4. LANSLIDING AND SLOPE STAPILITY ANALYSIS

4.1 Introduction

Landslides are very common in mountainous areas and have serious consequences for almost all construction activities. The main cause of landsliding is gravitational forces and it is a result of shear failure along sliding surface. Slope stability analysis is usually carried out to determine the degree of safety of a given slope.

This report is to provide slope stability analysis to assist the safety condition of the proposed site of Rawabi City. Slope stability analysis was carried out for several cases to cover all expecting conditions. It was carried out in models representing the excavations, loads due to buildings, backfill materials behind retaining wall building at Town Center, traffic loads, embankments of roads and expected seismic forces. This report also discusses the results of slope stability analysis and pointed out critical cases, explaining their effects and suggested correction measures.

4.2 Purposes

The purpose of this report is to assist the safety condition of the proposed site of Rawabi City, through the following:

- Slope stability analysis for all loading conditions.
- Identifying the critical cases regarding slope stability analysis.
- Mitigation processes required to overcome expecting critical cases.

4.3 Procedures

The procedures to carry this task are as follows:

- Selecting of critical sections.
- Detailed geometric description and loads for buildings, excavations, backfilling behind retaining walls and embankments and expected seismic forces.
- Site visit and inspection of the site along the selected critical sections. This is to provide the required geotechnical conditions and any other missing parameters.
- Slope stability analysis software called GeoStudio 2004 (slope/w) was used to carry out detailed slope stability analysis for the critical sections.

The loading conditions for slope stability analysis are as shown in Table 4.1 below.

Table 4.1: Loading conditions for slope stability analysis.

Loading Conditions	**Notes**
Basic	Including buildings, excavations and backfilling behind the retaining wall of the buildings and embankments.
Basic + Seismic Load	As above for loads but this case includes seismic analysis based on simple analysis method for seismic effect.

4.4 Landslides

In many parts of the world, especially in mountainous countries, landslides are very common and have serious consequences for almost all construction activities in these countries. Even relatively small changes of the stability may trigger landslides, especially in areas where slides previously have taken place. For more details regarding landslides specially, causes, investigation and analysis and methods of correction landslides see Appendix 4.1.

4.5 Slope Stability Analysis

Stability analysis is a check process by making calculation to determine the safety of slopes. This check involves determining and comparing the ratio of resisting forces or moment to the sliding forces or moment along the most likely rupture surface. The most likely rupture surface is the critical plane that has the minimum factor of safety. The stability analysis of a slope is not an easy task. Evaluation variables such as the soil stratification and its in-place shear strength parameters may prove to be a very difficult task. Seepage through the slope and the choice of a potential slip surfaces add to the complexity of the problem.

Stability analysis is carried out with the following basic assumptions:

- Failure is along a slip surface or failure surface which may be plane or curved and the problem will be solved as a two-dimensional plane problem.
- Soil strength properties are isotropic
- The safety factor is determined by the limit equilibrium method.

Slope stability analysis usually carried out for various loading conditions. The geometry of sections was represented exactly as found out through surveying. In addition to that, the soil layers were represented with their corresponding geotechnical parameters across each section in the software.

Slope stability analysis was carried out using software called GeoStudio 2004 (Slope/w). Results are then presented and conclusions and recommendations are stated for the proposed site of Rawabi City.

4.5.1 Geometrical Description of Critical Sections

Detailed AutoCAD drawings were prepared for all three critical sections in Hai 1 according to the surveying. Figure 4.1 shows the locations of all three sections across Hai 1., Figure 4.2 shows sections 1, 2 and 3. The selections of these critical sections were based on the height, slope and expected loads of buildings. Figures 4.3 and 4.4 show critical sections in Hai 2 and 4 respectively. Other virtual sections were selected and analyzed to cover all the studied area according to the sites topography and local geology (appendix 4.3 shows general sections through Hai 2 and Hai 4).

4.5.2 Geotechnical Parameters

The geotechnical parameters for modeling different types of soil within the study area are shown in Table 4.2. Three basic soil types exist at the site namely: Marlstone, hard Limestone and back fill materials behind retaining walls and embankments of roads. These properties were found out during site visit of the proposed site and the excavations within the site.

4.5.3 Slop Stability Software (GeoStudio 2004 slope/w)

GeoStudio 2004 (slope/w) software is part of comprehensive software package used to carry out slope stability analysis. Detailed descriptions of the software GeoStudio 2004 are summarized in Appendix 4.2. The descriptions include features, applications, input data, output data, types of analysis and results.

4.5.4 Factor of Safely

Appropriate factors of safety are required to ensure adequate performance of slopes throughout their design life. According to several references, factor of safety values for design purposes in our case should be as in Table 4.3.

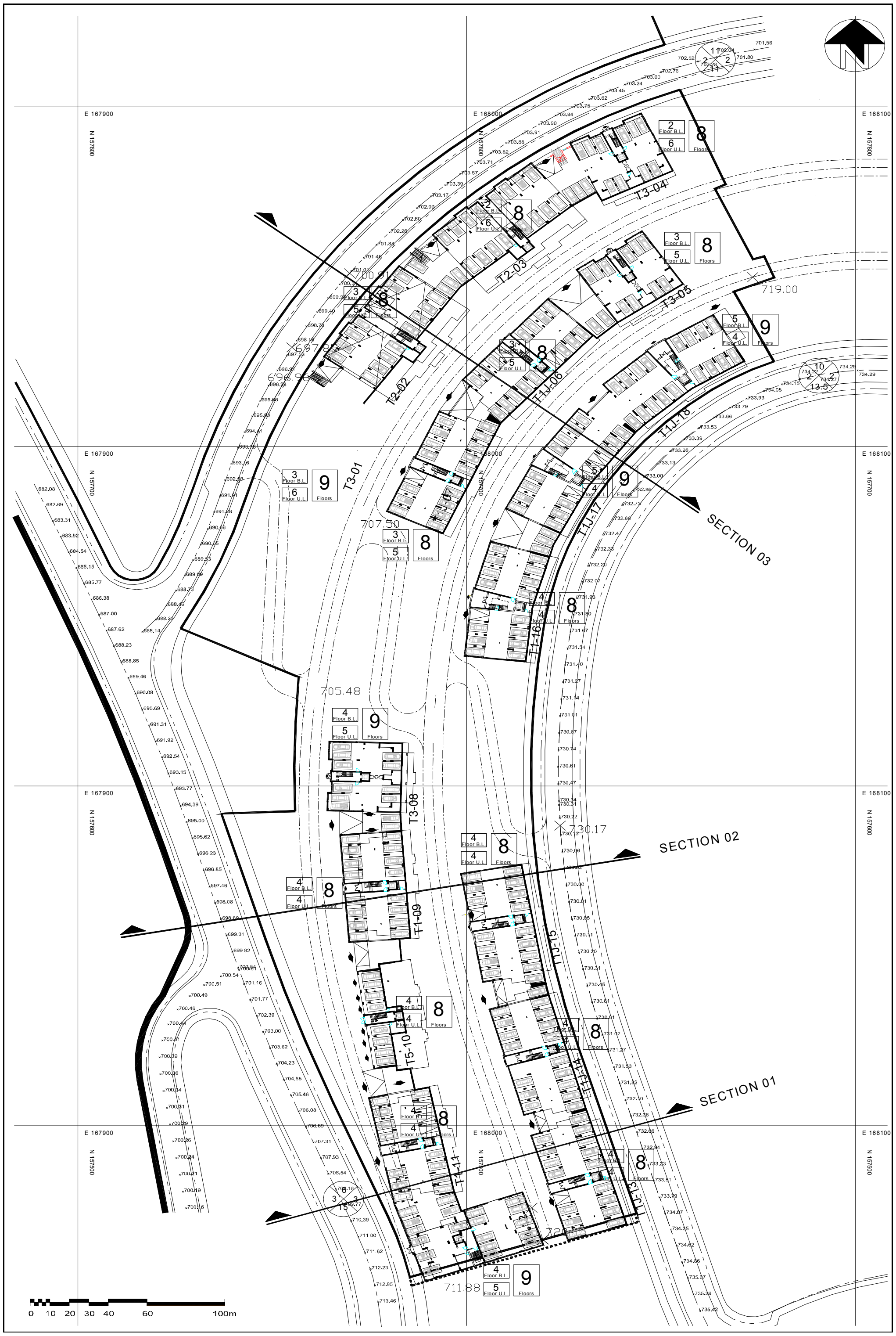

Figure 4.1: Locations of all three sections across Hai 1.

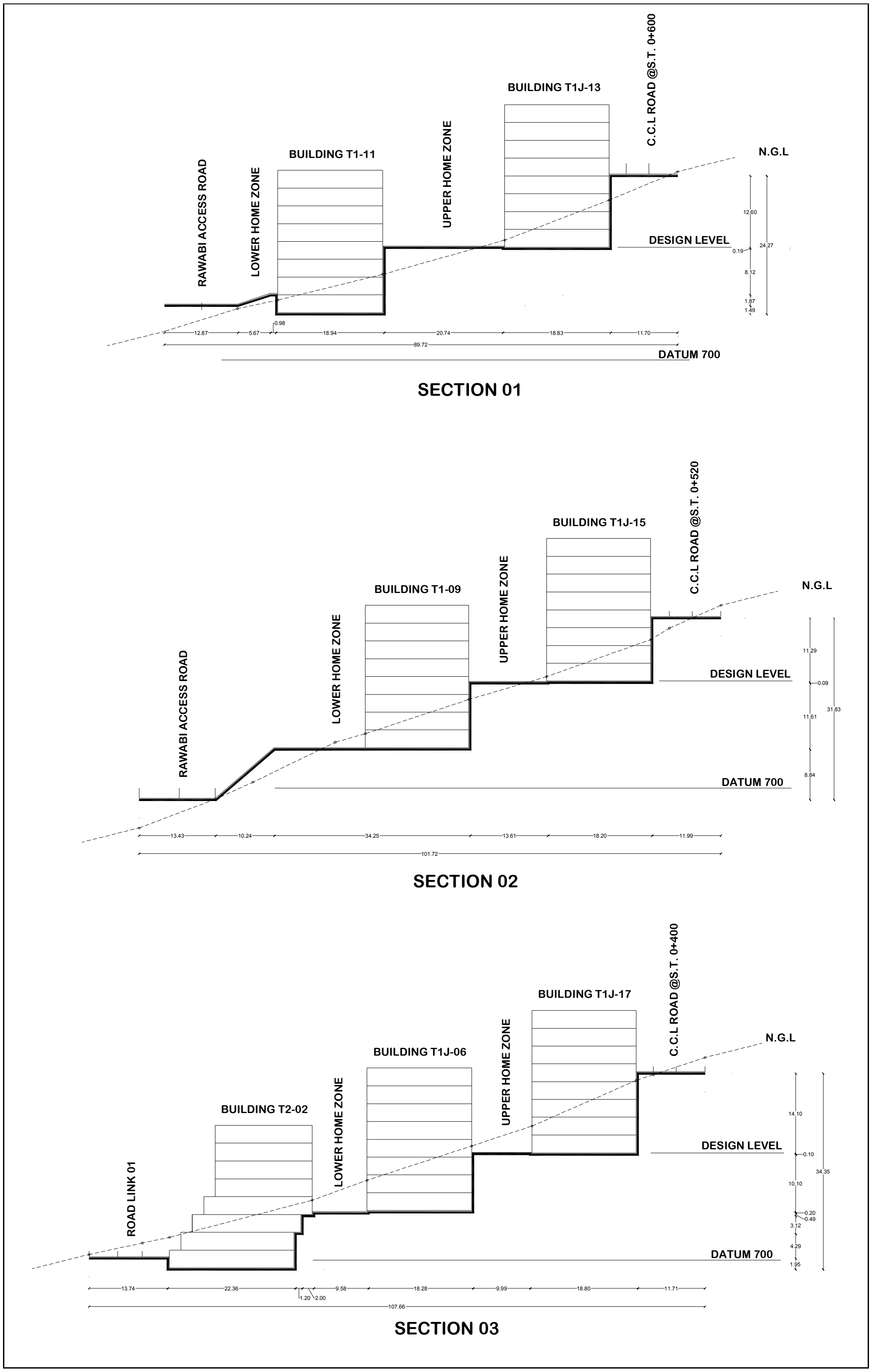

Figure 4.2: Critical sections in Hai 1

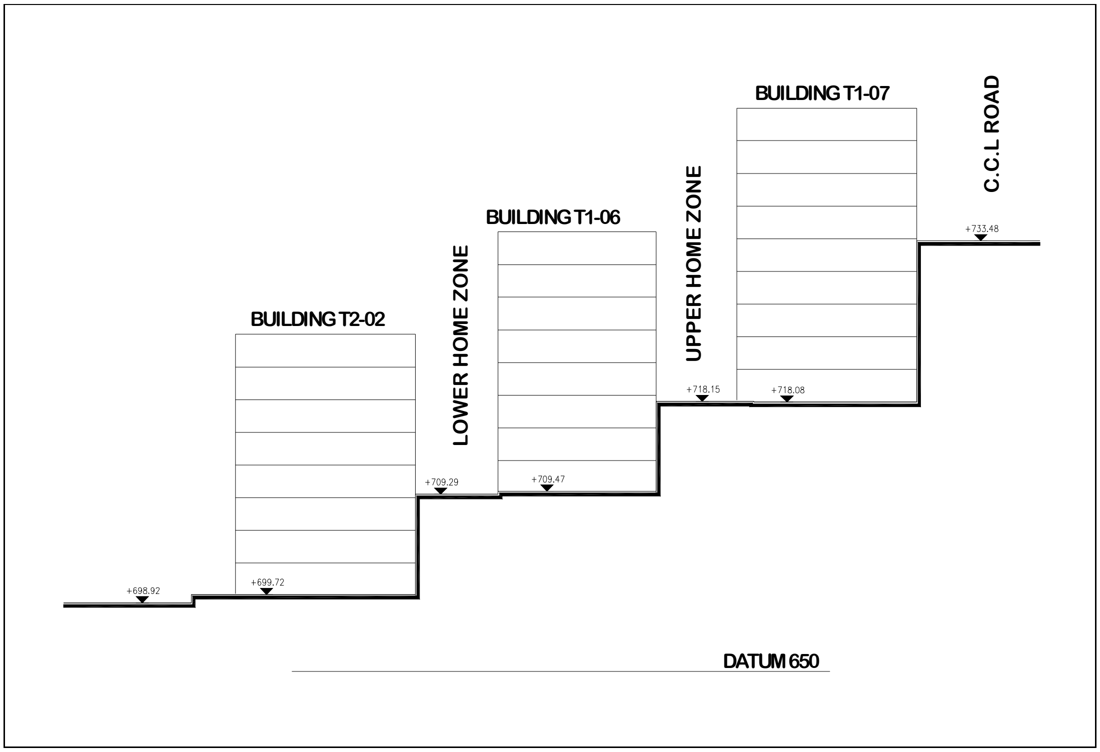

Figure 4.3: Critical sections in Hai 2

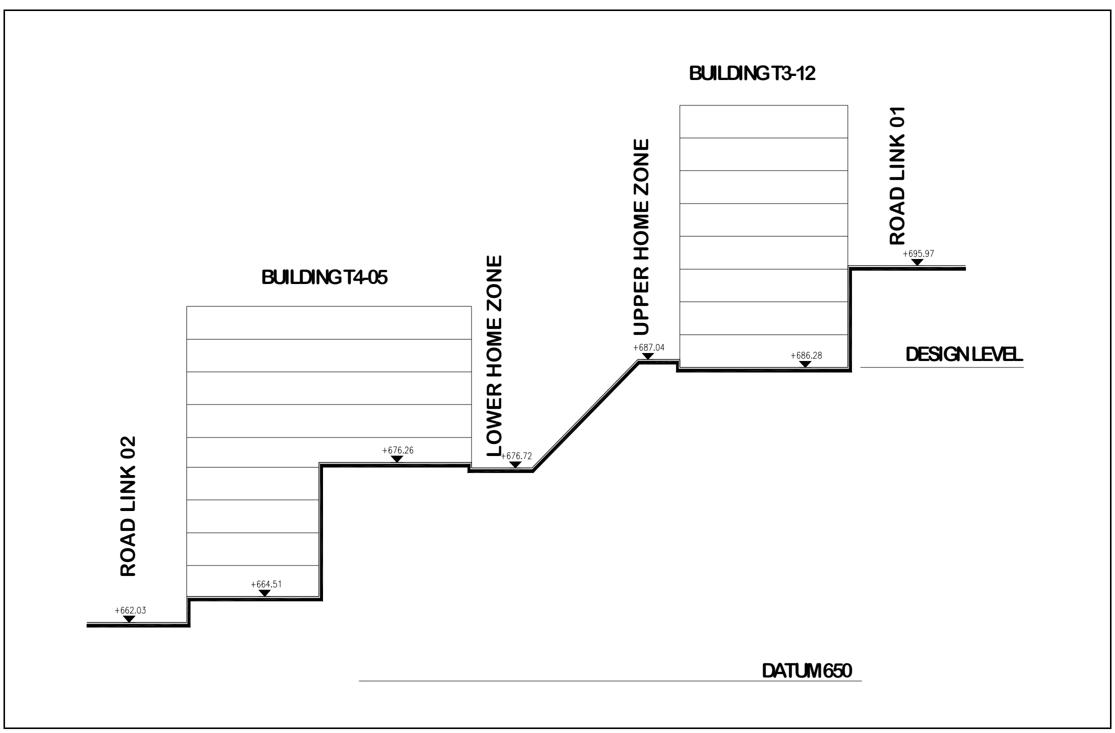

Figure 4.4: Critical sections in Hai 4

Table 4.2: **Geotechnical parameters for different types of soil**

Type of Soil	Geotechnical Properties according the Software	Descriptions
Marlstone	Undrained conditions (Angle of internal friction = 0°): ➢ Unit weight = 17 kN/m^3. ➢ Cohesion = 80 kN/m^2.	The worst condition for this type of soil is assumed that is to say marlstone becomes marl soil due to wetting (infiltration of water) and hence poses the undrained conditions
Hard Limestone	Mohr-Columb parameters: ➢ Unit weight = 20 kN/m^3. ➢ Cohesion = 500 kN/m^2. ➢ Angle of internal friction = 30°	Hard Limestone bedrock layer with cavities filled brownish silty clay of high plasticity. It is strength is reduced on purpose to account for cavities.
Backfill Soil	Mohr-Columb parameters: ➢ Unit weight = 17 kN/m^3. ➢ Cohesion = 0 kN/m^2. ➢ Angle of internal friction = 30°	Selected backfill behind retaining wall the properties used are the worst expected.
Retaining Wall of proposed building	Mohr-Columb parameters: ➢ Unit weight = 20 kN/m^3. ➢ Cohesion = 5000 kN/m^2. ➢ Angle of internal friction = 45°	This type of soil is used to represent the side of the building, it is considered very strong as the slope will not penetrate the building but the slope will be below the buildings.

Table 4.3: Minimum factor of safety required for each loading conditions.

Loading Conditions	Minimum Factor of Safety	
	For Temporary Structures	**For Permanent Structures**
Basic	1.3	1.8
Basic + Seismic Load	1.1	1.3

4.5.5 Procedure of Analysis

The procedure of slope stability analysis using software GeoStudio (slope/w define) is point out as follows:

- Geometrical modeling (two-dimensional representation) of selected sections through the site.
- Geotechnical modeling by inserting soil layers and geotechnical parameters for each layer within the selected sections.
- Factor of safety were found by slope stability analysis software GeoStudio

2004 (slope/w define) using limit equilibrium analysis by three methods, which are: Bishop, Ordinary and Janbu.

- Searching for the minimum factor of safety were done using techniques provided from the software. Such techniques are grid and radius and exit and entry methods.
- Auto search provided by the software, to find minimum factor of safety, was used. This required analyzing the problem with other modern methods such as Morgenstern-Price method. This is to verify the minimum factor of safety found above.
- Table was prepared showing the minimum factor of safety for all sections and loading conditions.
- Identifying the critical cases, such cases that have minimum factor of safety less than the acceptable limit.
- Re-analyze critical cases after suggesting correction measures to increase the factor of safety to acceptable limit.

Analysis of the slope for seismic forces may be done in two methods. First, simple method (pseudo static analysis) and would provide close results as for full dynamic analysis using slope/w software by introducing horizontal Peak Ground Acceleration (Z factor or PGA factor) to introduce seismic forces. The value of Z factor for Rawabi City site from the hazard map (or PGA map, see Fig. 1.3) equals 0.15 and it's very close to 0.20 (zone 2B). Second, more sophisticated dynamic analysis method based on finite element analysis using software quake/w, which is provided by the GeoSudio. The analysis begins by finding initial stresses based on gravity loads, and then dynamic behavior based on maximum expected earthquake record for the study site. Equivalent record is provided by quake/w by introducing maximum expected ground acceleration and duration of the earthquake. After finishing dynamic analysis, then slope/w program was used to determine factor of safety regarding slope stability.

Since full dynamic analysis explained above is very complex and provides higher factor of safety for slope analysis, it is conservative (be in the safe side) to do simple dynamic analysis by inserting Z factor to software slope/w rather than doing full dynamic analysis by finite element method using software quake/w. In addition to that strong record motion to the study site is not available and the record use is an interpolation one rather than real one.

4.5.6 Results of Slope Stability Analysis

Hai No. 1: Slope stability analysis was carried out for Hai 1 for the three critical selected sections. Figures 4.5 to 4.14 show slope stability analysis for all sections and cases in Hai 1.

Table 4.4 below summarizes the results of slope stability analysis. It presents the minimum factor of safety found for each zone for the basic analysis only.

Table 4.4: Results of slope stability analysis for the three selected sections through Hai No.1.

Section Name	Zone	Minimum Factor of Safety	Notes
Section # 1	Upper Building Zone	**7.6**	Safe, Stable Slope
	Lower Building Zone	**22**	Safe, Stable Slope
	Overall Stability	**7**	Safe, Stable Slope
Section # 2	Upper Building Zone	**10**	Safe, Stable Slope
	Lower Building Zone	**15**	Safe, Stable Slope
	Overall Stability	**5.8**	Safe, Stable Slope
Section # 3	Upper Building Zone	**8.3**	Safe, Stable Slope
	Middle Building Zone	**15**	Safe, Stable Slope
	Lower Building Zone	**18**	Safe, Stable Slope
	Overall Stability	**7.3**	Safe, Stable Slope

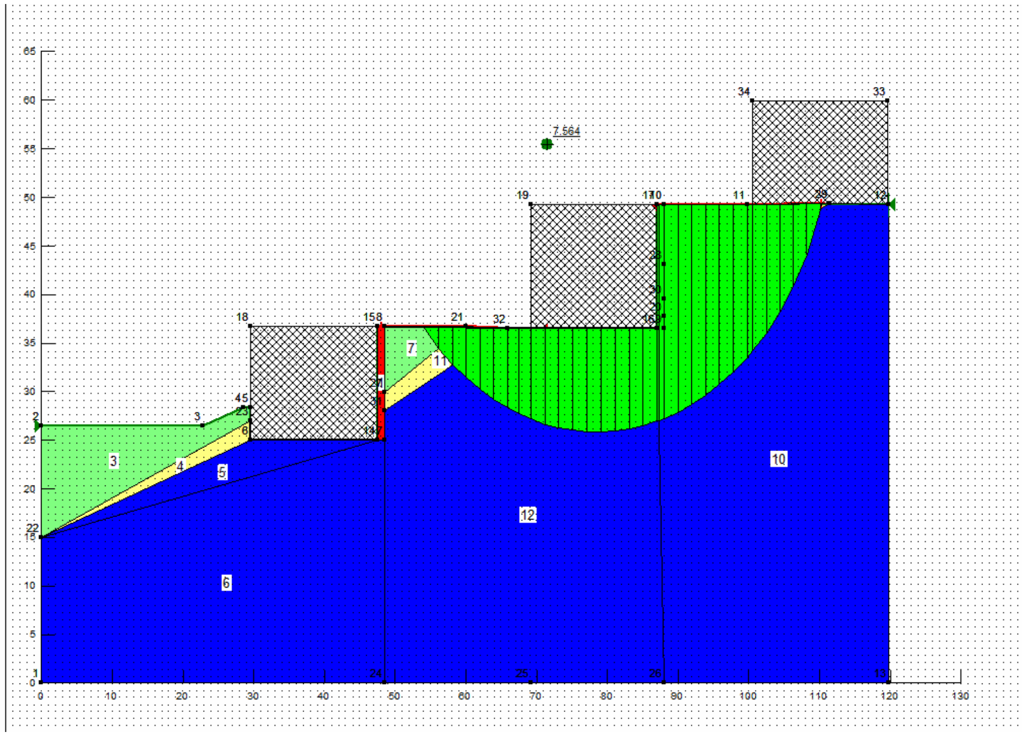

Figure 4.5: Slope stability analysis for section 1 upper zone (Minimum factor of safety = 7.6).

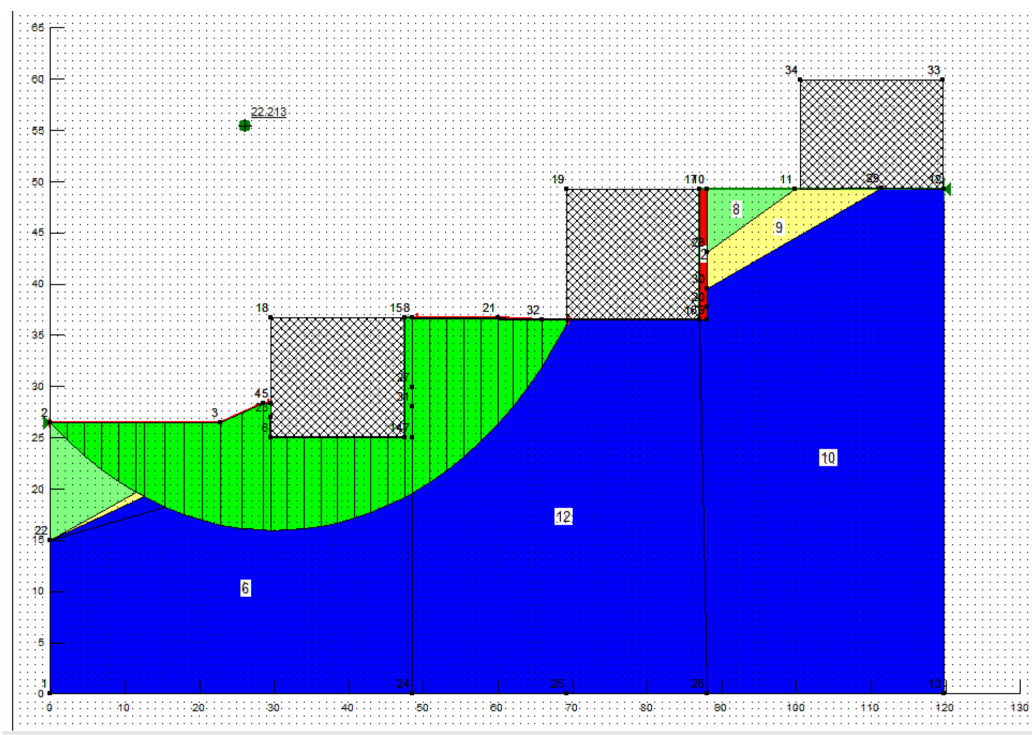

Figure 4.6: Slope stability analysis for section 1 lower zone (Minimum factor of safety = 22).

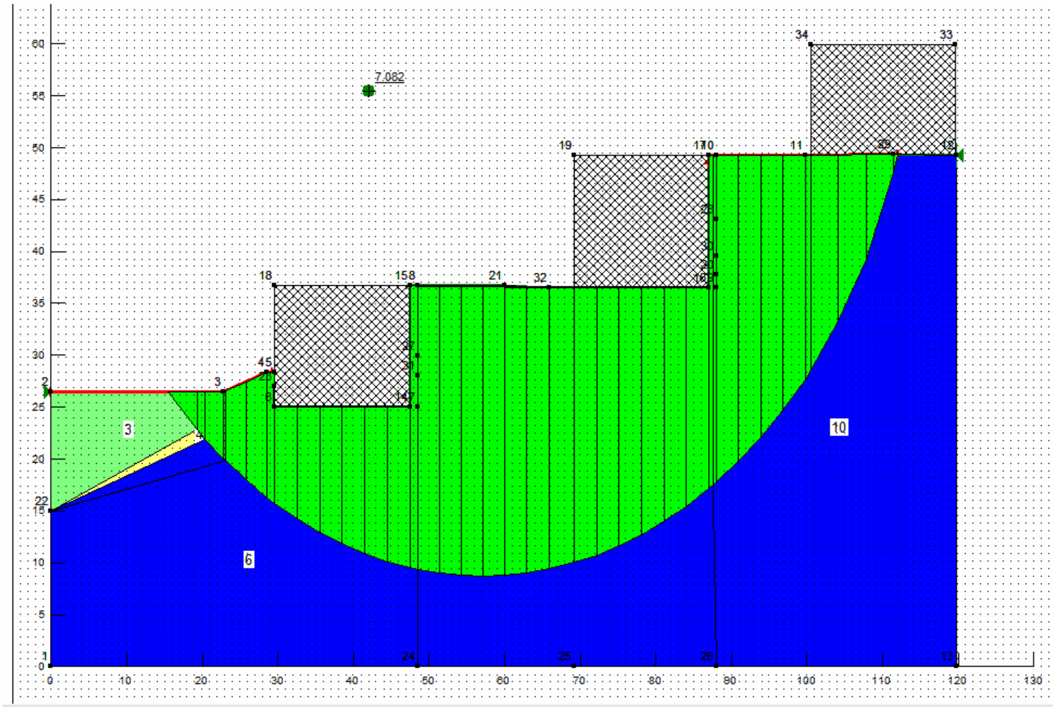

Figure 4.7: Slope stability analysis for section 1 overall zone (Minimum factor of safety = 7).

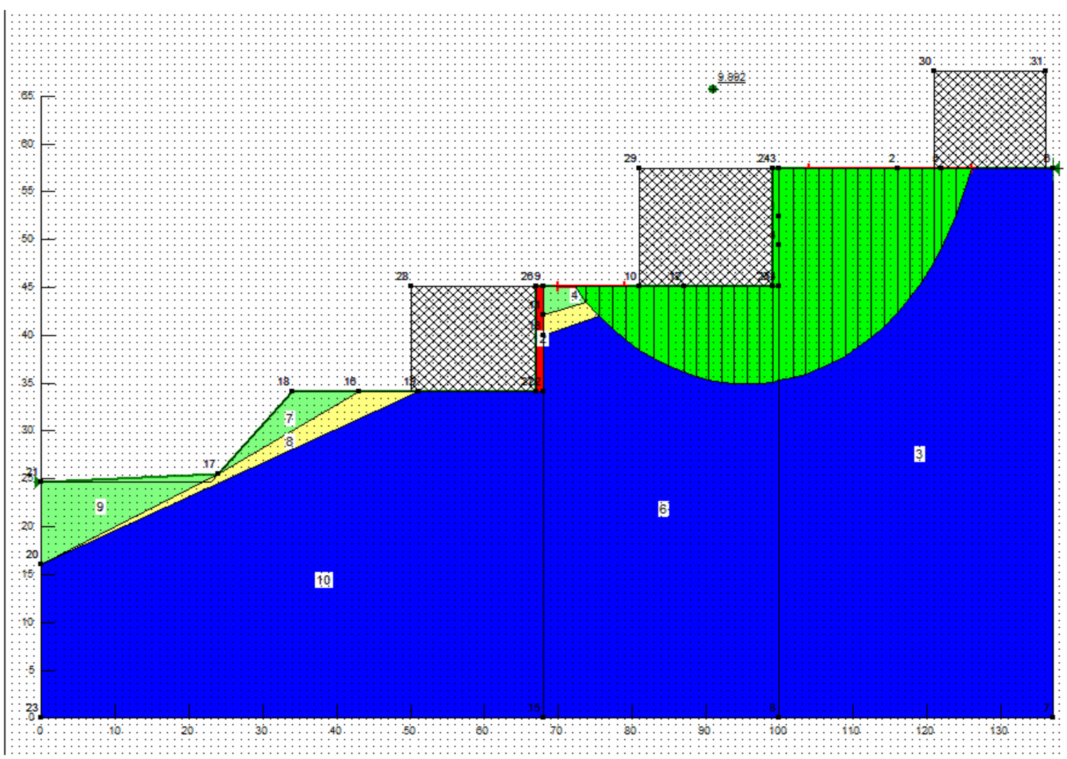

Figure 4.8: Slope stability analysis for section 2 upper zone (Minimum factor of safety = 10).

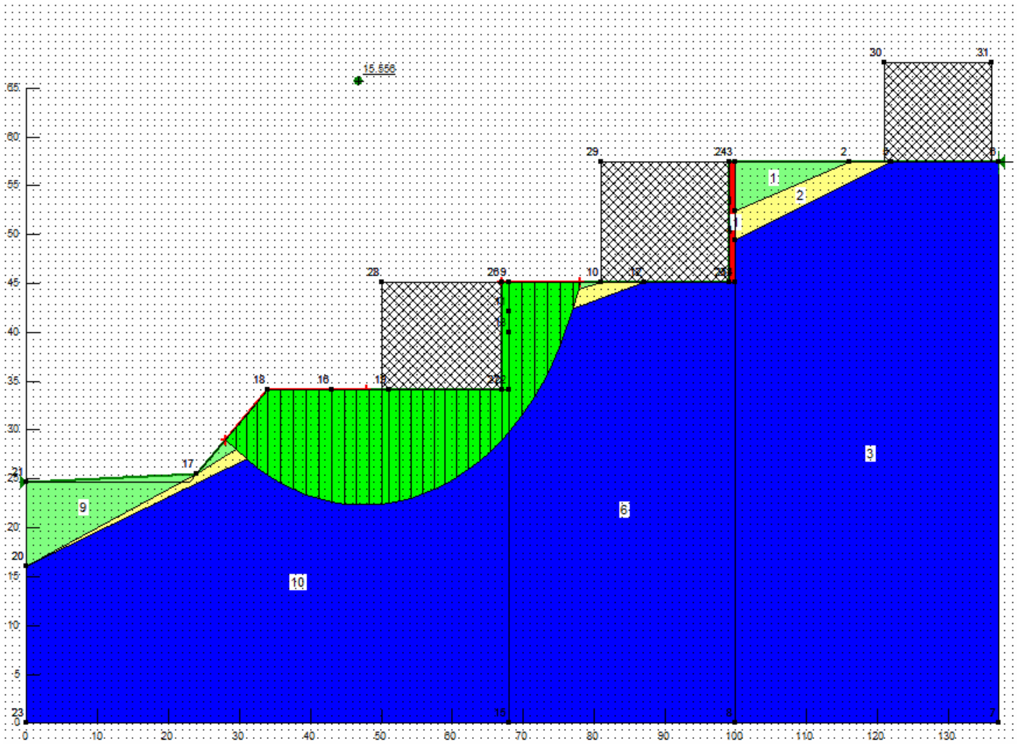

Figure 4.9: Slope stability analysis for section 2 lower zone (Minimum factor of safety = 15.6).

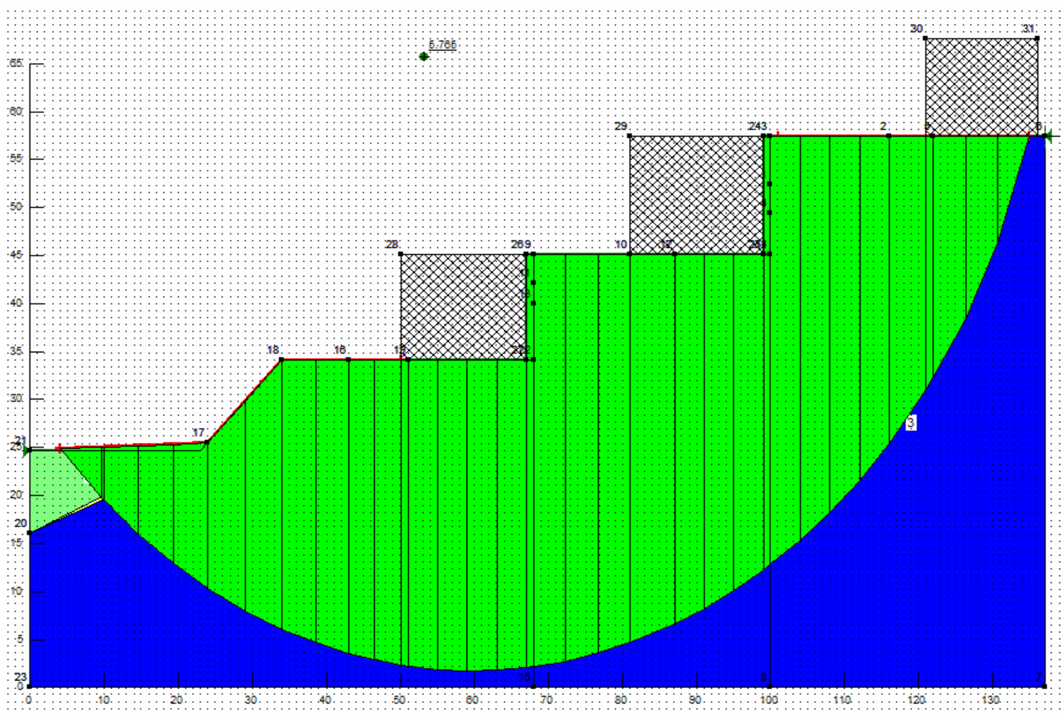

Figure 4.10: Slope stability analysis for section 2 overall zone (Minimum factor of safety = 8).

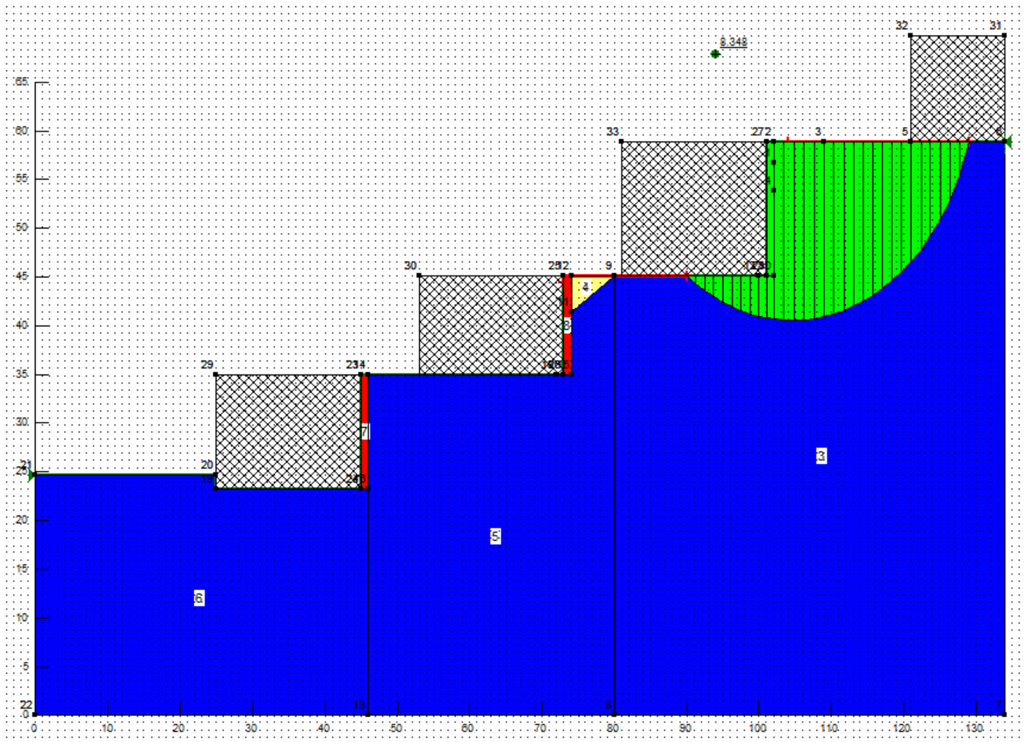

Figure 4.11: Slope stability analysis for section 3 upper zone (Minimum factor of safety = 8.3).

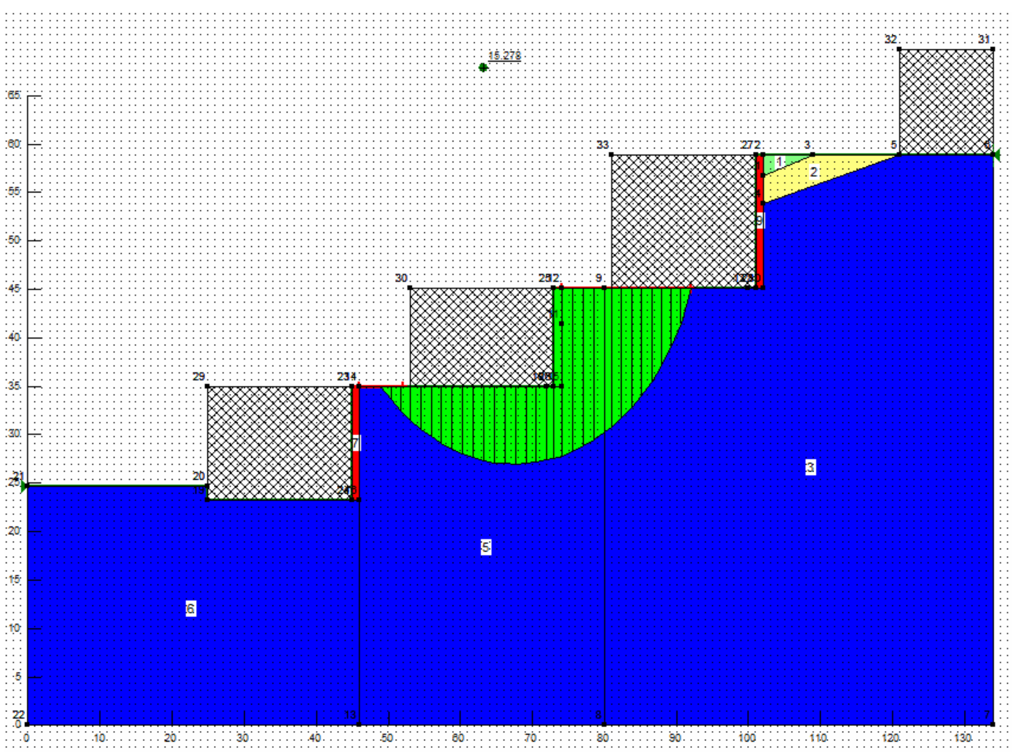

Figure 4.12: Slope stability analysis for section 3 middle zone (Minimum factor of safety = 15).

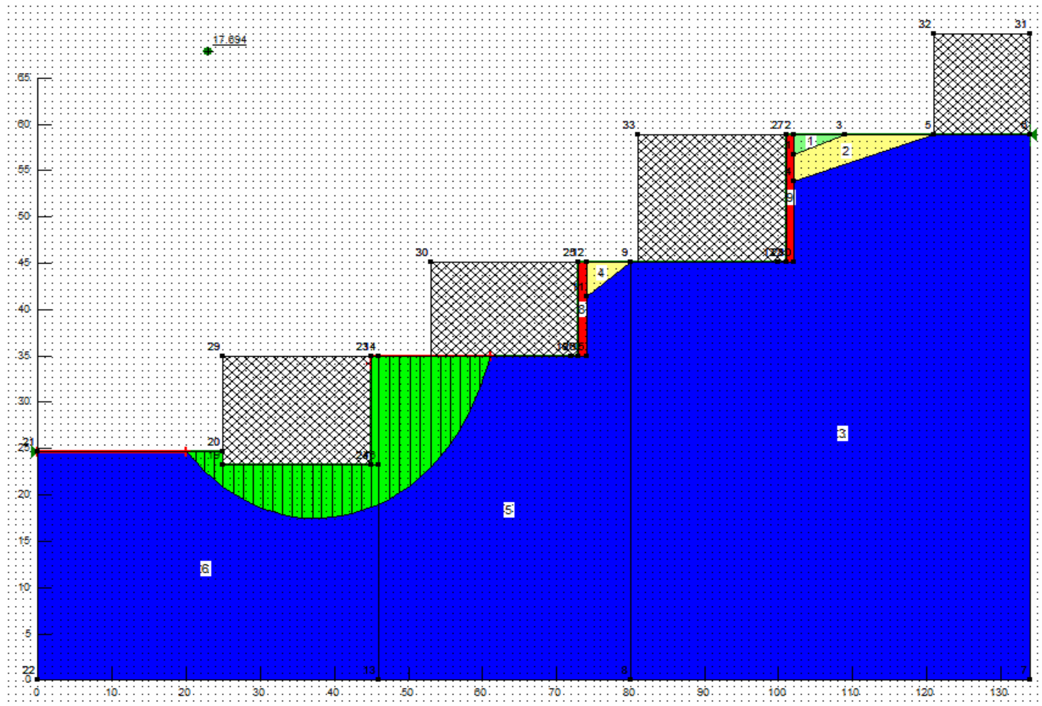

Figure 4.13: Slope stability analysis for section 3 lower zone (Minimum factor of safety = 18).

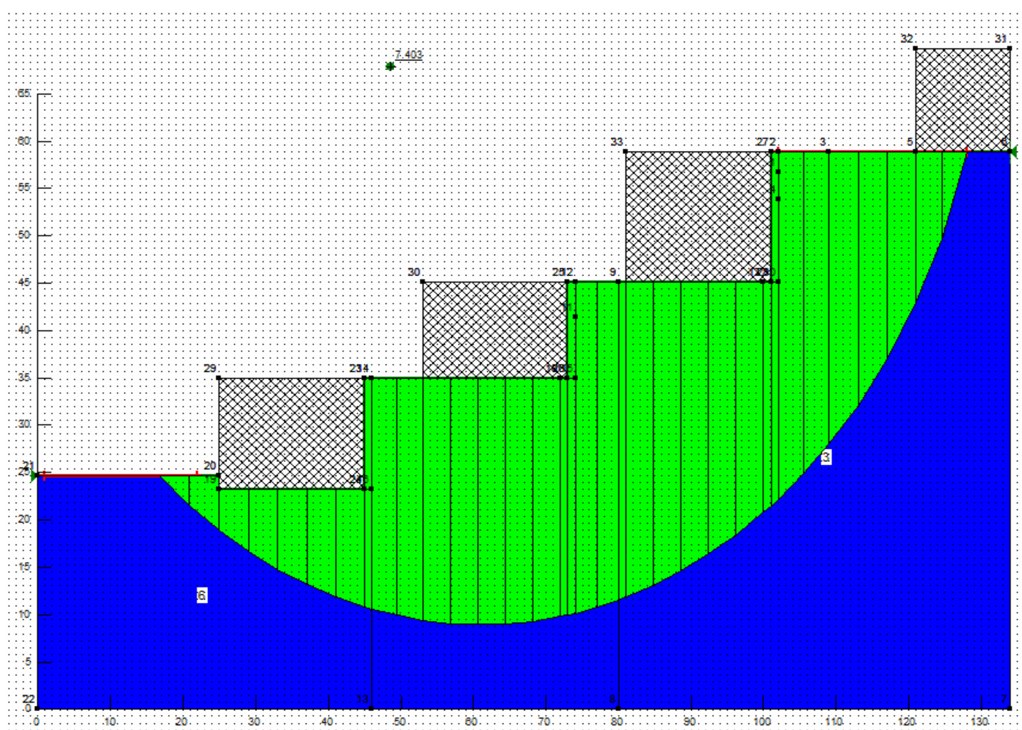

Figure 4.14: Slope stability analysis for section 3 overall zone (Minimum factor of safety = 7.4).

Seismic analysis based on pseudo static method as described in GeoStudio 2004 (slope/w) was performed for the critical case. The critical case here is the least factor of safety in Table 4.4 which equals 5.8 and it was for the case section 2 overall stability. Pseudo static method in GeoStudio is based on entering the expected horizontal earthquake acceleration according to seismic zone. In this case it was taken as 0.2g. The result is shown in Figure 4.15 below and the minimum factor of safety = 3.6.

<u>Virtual Sections</u>: Since there are no sections provided other than Hai 1 in addition to general sections for Hai 2 and Hai 4, virtual sections were suggested as described above. Slope stability analysis was carried out for different scenarios regarding building, excavations, backfilling behind retaining walls and embankment of roads. Scenarios are as follows:

- Increase building loads by 2-story
- Increase excavation by 2-story.
- Adding building loads (22-story) on top of slope (Town Center).

Figure 4.16 shows typical virtual section that has two extra excavation stories. Figures 4.17 to 4.19 present results of slope stability analysis for virtual sections.

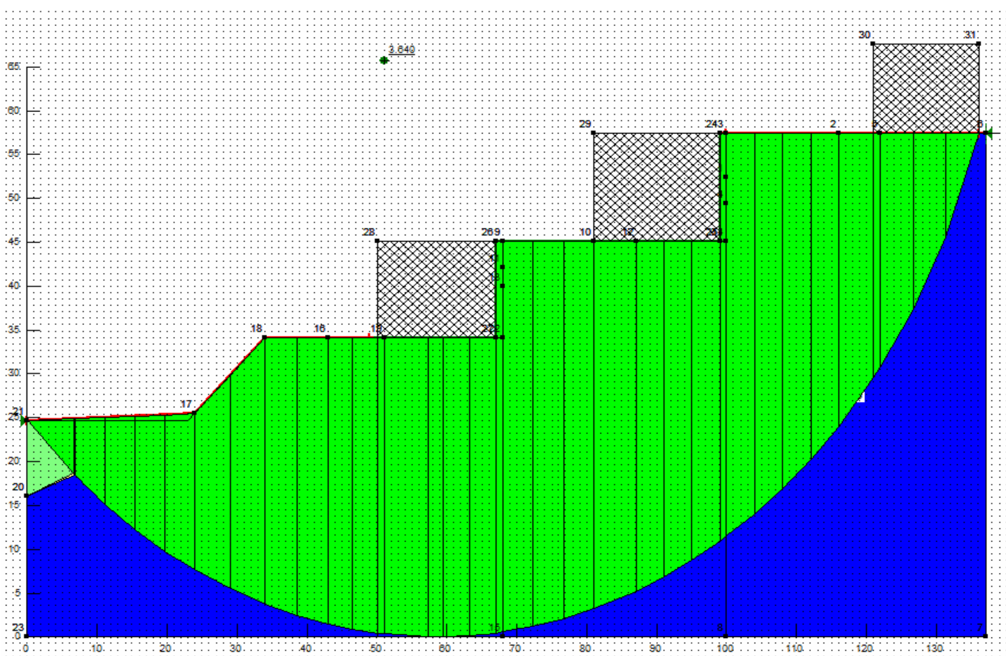

Figure 4.15: Slope stability analyses for basic and seismic loads for the critical case which is section 2 overall stability case (minimum factor of safety = 3.6)

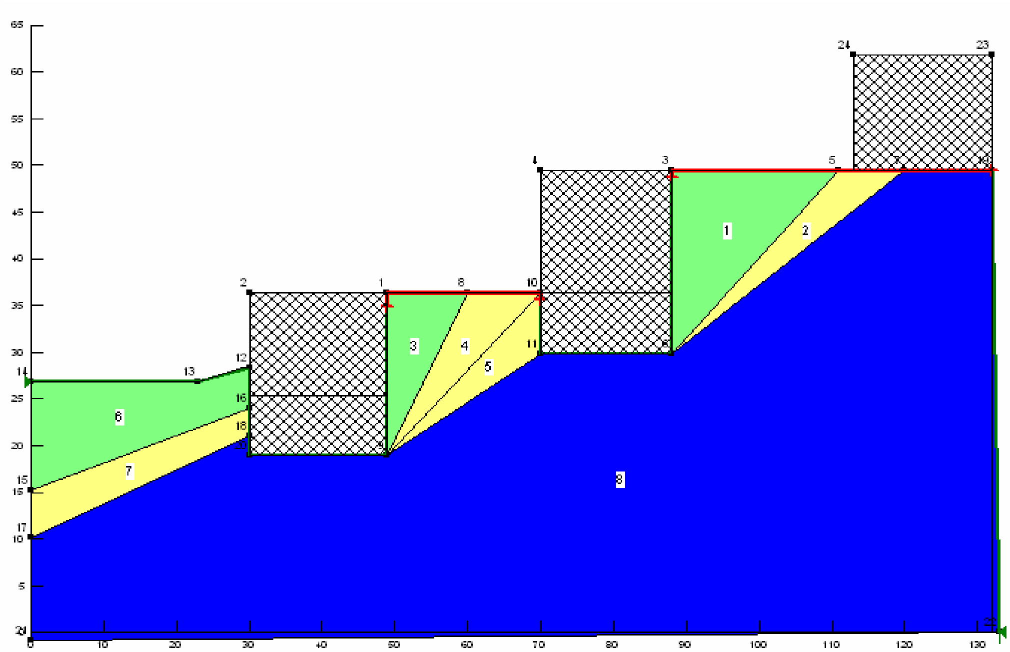

Figure 4.16: Typical virtual section showing increases in the backfill materials and marl layer.

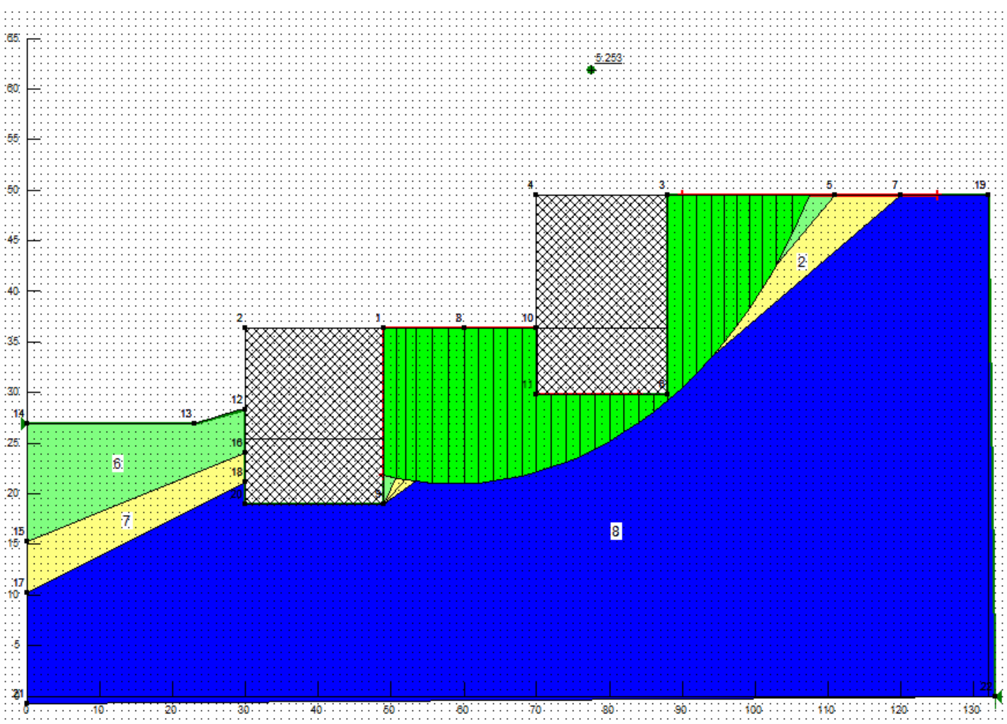

Figure 4.17: Slope stability analysis for basic load minimum F.S. = 7 and for basic loads and seismic loads minimum F.S. = 4.7 for 2-story extra excavations and loads for upper zone.

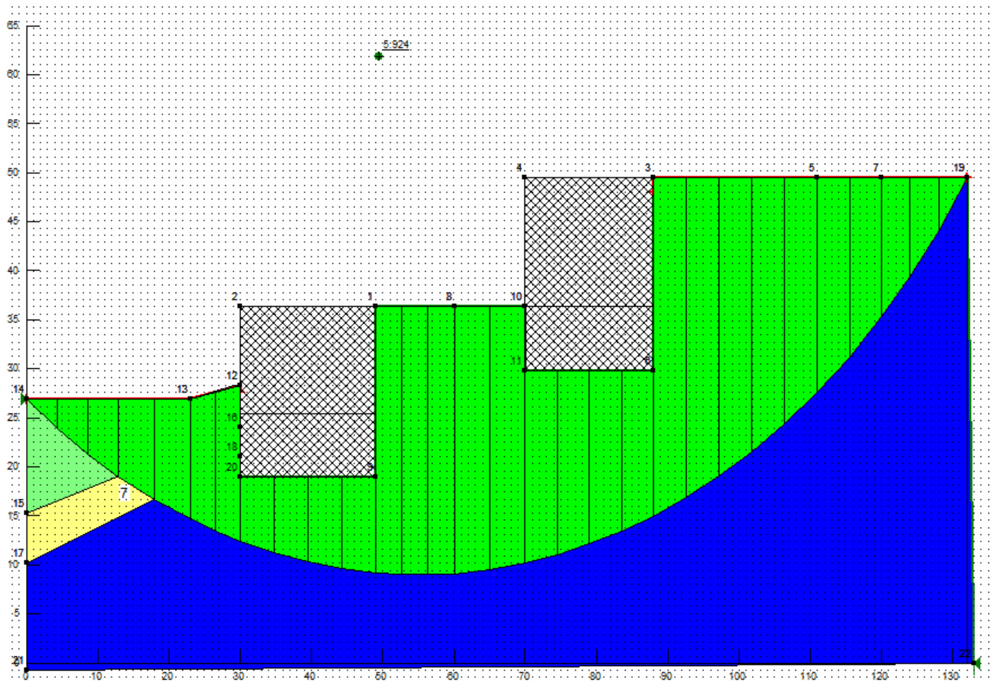

Figure 4.18: Slope stability analysis for basic load minimum F.S. = 10 and for basic loads and seismic load minimum F.S. = 5.5 for 2-story extra excavations and loads for overall zone.

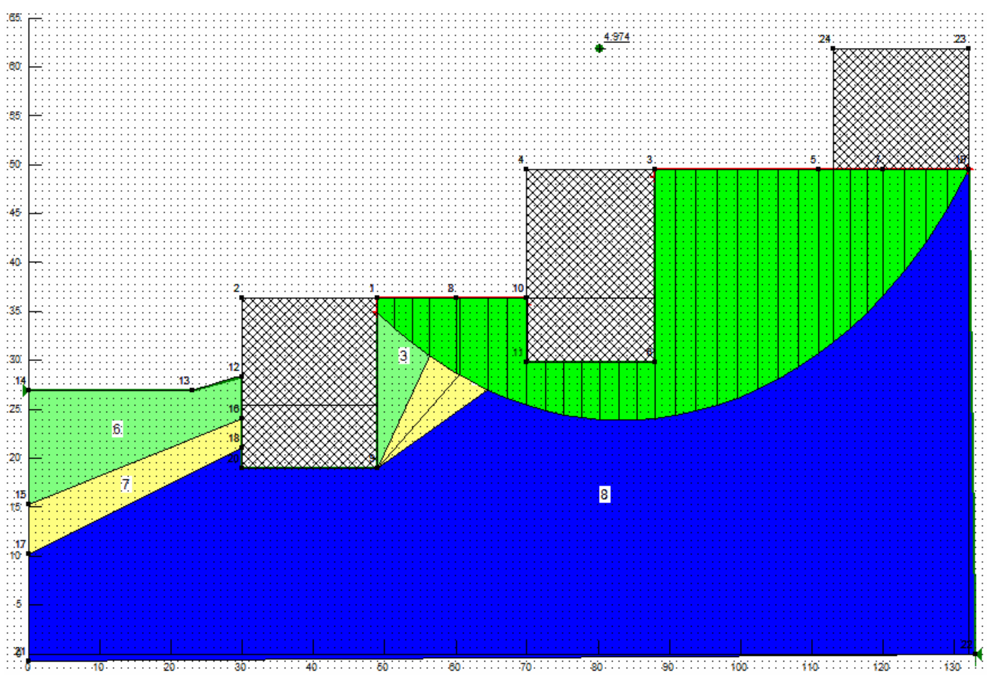

Figure 4.19: Slope stability analysis for basic load minimum F.S. = 6.2 and for basic loads and seismic loads minimum F.S. = 4.5 for 2-story extra excavations and loads and adding 22-story building on the top.

Hai 1, 3, 5 Section (this section is provided on 14-6-2010 by the owner): After the analysis of sections through Hai 1 and virtual sections were done. The section is shown in Figure 4.20. Although it is not align on the same line, it is assumed to be continuous and aligned on the same line so that to be conservative and in the safe side. Moreover, analysis of each section separately through Hai 1 or Hai 3 or Hai 5 have slope stability results safer than those of virtual section.

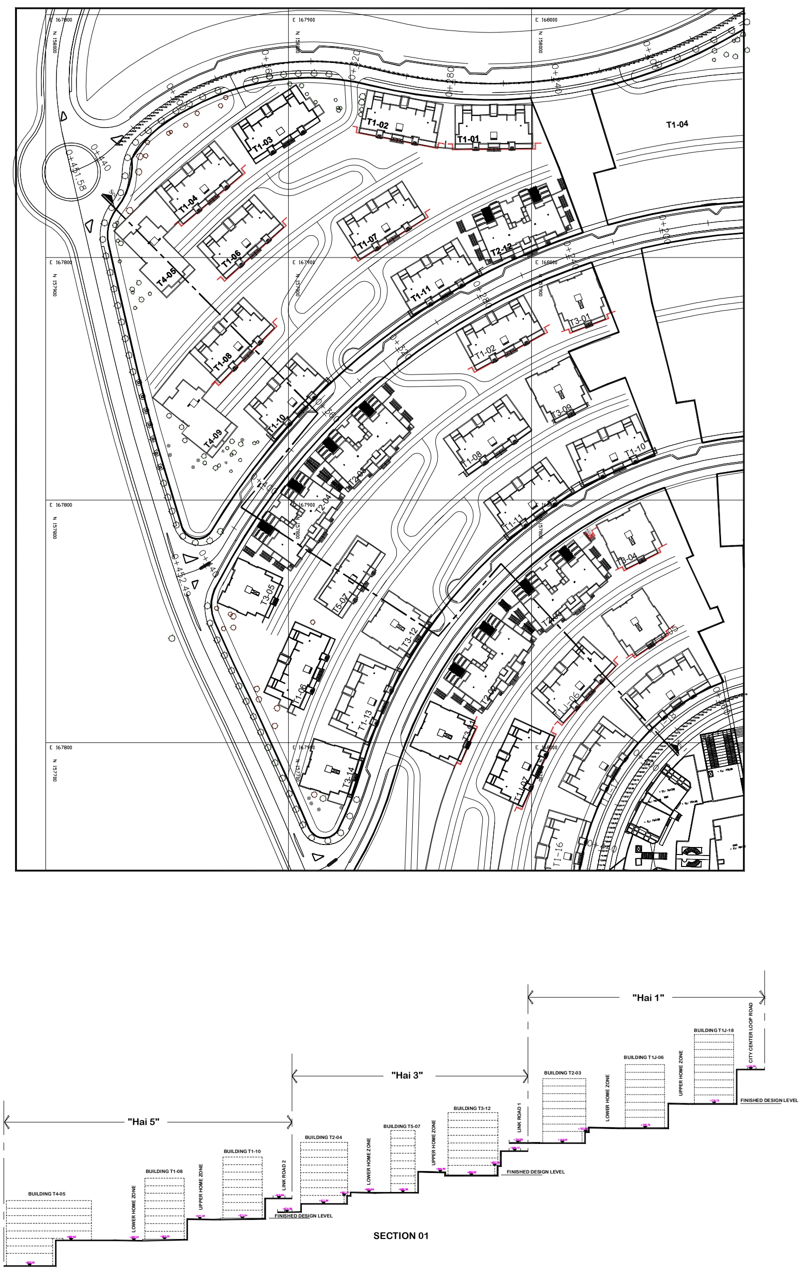

Figure 4.20 The section through Hai1, Hai3 and Hai 5.

Figure 4.21 shows the section through Hai 1, Hai3 and Hai 5 as drawn using GeoStudio (slope/w) and as mentioned earlier they assumed align on the same line.

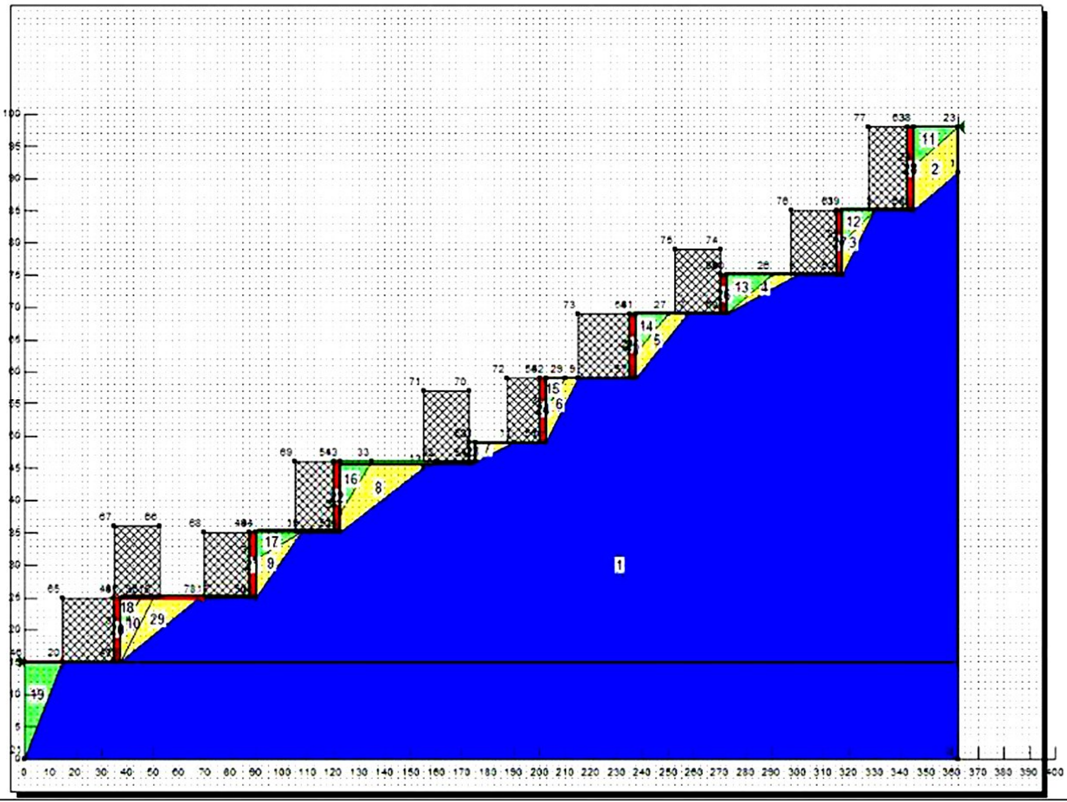

Figure 4.21 The section through Hai1, Hai3 and Hai 5 as drawn using GeoStudio (slope/w).

Slope stability analysis shows that the slope through the section of Hai 1, Hai 3 and Hai 5 are safe and factor of safety of at least 7.8. Factor of safety is decreased to 5 when seismic forces are introduced as 0.2 g horizontal acceleration. Figure 4.22 shows typical slope stability analysis for basic loads while Figure 4.23 shows typical slope stability analyses for basic plus seismic loads.

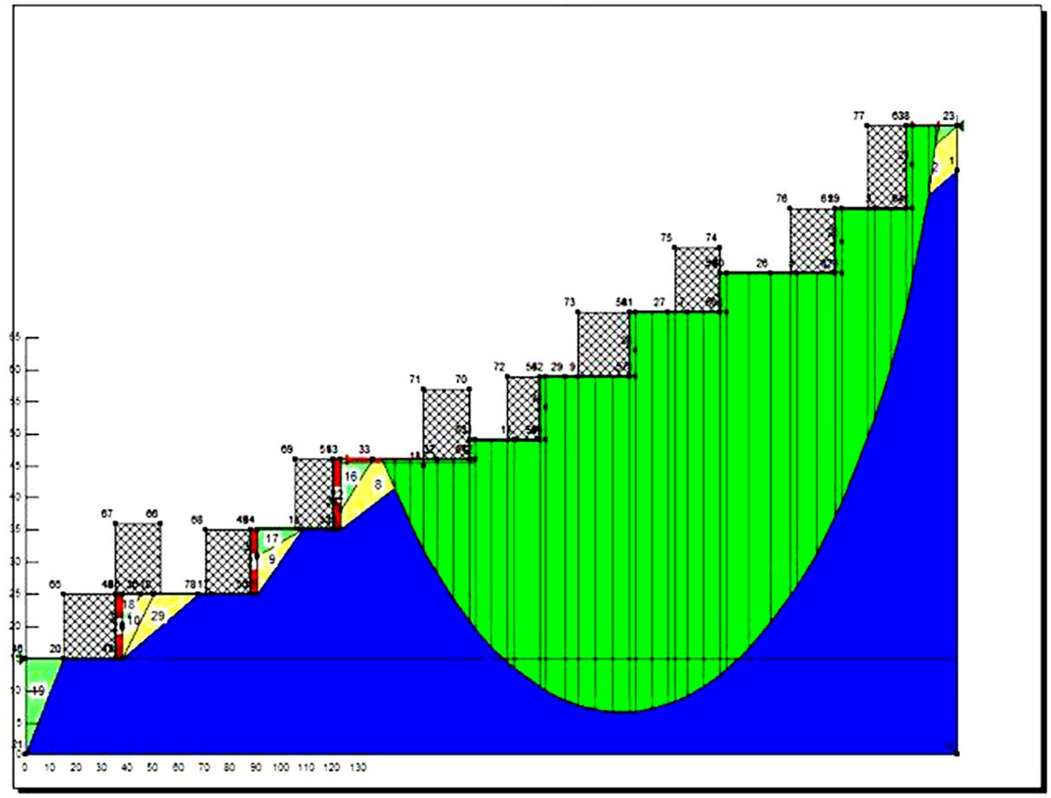

Figure 4.22 Slope stability analyses in section through Hai1, Hai3 and Hai 5 for basic loads

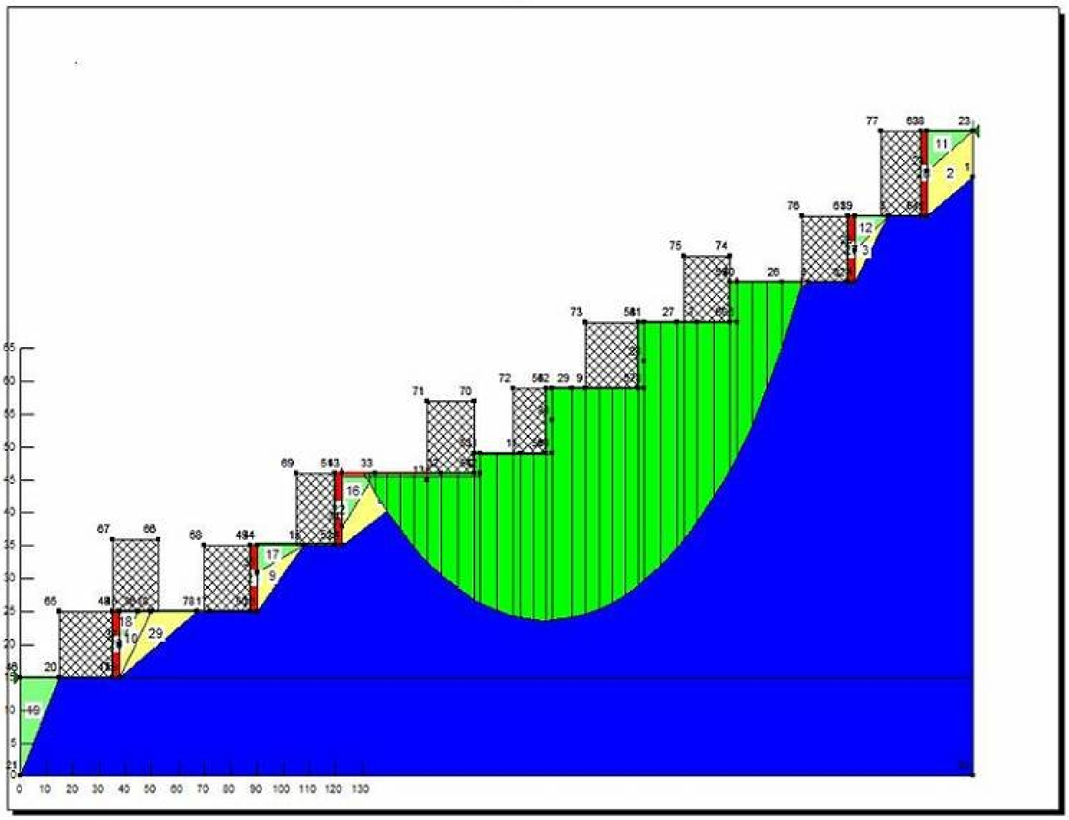

Figure 4.23 Slope stability analyses in section through Hai1, Hai3 and Hai 5 for basic plus seismic loads.

4.5.7 Analysis of the Results

Slope stability analysis results are shown in the above section. The results for Hai 1 are found utilizing the sections provided by the owner. Virtual sections with different scenarios as described above are also analyzed for slope stability. In addition to that new section provided by the owner as mentioned above on 14–06- 2010 through Hai 1, Hai 2 and Hai 3 are also analyzed.

Comparing the results with the minimum required factor of safety (1.3 for temporary structures and 1.8 for permanent structures); it is shown that the site is stable and the values of factor of safety for slope stability are higher than the limits for permanent structures.

Slope stability analysis with basic loads plus seismic forces for critical cases were analyzed and shown that the factor of safety is above minimum.

4.6 Conclusions

The site of Rawabi City shown to be safe regarding slope stability taking into account critical sections and all loading cases including backfilling behind retaining walls of the buildings and embankment of the roads. This analysis was carried out for basic cases and taking into account seismic effects. The analysis of slope stability was carried out for critical sections through Hai 1, virtual sections through the rest of the site and new section through Hai 1, Hai 3 and Hai 5 as they provided by the owner later.

Local slope instability was observed during slope stability analysis in the sites where roads are to be constructed due to low quality backfill materials assumed in analysis. Most slip surfaces were observed to be tangential to the hard limestone bedrock layer.

It is important to note that the limestone bedrock layer existing at the site is shown to be of horizontal bedding layers. This is verified by site visits of our experts (Geologists and Geomorphologists) and the outcrops of the limestone bedrock layers in the site. However, the limestone layer in the above figures is shown to be of high inclination which is not real and it is due to variation of horizontal and vertical scales.

According to Rawabi site visit by our experts (Geologists and Geomorphologists), it shows that the soil strata (limestone bedrock, marlstone and marl soil) in Rawabi site through Hai 1 to Hai 6 are almost horizontal.

4.7 Recommendations

The recommendations regarding slope stability analysis for Rawabi City site are as follows:

- The site is safe regarding landsliding and slope stability as found from analysis in different sections through Hai 1, other locations using virtual sections, and the section provided later by the owner through Hai 1, Hai 3 and Hai 5.
- Slope stability analysis should be carried out for other real sections different than Hai 1 and general sections through Hai 2 and Hai 4 as they available from the owner.

- Any changes other than given or assumed regarding sections, loads, backfilling, etc. should be re-analyzed for slope stability.
- All buildings should be constructed on the hard limestone bedrock layer to ensure that there are no problems regarding slope instability.
- Backfill materials to be used behind retaining walls and as embankments for constructing roads should be selected according to standards of high quality backfill materials.
- Drainage system should be provided all over the site to drain the rainfall water and any other sources of water so that it will not reduce the strength of the marl layer and increase the lateral earth pressure against the retaining walls.

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