslide 02 rows of Soil Nails are proposed in the toe portion of Lower Level Slide since at this place the critical slip surface passes through a very shallow depth and hence Soil Nails can be effectively be used instead of installing deep seated Anchors to save the cost. The specifications for each Soil Nail applied in limit equilibrium analysis are shown in snapshots below (Plate VII.1).

STABILITY MODELING

Mangti Landslide lies in Zone-V of Seismic Zones of India and looking towards the earthquake history of the study area the stability modeling is carried out including the seismic zone factors mentioned in IS 1893 (Part 1): 2002. The structural layout plan of reinforcement elements is depicted in Figures 8.5a & b, and the simulated results obtained is shown in Table 7.5. A detailed report of the stability modeling derived from Geo-SLOPE/W is presented as **ANNEXURE – 5.**

Table 7.5 - Estimated Factor of Safety from Various Analysis Techniques, Applying Reinforced Structural Elements for Upper and Lower Level-Mangti Landslide

Reinforced Structural Elements		Bishop	Janbu	Morgenstern-Price	GLE
Upper Level Slide	Moment Equilibrium	1.140	-	1.125	1.125
	Force Equilibrium	-	0.942	1.119	1.125
Lower Level Slide	Moment Equilibrium	1.125	-	1.115	1.115
	Force Equilibrium	-	0.860	1.112	1.115

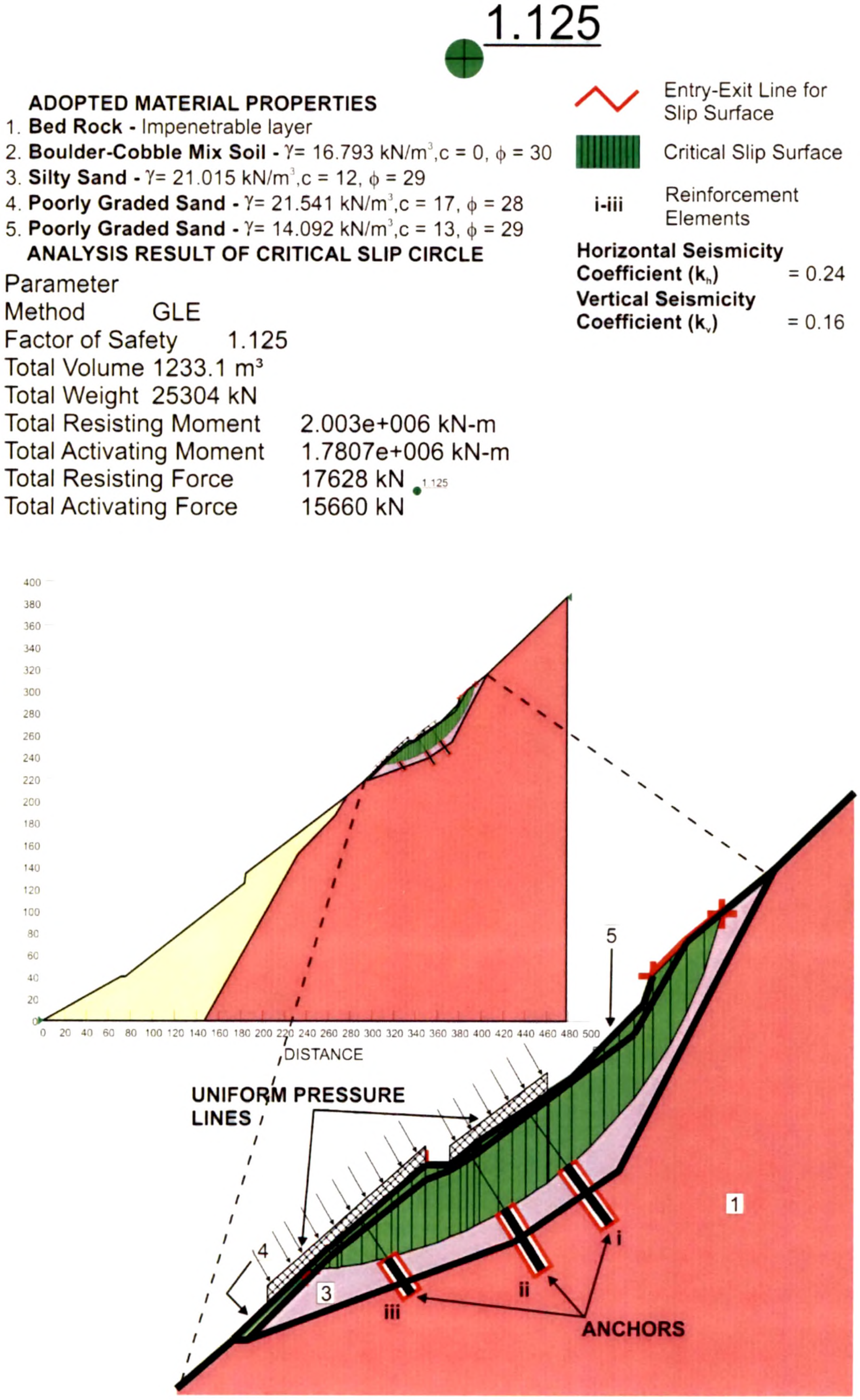


Figure 7.5a – 2-D GeoSlope Slope Stability Model of Upper Level-Mangti Landslide

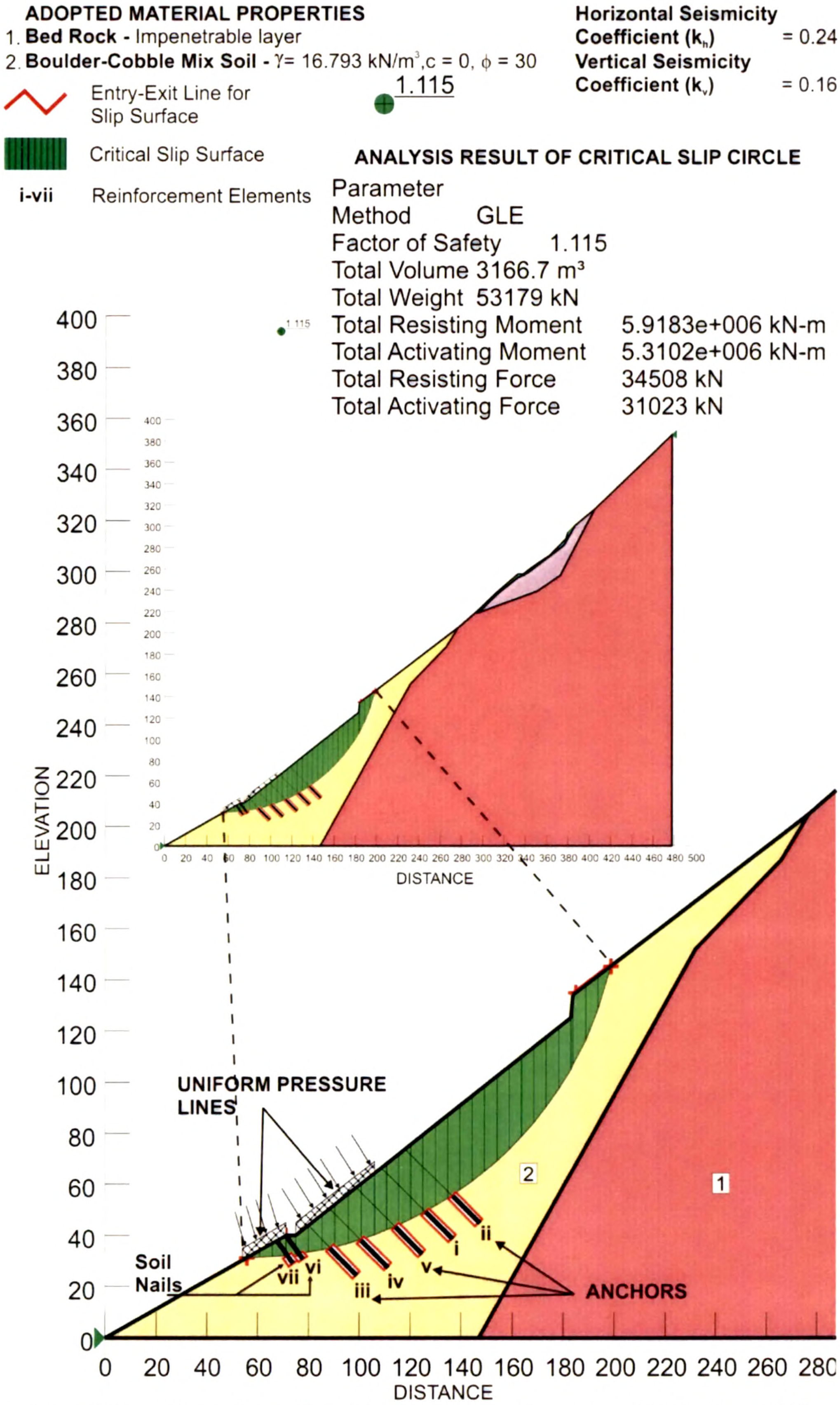
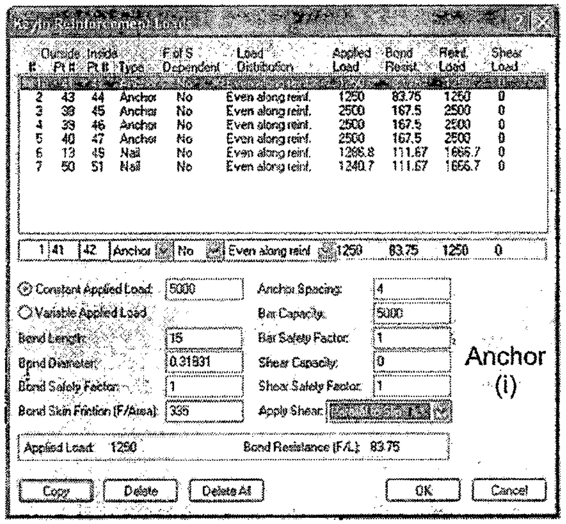
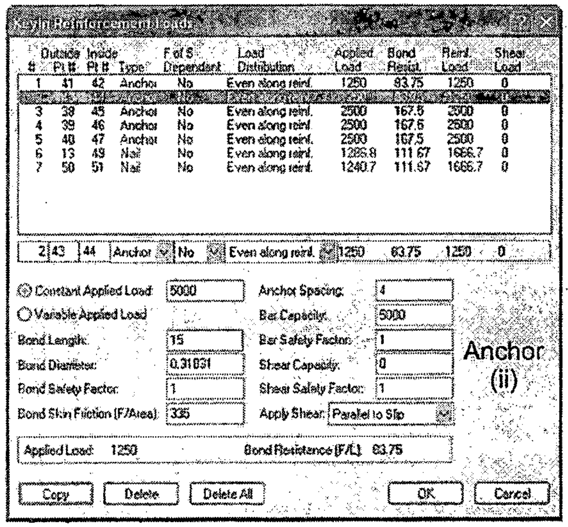
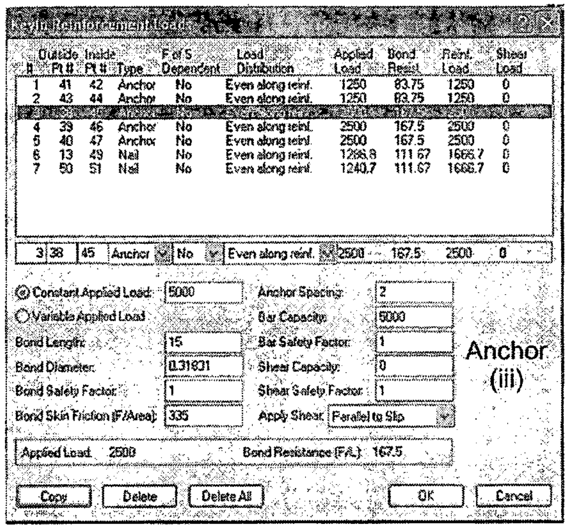
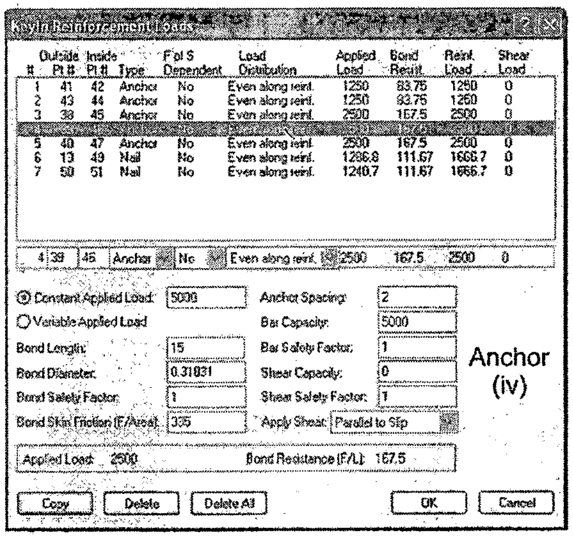


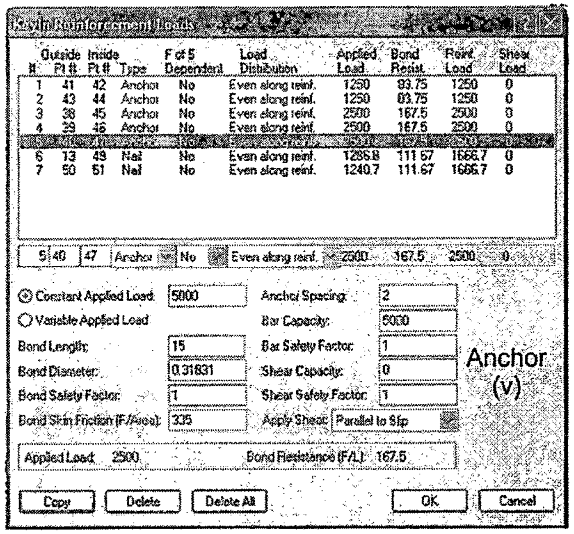
Figure 7.5b – 2-D GeoSlope Slope Stability Model of Lower Level-Mangti Landslide











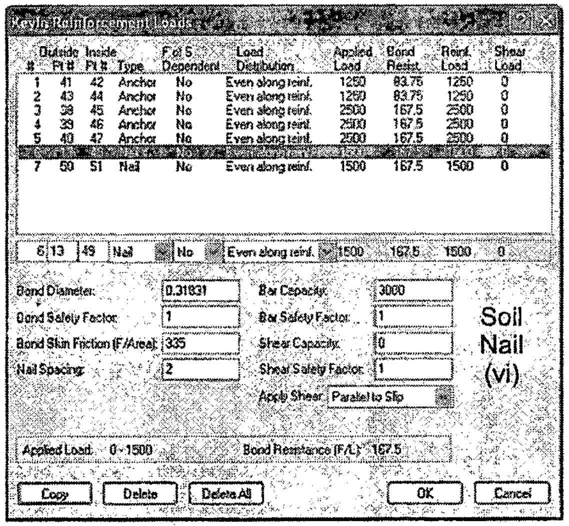


Plate VII.1 – contd.....

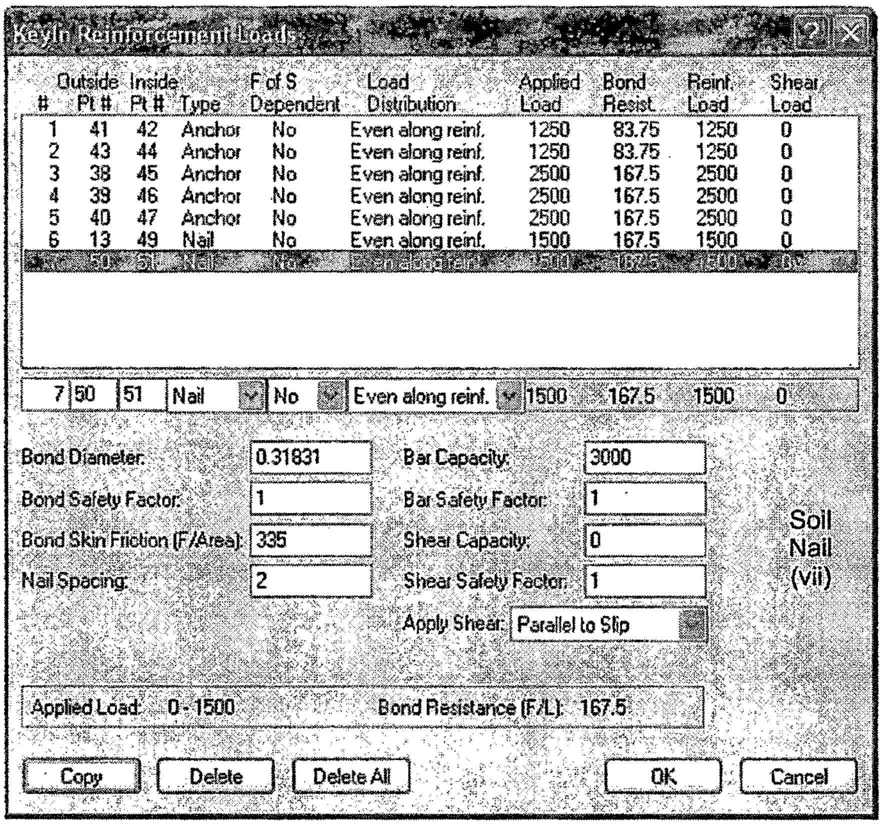


Plate VII.1 - Snapshots of The Recommended Reinforcement Parameters for Anchors and Soil Nails- Mangti Lower Level Slide

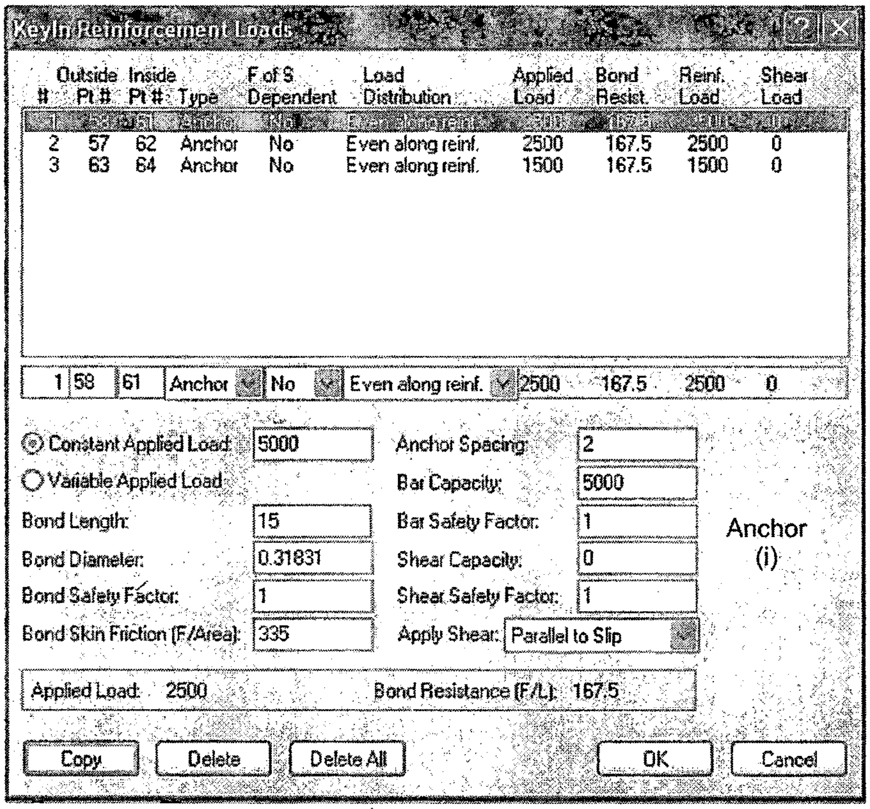
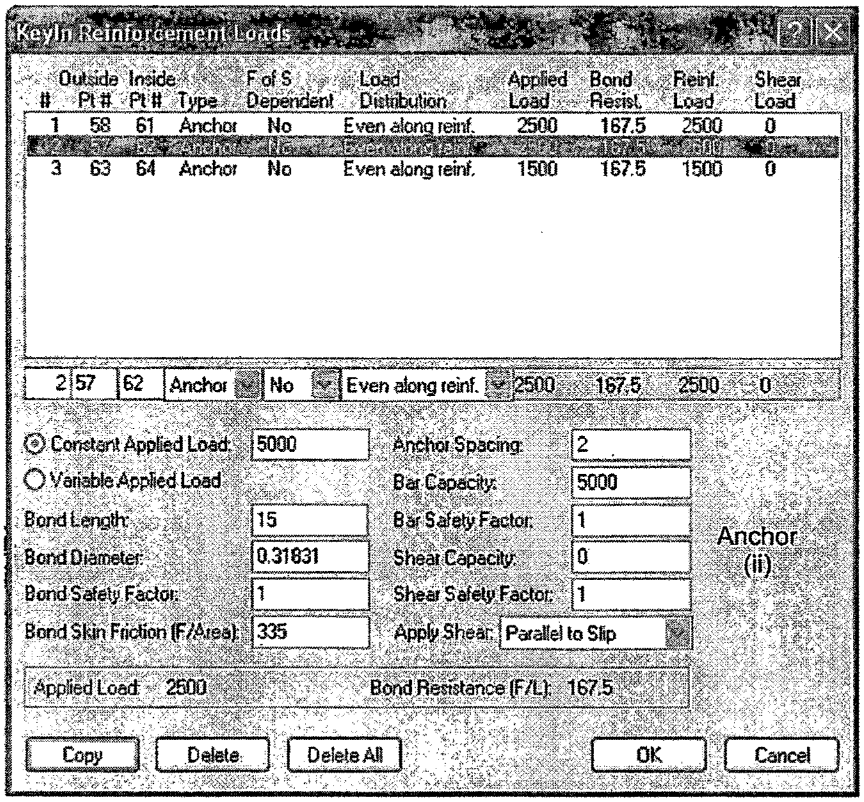


Plate VII.2 – contd......



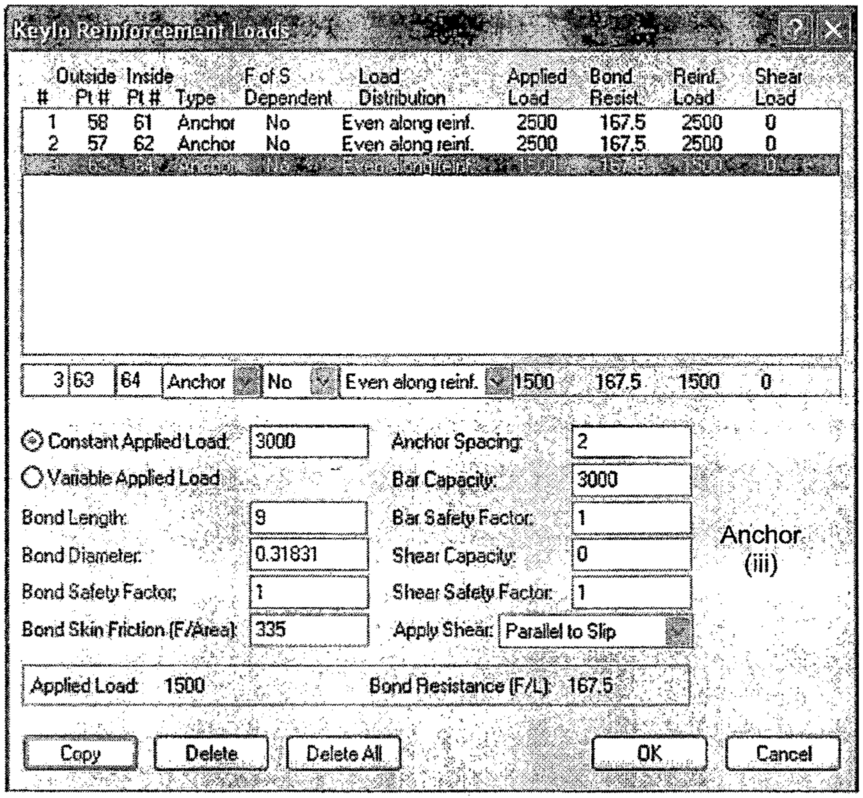


Plate VII.2 - Snapshots of The Recommended Reinforcement Parameters for Anchors - Mangti Upper Level Slide