SLOPE STABILITY EVALUATION IN AND AROUND KODAIKANAL TOWN, TAMILNADU

Ph.D THESIS

by

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DEPARTMENT OF EARTH SCIENCES
INDIAN INSTITUTE OF TECHNOLOGY ROORKEE
ROORKEE- 247667, INDIA
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ROORKEE

CANDIDATE’S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled **“SLOPE STABILITY EVALUATION IN AND AROUND KODAIKANAL TOWN, TAMILNADU”**, in partial fulfilment of the requirements for the award of the Degree of Doctor of Philosophy and submitted in the Department of Earth Sciences of the Indian Institute of Technology Roorkee, Roorkee is an authentic record of my own work carried out during a period from Dec, 2011 to March 2018, under the supervision of Dr. R. Anbalagan, Professor, Department of Earth Sciences, Indian Institute of Technology Roorkee, Roorkee.

The matter presented in the thesis has not been submitted by me for the award of any other degree of this or any other Institution.

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This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

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Signature of Supervisor **Head of the Department**

Date:

ABSTRACT

In the recent times, land development is given top priority in view of ever expanding urbanization phenomenon. On the other hand, land conservation is an important aspect in order to preserve the already developed land categories. In this context, it is essential to understand the nature of hazard associated with urbanized land areas. This is particularly true in case hill towns such as Kodaikanal, in Tamilnadu where the expansion of the town limit is taking place without taking into consideration the inherent characteristics of the terrain. Land use suitability assessment is of great importance in order to protect the land from geological disasters, ecological risks, economic and human loss in such areas.

The study area, Kodaikanal, referred as the "Princess of Hill stations", a small but popular hill station with an area of about 22 sq. km., is situated in Tamilnadu, India, was chosen as it is facing the onslaught of unplanned urbanization for the past about a decade and the consequent instabilities at many locations.

In this study, slope instability assessment has been carried out by using preparing the landslide hazard zonation (LHZ) map of the area using Landslide Hazard Evaluation Factors (LHEF) rating scheme. This process helps to identify the landslide potential in different hill slope facets and particularly to identify high hazard and very high hazard zones. For that purpose, the basic causative factors such as lithology, structure, slope morphometry, relative relief, land use and land cover, and hydrogeological condition as well as external factors like seismicity and rainfall were used to classify the slopes into different landslide hazard zones.

A total of 96 facets were delineated of which there are 73 are debris slopes and 23 are rock slopes. The LHEF ratings were given facet wise. From the prepared Landslide Hazard Zonation (LHZ) map, the facets falling under very high hazard zones were taken up for detailed analysis. For individual slopes falling in very high hazard and on debris materials, shear strength parameters were estimated from the samples collected from respective slopes, cross-sections were prepared across the hazard prone slopes and factor of safety (FOS) was calculated. It is observed from the stability analysis that the rock slopes are stable with FOS more than 1 while the talus slopes are only marginally stable under dry condition. Depending upon the extent of slope instability and taking into consideration the site conditions, suitable remedial measures have been suggested.

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CHAPTER 1
INTRODUCTION

Landslides may not be as spectacular as floods or hurricanes. Yet over time, they have caused sustained damages to property and loss of life than other geological disasters. “Landslide” refers to failure of a slope, causing downward and outward movement of the slope material i.e. rock, debris or soil through sliding, flow, or fall. In fact, the term “Landslide” is used as a synonym for the more general term ‘Mass wasting’ which includes a wide variety of movements such as slides, slumps, debris flow, topples, creeps, debris avalanches and other complex movements (Varnes, 1958, 1975). Many systems of classifications for landslides were proposed by many workers in the past. However, the classification by Varnes (1978) is considered as the most comprehensive system and widely followed by both Geologists and Engineers. In recent times, landslide studies have drawn more attention due to increased urbanization on the hilly terrains, leading to extensive occurrence of landslides (Aleotti and Chowdhury, 1999).

Landslide mapping and hazard analysis are of great help to planners and field engineers for selecting suitable locations to implement development schemes in mountainous terrain, as well as, for adopting appropriate mitigation measures in hazard-prone unstable areas (Anbalagan 1992). It helps to understand about distribution of hazard prone slopes and hence can be of assistance to avoid those slopes or adopt suitable control measures in advance while implementing developmental schemes (Gupta et al 1993, 1995, 1997). Landslide analysis is used to identify the causative factors and to estimate the relative contribution of factors causing slope failures, to establish a relation between the factors and landslides, and to predict the landslide hazard in the future based on such a relationship (Anbalagan et al 1996, 2008; Bhasin et al 2002). A Landslide Hazard Zonation (LHZ) map divides the land surface into zones of varying degree of stability based on an estimated significance of causative factors in inducing instability (Anbalagan, 1992; Ayele et al 2014). The statistical – probabilistic approach can also be used to rate the governing factors (Hamza et al 2017, Gupta et al 1997).

Slope stability analysis helps to understand the status of stability of a vulnerable slopes and the probable failure mechanism (Kannan et al, 2013). In case of excavation or road construction, it helps to design a suitable geometry that will be stable under the existing conditions of the area (Anbalagan, 1992). This analysis will also help to arrive at suitable control measures.

In India, quite a number of states are prone to landslide hazards with different degree of damages. According to Geological Survey of India (OCBIS GSI, 2018), nearly 15% of India's landmass or 0.49 million sq km area is prone to landslide hazard. Out of this, 0.09 million sq. km lies in Western Ghats and Konkan hills (Tamil Nadu, Kerala, Karnataka, Goa and Maharashtra). In Tamil Nadu, landslides are mostly reported in Nilgiris, Kodaikanal and Yercaud and other such places. While the landslides of the Himalayas are demonstrated to be predominantly due to active tectonics, the landslides of the Western Ghats are attributed to excessive weathering and rainfall (Ramasamy, 2005). The damages caused by landslides can be prevented to a great extent if developmental strategies in mountainous terrain are carefully planned and executed for example, construction of roads and buildings.

In the present research, Kodaikanal hill in Dindigul district of Tamil Nadu state has been taken up, as the area had witnessed several causalities caused by landslides along with blocking the state highway and other link roads for several hours. The present study focuses on landslide hazard problems on semi-regional scale as well as related to slope stability of individual slopes, constituting the Kodaikanal Township. The detailed stability analysis of different potential slopes indicates the probable failure mechanism, the cause of failure and the status of stability in terms of factor of safety. In addition, suitable stable slopes around the township were also identified for further expansion and town planning. In case of excavation or road construction, it helps to design a suitable geometry that will be stable under the existing conditions (topography, geology and slope) of the area. The environmental conditions like vegetation, rainfall, ground water condition are also taken into consideration. Expanding urbanization and changing land use practice have increased the incidences of landslide disaster. As catastrophic events, landslides can cause human injury, loss of life, economic devastation destroy construction works and cause environmental loss to natural habitats. But the knowledge of engineering geology helps us to have a better understanding of geology, and role of geotechnical slope stability analysis during the construction of any engineering structures without causing major damage by identifying potential slide zones and treating them with appropriate remedial measures. This is one of the main objectives of the study that has been carried out.

1.1 Study area - A Brief Profile

The present study area, Kodaikanal, hailed as the “Princess of Hill Stations” is located in the Dindigul district of Tamil Nadu in the southern tip of the Palani Hills and covers an area of about 22 sq km (Fig. 1.1). With a maximum elevation is 2517m Kodaikanal draws many tourists due to its marvelous scenic beauty. It is a part of the Western Ghats which is designated as one of the eighteen Biodiversity hotspots of the world. The word Kodaikanal is an amalgamation of two words: Kodai - kanal refers to "Gift of the Forest" in the Tamil. The Pillar Rock, Green Valley View, Silver Cascade, Coalkers Walk, Devils Kitchen, Dolphin Nose, etc. are few of the magical locations that mesmerizes everyone and one can experience the exquisite locale of Kodaikanal. The centre of town is occupied by a landmark star shaped artificial lake known as Kodaikanal Lake with a 5 km circumference.

1.2 Location and Accessibility

Kodaikanal is one of the premier hill stations nestled at an average altitude of 2133m above mean sea level in the Kodaikanal hill of Western Ghats. It is bound by 77º14’26"E and 77º45’28" E longitudes and 10º6’25"N and 10º 26’54" N latitudes and falls in parts of the 58 F/7, 8, 11 and 12 Survey of India Toposheets on 1:25,000 scale.

The study area is well connected by road with distant train connectivity. The State Highway, SH 156, connects Kodaikanal to the important neighboring cities namely Dindigul, Madurai, Palani and Batlagundu. There is a 49 km shortcut road from Periyakulam to Kodaikanal via Kumbakarai and Adukkam. The nearest railway stations from Kodaikanal town includes (i) Palani station located about 64 km north, (ii) Kodaikanal road station located about 80 km south east, (iii) Dindigul Junction located about 100 km east and (iv) Madurai Junction located about 114 km east. The nearest airports are Madurai (115 km), Coimbatore (170 km) and Trichirapalli (197 km).

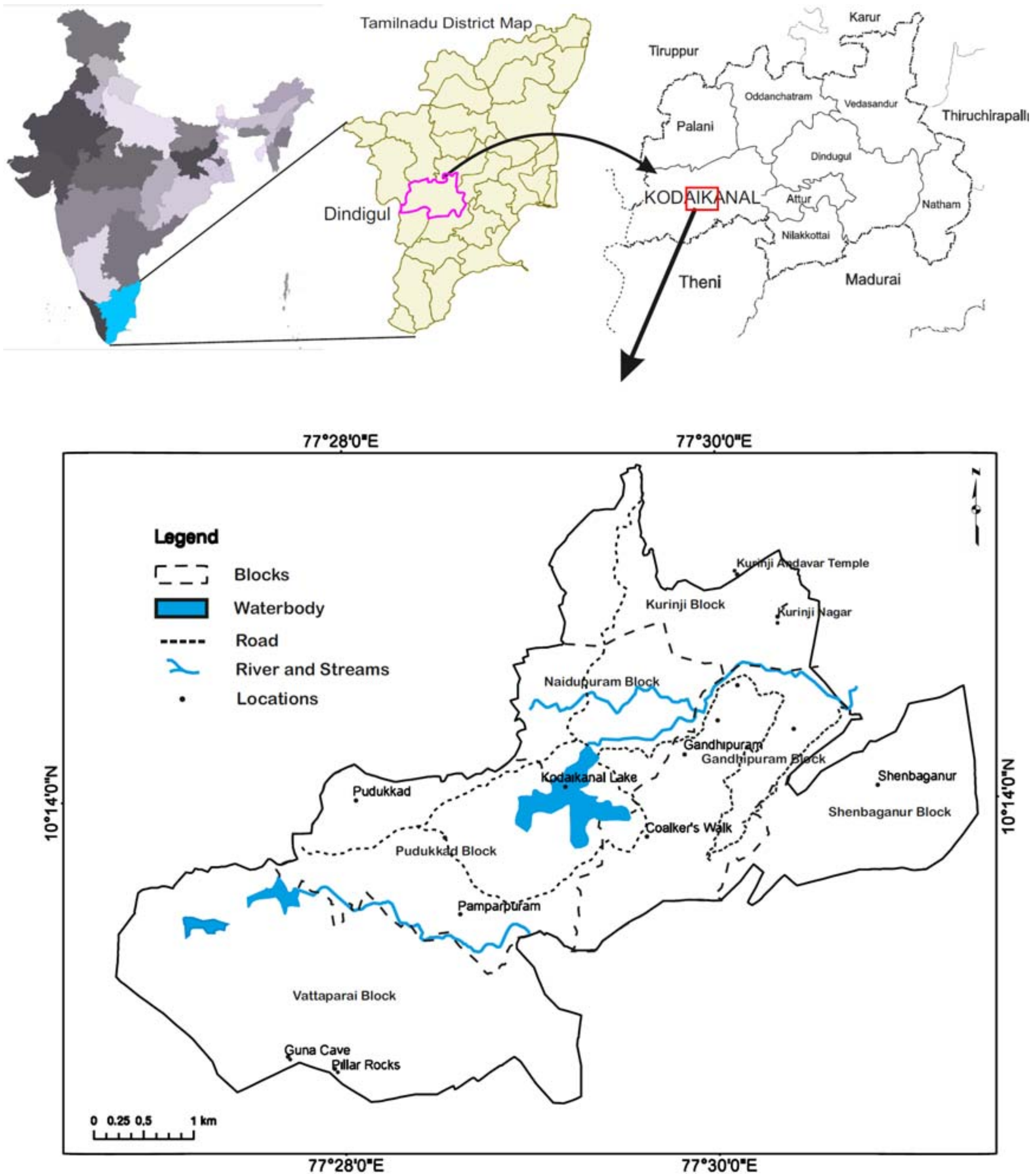


Fig. 1.1 Location map of the study area

1.3 Physiography

These hills form the eastward spur of the Western Ghats. The major portion of study area is formed by hills with the maximum elevation is 2517 m. It has an irregular basin as its heartland, the centre of which is now Kodaikanal Lake a 5 km circumference manmade lake. The study area is a terrain having high elevated structural ridges and adjacent structural valleys striking NNW-SSE and ENE-WSW (Prakash et al, 2012). The settlements are scattered as sporadic patches of urbanization are often seen between the agricultural terraces and are densely populated in isolated pockets.

1.4 Climate

Kodaikanal lies in dry tropical belt and has a monsoon influenced subtropical highland climate. The temperature remains pleasant throughout the year, even during summers. The hot months of Summer are March, April, and May with mean temperature ranging from 10.1°C to 20.9°C while the cool months of winter are November, December, January and February with the mean temperature ranging from 8.1°C to 17.5°C. The South-West monsoon starts in the month of June and extends up to August whereas the North-East monsoon starts in October and extends up to December with an average annual rainfall of 1650 mm. During rainy season, about 70 to 80% of annual rainfall is received and is characterized by humid conditions.

1.5 Drainage

The star shaped man made Kodaikanal Lake that is situated in the centre of the study area has a circumference of around 5km. In addition to the Lake, there are two Kodaikanal Reservoirs positioned to the west of the lake that are falling within the Palani Conservation Forest Area. East flowing Palar River that is originating from the Kodaikanal Lake is the major river that drains the area along with two other streams, Bear Shola stream and Levinge Stream. The Bear Shola stream which is located to the north of the Kodaikanal Lake, flows eastwards and joins the Palar River further ahead. The Levinge stream is situated to the southwest of the Lake and is flowing towards the SW and joins the Kodaikanal Township Reservoirs.

1.6 Flora and Fauna

Kodaikanal is a part of the Western Ghats designated as one of the eighteen Biodiversity hotspots of the world with variety of endemic flora and fauna. Its opulence of orchids, epiphytes, pear, big trees, eucalyptus, cypress, acacia and Shola forests are only one of its kind. The forest serves as traditional animal corridors for bison, deer, elephants and the tiger. Due to the temperate climate of the area orchards are swarmed by trees of apple, pear, plum, peach, orange and banana. In addition to fruit crop it is rich with the flower crops such as Carnation, Rose, Gladiolus, Rhododendron and Magnolia (TNTDC, 2017). Agricultural field that makes up a dominant part of the study area cultivates varieties of vegetables and spices. Vegetables like carrot, beans, peas, potato, beet root, cabbage, cauliflower, and radish as well as spices like cardamom, pepper, coffee, tea, garlic, ginger, and clove are cultivated in the study area (TNAU, 2001).

1.7 Literature Review

The increased frequency of landslide incidences have become common in mountainous terrains under all climatic conditions, throughout the world causing loss of life and billions in monetary losses each year. Landslides cause long-term economic disruption, population displacement, and negative effects on the natural environment. Landslides often are characterized as local problems, but their effects and costs frequently cross local jurisdictions and may become state or provincial or national problems.

Landslides have been studied worldwide due to the attention it has captured by its damaging effects. Deterministic, statistical, empirical, and monitoring methods are approaches that are often used for slope stability assessment (Hartle’n and Viberg, 1988). Varnes (1984) outlines the term zonation as the procedure of dissection of land surface into parts and grading of these areas based on the degree of actual or probable hazard from landslides or other mass movements. BIS code: IS 14496 (Part-2) – 1998 deals with the concept of landslide hazard zonation mapping adopting a slope facet concept and identifying a rating scheme for the basic causative factors in inducing instability. Courture (2011) explained the concept of landslide hazard as division of land into somewhat homogeneous areas or domain and their ranking according to the degrees of actual or potential landslide susceptibility, hazard or risk or applicability of certain landslide related regulations.

Many landslide hazard zonation mapping methods have been published for different terrains (Chowdhury, 1978; Gupta and Joshi, 1990; Anbalagan, 1992; Pachauri and Pant, 1992; Gupta et al., 1993; Gupta and Anbalagan, 1995; Sarkar et al., 1995; Anbalagan, 1996; Virdi et al., 1997; Nagarajan et al., 1998; Gupta et al., 1999; Saha et al., 2002; Chowdhury et al., 2003; Anbalagan et al., 2007; Ramasamy and Muthukumar, 2008; Sundriyal et al., 2007; Sharma, 2008; Bhandary, 2013; Raghuvanshi, 2014). Depending on topographic, geologic and hydrologic variables, and even climatic conditions and changes in land use, variations in landslide susceptibility have been proposed by many authors (Montgomery and Dietrich, 1994;

Dietrich et al., 1995; Wu and Sidle, 1995, Grøneng et al., 2005). Rainfall in hill slopes contribute largely towards the change in groundwater pressure and that pressure redistribution includes a large component normal to the slope (Iverson and Major, 1987; Reid et al., 1988; Haneberg, 1991; Baum and Reid, 1995; Iverson et al., 1997; Torres et al., 1998; Bhasin et al 2002; Dahal et al 2008; Pal, 2012; Sundriyal et al, 2015). Similar is the involvement of earthquakes in inducing landslides in seismically active zones. (Dahal et al., 2013). Panikkar and Subramaniyan (1997) carried out landslide hazard assessment using GIS based weighted overlay method in the area around Dehradun and Mussoorie of Uttar Pradesh, currently Uttarakhand in India. Several plausible attempts have been also made in modeling landslides to understand the underlying mechanism and also to help in predicting the occurrence of the hazard (Nordvik et al., 2009; Michoud et al, 2013). The study revealed that rapid deforestation and urbanization have triggered landslides in the study area.

Many cases of geotechnical investigations on landslides in Himalayan and North Eastern regions were reported in the literature. As per the Geological Survey of India's record, the study of landslides in India dates back to the 1880's, when Sir R. D. Oldham studied the problem of slope stability in Nainital. The Nilgiris in the Western Ghats entered an anxious era of landslides since the calamitous landslides of 1978. Even though Nilgiri hills were subject for slope instability in the southern terrain, there were only very few studies carried out in the other regions of Western Ghats of the southern India. In the recent times, due to the increasing incidences of landslides, Kodaikanal is being taken up for landslide analysis. The first attempt of Landslide Hazard Zonation (LHZ) of Kodaikanal area by Geological Survey of India (GSI) was carried out by P.C.D. Mony and B. Lakshminarayanan during FS 2007-08, with an objective to assess the landslide hazard along the road corridors leading to Kodaikanal (Lakshminarayanan and Mony, 2009). . The study brought out 69 incidences of landslides within 2 km wide corridor of the transportation lines. A study involving preparation of macro-scale landslide hazard zonation map covering 800 km^2 area in and around Kodaikanal was undertaken during 2008-10 by Thanavelu. Bagyaraj et al, 2011 studied the significance of soil characteristics, erosion phenomena and landform processes by using remote Sensing and GIS for Kodaikanal Hills. Saranathan et al, 2012, carried out landslide hazard zonation of a part of Kodaikanal under the Thevankarai Ar sub watershed using the BIS code: IS 14496 (Part-2) – 1998. GIS based weighted overlay method was used to analyze the landslide hazard zonation in parts of Kodaikanal by Gurugnanam et al, 2012. Remote sensing and GIS were used to study the hazard in the Kodaikanal area by few authors (Nagaraj et al, 1998, Saranathan et al, 2010; Bagyaraj et al., 2011; Mayavanan and Sundaram, 2012; Bagyaraj et al., 2014; Rajamohan, 2014; Anbazhagan and Ramesh, 2014; Kannan et al., 2015; Ramesh et al., 2017). Even though studies are starting to emerge in and around Kodaikanal hills, no consolidated study has ever been carried out within the township area of Kodaikanal.

1.8 Research Gap

The research focuses mainly on landslide hazards, which results due to disproportionate urbanization in fragile mountainous terrains such as Kodaikanal. In fact, in a fast growing tourist township like that of Kodaikanal, a comprehensive landslide study incorporating impacts of urbanization has not been done so far. In the present study, the LHZ map helps to identify the important landslide prone slopes and the further detailed studies provide inputs to understand the mechanics of failure, causes of failure and also the status of stability. Taking into consideration the urbanization pattern, favorable slopes have been identified for future development activities.

1.9 Objectives

a) Landslide hazard zonation (LHZ) of Kodaikanal town and identification of landslide prone slopes

b) Detailed slope stability analysis of important potentially unstable slopes taking into consideration the mechanics of failure

c) Suitable remedial measures for unstable slopes

d) Identification of suitable locations for future urbanization

CHAPTER 2

GEOLOGICAL SETTING

The Palani hills, which rise abruptly from the plain, form a part of the Western Ghats. The general trend of the hill ranges is found to be in north east to south west. The study area forming a part of northern slope of Palani hills comes within the southern granulite terrain of South India. The Kodaikanal area of the Madurai block lies between the Palghat-Cauvery and the Achankovil shear zones.

2.1 Regional Geology

The Kodaikanal area comprises a portion of the Southern Granulite Belt (SGB), which is essentially a high grade Charnockite-Khondalite terrane of granulite facies of rocks. The granulite-facies metamorphism occurred at c.2.6-2.5 Ga (Griffiths et al., 1987; Rogers and Mauldin, 1994). Although the isotopic history of the major Madurai block remains largely unknown, recent reconnaissance studies provide evidence for a Pan-African event (Bartlett et al., 1995).

The Kodaikanal massif encompasses the Annamalai, Palani and Cardomom hills and is the largest upland block of granulites of South India. The Kodaikanal plateau corresponds to the ‘Upper Palanis’. The western or the upper Palani hills form the top of a plateau of around 170 sq. km. area with an average elevation of 2800m AMSL. Major portion of Kodaikanal taluk is covered by Charnockite rock, about 90% of the taluk area. The remaining area comes under Hornblende-Biotite gneiss. One of the gneissic bands is running along Palani ghats road and Bharati Anna nagar area and another small batch of gneissic band is seen in Pillaiyar Totti area.

Kodaikanal sits on a plateau at 2133 m above the southern escarpment of the upper Palani Hills, between the Parappar and Gundar Valleys.These hills form the eastward spur of the Western Ghats. The highest peak in the hill range is Vembadi Shola Ridge (RL 2502 m). The valley topography is conspicuous in the Kodaikanal hills. The most common trend of the ridges and valleys is NE-SW followed by NW-SE trend. The plateau is characterized by deeply dissected steep to very steep fringe slopes, moderately dissected valleys with steep slopes in the intermediate part and undulating plateau land at the central part. The hill range is bound by Chatrapatti Shear in the north and Surliyar Shear in the south.

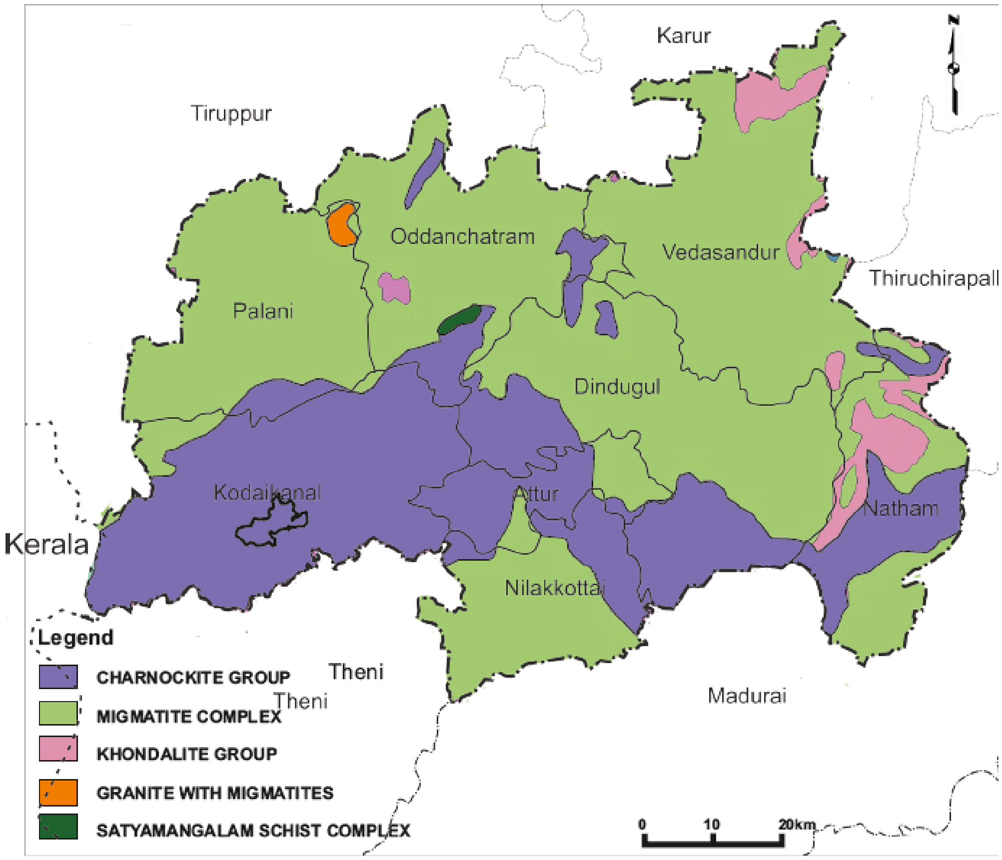


Fig. 2.1 Regional Geology Map of Dindigul district, Tamil Nadu (Modified after Geological and Mineral Map of Tamilnadu and Pondicherry published by Geological Survey of India, 2006)

The Kodaikanal hill exposes quartzite and calc gneiss of Khondalite Group, charnockite, pyroxene granulite, pyroxenite and Banded Magnetite Quartzite of Charnockite Group, hornblende biotite gneiss, granite gneiss and garnetiferous quartzo feldspathic gneiss of Peninsular Gneissic Complex. More than 80% of the Southern Granulite Terrane is covered by varied lithologies of Archaean and Proterozoic age groups namely, Sathyamangalam Group (>3200 Ma), layered mafic and ultramafic complexes, Bhavani Group (~3000 Ma), Kolar Group (~2900 Ma), Khondalite Group, Charnockite Group (~2600 Ma) and Migmatitic complex (2200-2250Ma) (Fig 2.1 and Table 2.1). The Kodaikanal hills form one of the chief charnockite massifs which are bluish grey and coarse grained more or less of uniform type of charnockite formation of older granulites and traversed at places by pink granites. Soil and laterite, developed due to weathering of bedrock, form the capping material.

2.1.1 Sathyamangalam Group

The Sathyamangalam Group of rocks is considered to be equivalents of 'Sargurs' of Dharwar craton exposed in the central and northwestern part of the Indian Peninsula. The Satyamangalam Schist Complex is observed in the south of the Oddanchatram taluk of the Dindigul district and it occupies only a very minor portion of the region.The Group consists of quartzite - fuchsite - kyanite - sillimanite and banded iron formation, sillimanite schist - garnet, kyanite - schist, corundum bearing mica schist and talc-tremolite schist; calc granulite, crystalline limestone/marble, ortho-and para amphibolites (Gopalakrishnan, et al., 1975).

2.1.2 Bhavani Group

The rocks belonging to Bhavani Group occur around Bhavani town (north of Palar River) in the form of typical exposures of Peninsular Gneissic Group of rocks. The gneissic rocks also occur extending from Kerala border in the west through parts of Coimbatore, Erode, Salem, Namakkal, Tiruchirapalli and Perambalur districts towards the east coast. In the Dindigul district, the granite with migmatites is found at the north east border of the Palani taluk bordering the Oddanchatram taluk. The rock types in this group include mica gneiss, quartzo-felspathic gneiss, augen gneiss, hornblende gneiss, hornblende-biotite gneiss, biotite gneiss, granitic gneiss and pink migmatite (GSI, 2006).

2.1.3 Khondalite and Charnockite Groups

The Khondalite and Charnockite Group of rocks (also equivalents of Eastern Ghats Super Group) and their reworked equivalents are the dominant variety of rocks in the SGT. The Khondalite Group essentially consists of rocks of sedimentary parentage such as quartzite and garnet-sillimanite gneiss - graphite - cordierite (metapelites) and occur mostly to the south of Palghat-Cauvery Shear Zone (PCSZ). They are often interfolded and inter banded with mafic granulite/amphibolite and charnockite. The Charnockite group, comprising charnockite (hypersthene bearing granite), two-pyroxene granulite, banded quartz-magnetite granulite/banded magnetite quartzite and thin pink quartzo-feldspathic granulite, are extensively developed in the north-eastern sector of the SGT. (Gopalakrishnan et al., 1976, Suganvanam et al., 1978).

Table 2.1. Regional Tectonic succession observed in and around Kodaikanal area (Modified after GSI, 2014)

Era	Age	Group	Major Rock Type
Proterozoic to Palaeozoic	390-550 Ma	Younger Granite	Granite
Late Archaen To Proterozoic	2200-2550 Ma	Migmatite complex Peninsular Gneissic Complex – II	Older granite / granitoids Pink migmatite Pink augen gneiss Hornblende gneiss Hornblende-biotite gneiss Garnetiferous quartzo-feldspathic gneiss Garnet – biotite gneiss
Late Archaean	2600 Ma	Charnockite Group	Magnetite quartzite Pyroxene granulite Charnockite
Archaean		Khondalite Group	Calc granulite Limestone Quartzite Garnet – sillimanite-graphite gneiss
	3000 Ma	Peninsular Gneissic Complex-I (Bhavani Group)	Pink migmatite Granitoids gneiss Fissile hornblende gneiss
	3200 Ma	Sathyamangalam Group	Amphibolites, basic and ultrabasic rocks Sillimanite–kyanite-corundum-mica schist Fuchsite – kyanite ferruginous quartzite.

They are also well exposed in the Dindigul district. The Charnockite and Khondalite Group together cover about 30% of the district. The Charnockite Group of rocks runs as a linear band in the south of the district covering a major portion of the Kodaikanal taluk and Attur taluk along with the neighbouring taluks, Dindigul, Nilakottai, Natham and

Oddanchatram taluks. In the meanwhile the Khondalite group is observed in only two taluks, Natham and Vadasandur, located in the far east side of the Dindigul district.

2.1.4 Migmatite Complex

The rocks of the Khondalite and Charnockite Groups have been subjected to regional migmatisation and retrogression with influx of quartzo-feldspathic material resulting in the formation of different types of gneisses such as biotite gneiss, hornblende gneiss, augen gneiss, garnetiferous biotite gneiss, garnetiferous quartzo-feldspathic gneiss depending upon the parent rock (GSI, 2006). These rocks are grouped under migmatite complex. These rocks have also experienced multiple deformations and polymetamorphism with concomitant anatexis giving rise to a range of migmatites. The Migmatite Complex covers a major portion of the Dindigul District. The migmatites are exposed in all the taluks, Palani, Oddanchatram, Vedasandur, Kodaikanal, Dindigul, Attur, Natham and Nilakkottai, of the district in varying proportion. In the Kodaikanal Taluk, it occupies a very small region in the far northwest corner of the taluk.

2.2 Geology of Kodaikanal Area

The study area (Fig 2.2) lies within the Kodaikanal taluk of the Dindigul district. Charnockite rock are exposed in the area with thin to thick overburden cover at places. The overburden soil comprises humus material, lithomarge, and slope wash materials. Fresh rock outcrops are seen on the cut slopes of roads and terraces as well as scarp faces seen on hills. Particularly Caolker’s Walk and Guna Cave area charnockite exposures are well observed. The charnockite seen in the area are leucocratic to mesocratic, characterized by grey color, medium to coarse grained with phenocrysts of feldspar. The gentle to very gentle slopes observed in the middle of the town generally consists of thick overburden materials with rock exposures seen intermittently either in stream cuts or other cut slopes. Rock outcrops show varying degree of weathering ranging from highly weathered to moderately weathered depending on slope gradients and other local factors. Fairly fresh charnockites could be seen at many places on steep slopes. The major roads that traverse the study area apart from the local roads are - State Highway, SH156 and the Major District Road, MDR117, MDR 217 and MDR896. The state highway connects Kodaikanal to Palani in the north, Batalagundu in south and Dindigul in east.

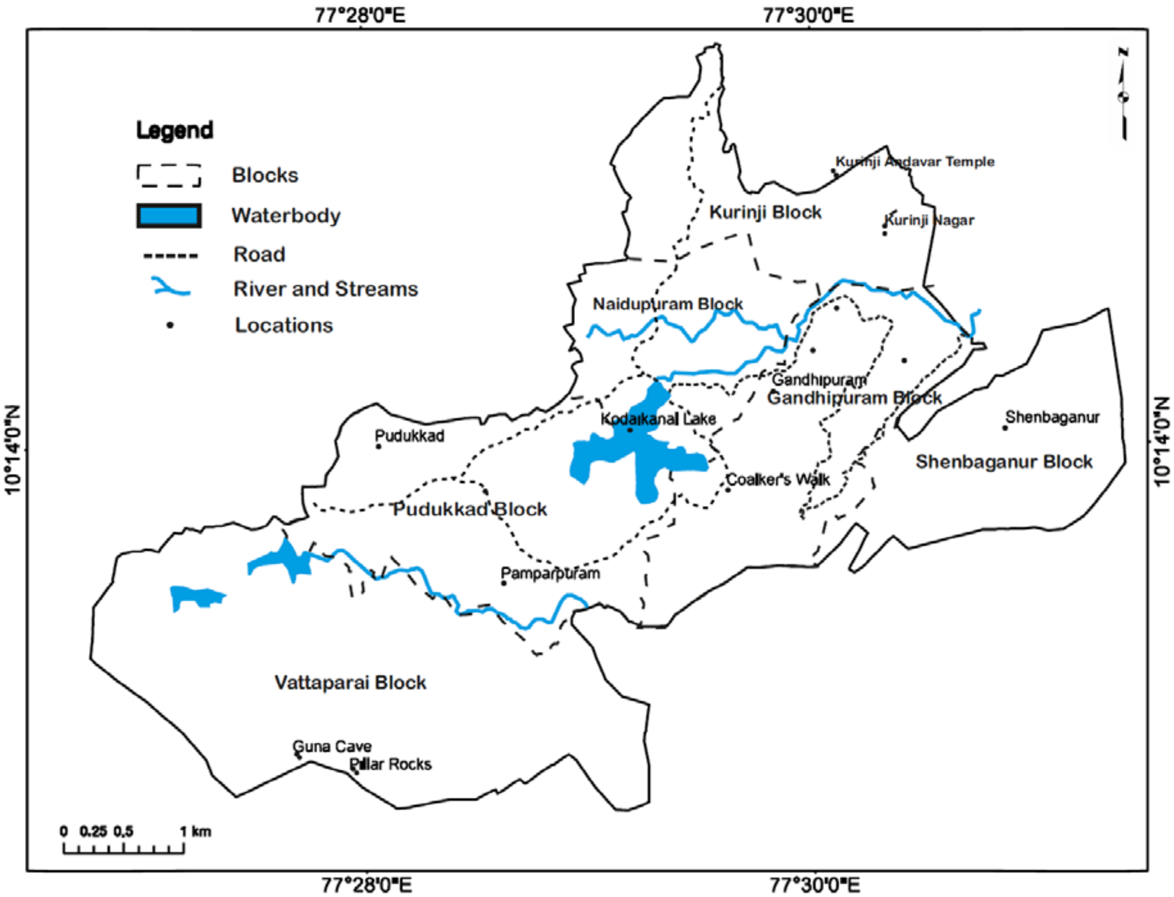


Fig 2.2 Map of the study area showing important blocks of Kodaikanal Town

Situated in the centre of the town is a star shaped manmade lake having a 5 km circumference called Kodaikanal Lake. There are two more water reservoirs within the Kodaikanal Township and they are located in the west within the Palani Hills Forest Conservation area. Roughly flowing in the eastward direction is the Palar River, which is one of major drainage seen in the area along with two other streams, Bear Shola Stream and Levinge stream. Apart from these, 5 waterfalls are also located in these streams within the study area. The Silver Cascade waterfall located in Palar River borders the eastern periphery of the township. The Bear Shola Falls is located on the northern periphery. Fairy Falls, Liril Falls and Vattakanal waterfalls are located on the east of the Kodaikanal Lake within Levinge stream.

2.3.1 Kurinji Block

The Kurinji block located on the northern part of the study area, consists dominantly of thick debris material with intermittent rock exposures. The moderately gentle slopes having debris materials are being used for terraced cultivation. The thickness of the debris varies from a minimum of 5m to more than 20m (Fig 2.4). The thick debris is seen particularly in the lower reaches. The slopes in the area varies from gentle to steep (<20° to 45°). The slopes in the upper reaches are gentle to moderate supporting terraced cultivation and high urbanization can be seen in this reach. The lower reaches of Kurinji Nagar are particularly steeper with slope angles of 45° or more. The geological discontinuities observed in the area are plotted in a stereonet (Fig 2.3).

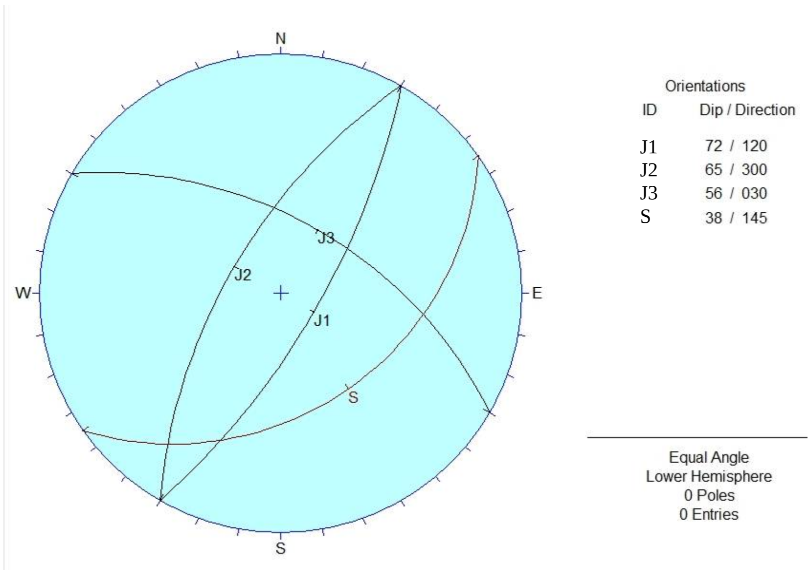


Fig 2.3 Stereoplot of discontinuities in Kurinji block

The Palar River flowing at the toe has been mainly responsible for the instabilities of the slope in the lower reaches. The river flows eastwards and further down, the Silver Cascade Falls can be seen close to the border of the Gandhipuram Block. Charnockite rock exposures are seen on the steep valley slope just adjoining the Palar River. Since the area has good vegetation cover including trees, shrubs and grass, the surface retains moisture to produce damp condition in most parts of the area and only a small part of the area is found to be in dry condition. The fairly thick overburden cover with steep slopes in the Kurinji Nagar area is prone to circular failure. The following are the readings of the structural discontinuities observed in the area:

Joint, J_1: Strike – N300°; Dip- 72º towards N120º; dipping into the hill

Joint J_2 : Strike – N120°; Dip- 65º towards N300º; dipping towards the valley

Joint J_3: Strike – N210°; Dip-56° towards N30°; dipping into the hill

Slope: Dip-38 towards N145°

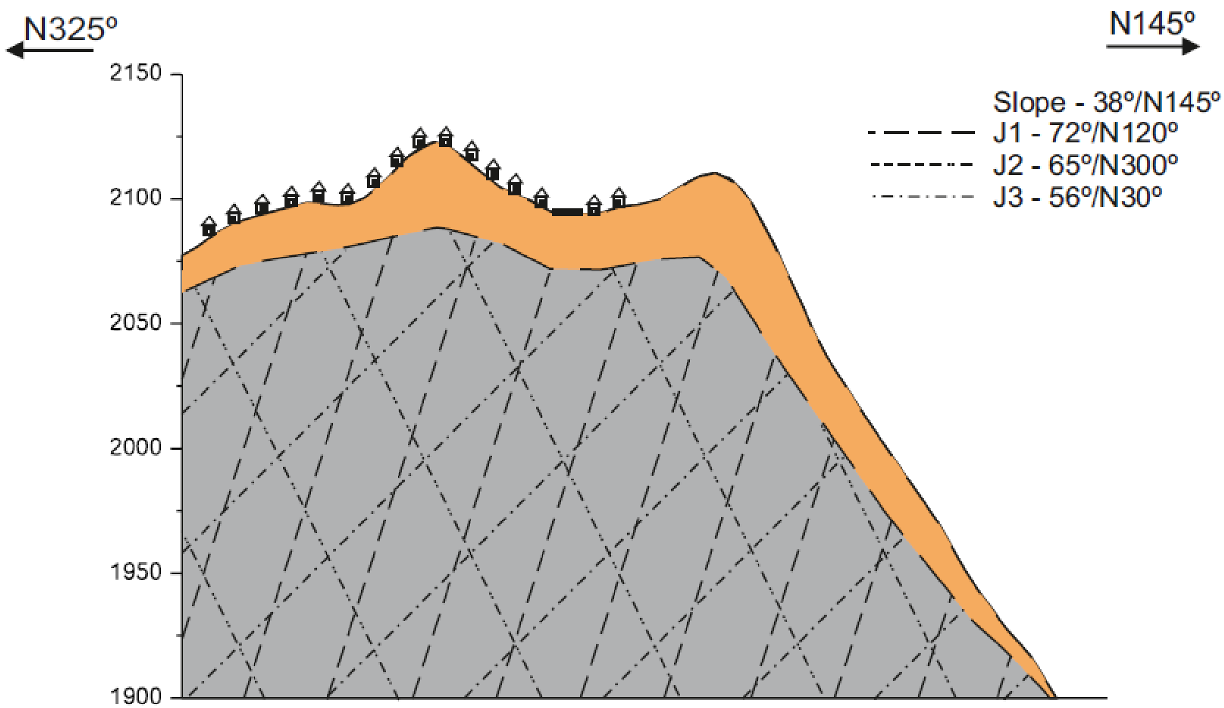


Fig 2.4 Cross Section along the Kurinji block

2.3.2 Naidupuram Block

Located to the north of the Kodaikanal Lake, the Naidupuram block has well developed exposures of charnockite rock with thin (<5m) debris cover at places. The Bear Shola Stream flows towards east in the middle of the area. The side slopes are generally moderately steep (30°-35°) to steep (>45°). While the right bank slope is moderate just adjoining the river course, the upper slopes are gentle to very gentle in nature. The entire right bank is densely urbanized up to the water course. The left bank slope is steep in general with thin overburden cover (about 2m) in the lower reaches. Urbanization can be observed in the lower reaches however the barren rocks are exposed in the middle and upper reaches with no manual encroachment. However, the top slope and further northwards, the slopes are gentle to very gentle where high urbanization can be noticed. A thin layer of overburden soil is generally present in most of the locations over the rocks (Fig 2.6) particularly on the hill top and the lower portion of the slope.

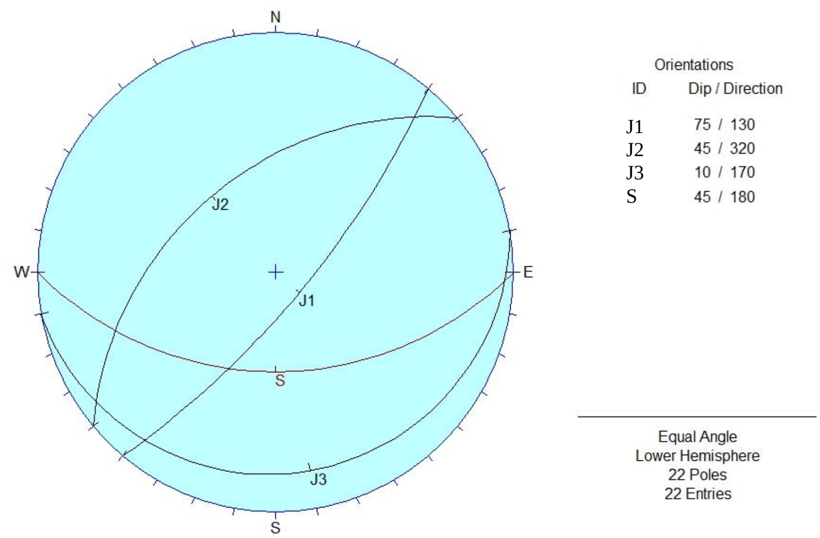


Fig 2.5 Stereoplot of discontinuities in Naidupuram block

The charnockite is medium to coarse grained and moderately weathered with a typical dark grey color. Joints are well developed in the area. The joints studied and plotted in a stereonet (Fig 2.5). The plotting indicates three sets of joints. The Bear Shola stream flowing towards East is present in the middle of the block, which joins the Palar River further ahead. The Bear Shola Falls is located close to the western periphery of the block. The slopes in this area are damp though few wet patches were observed at places on the cut slopes. Moderate Urbanization is seen in the lower reaches on left bank slopes. On the right bank, urbanization can be seen nearly on the entire slope. Agriculture is practiced in both the banks, seen in the lower and upper reaches in the left bank.

Joint, J_1: Strike – N310°; Dip-75º towards N130º; dipping towards the valley
Joint J_2 : Strike – N140°; Dip-45º towards N320º, dipping into the hill
Joint J_3: Strike – N350°; Dip-10º towards N170º, dipping towards the valley
Slope: Dip-45º towards N180º

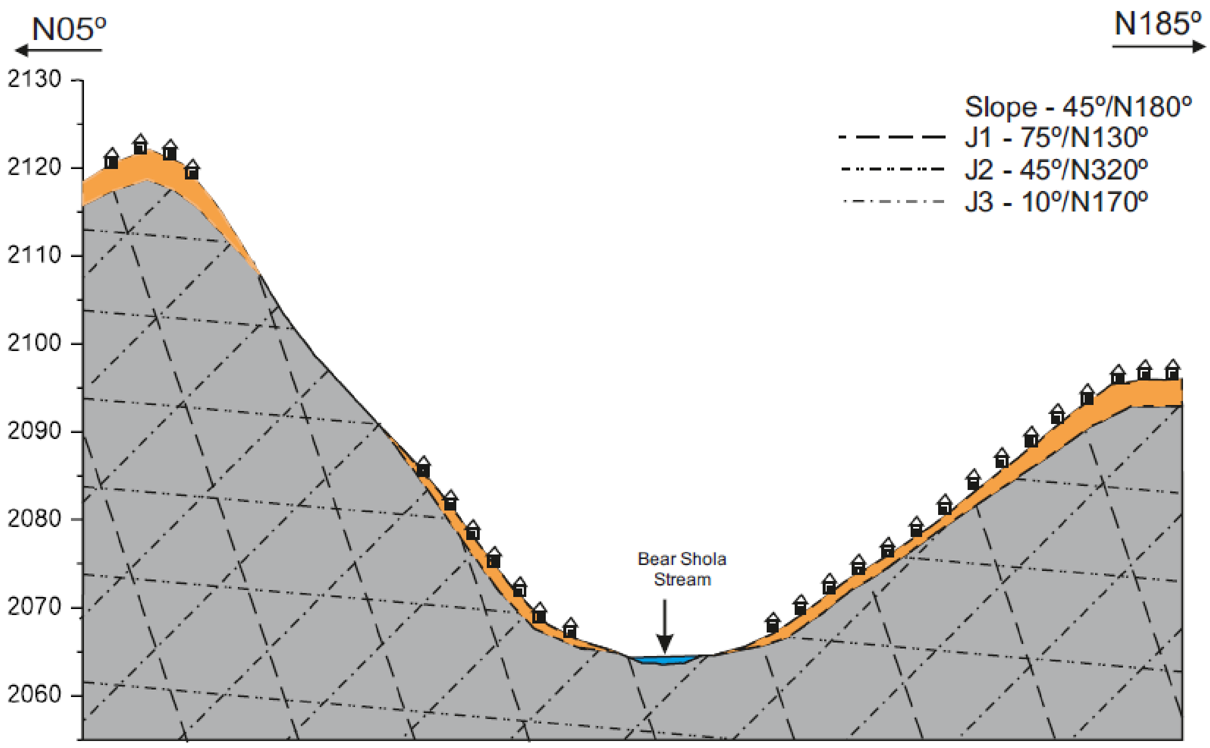


Fig 2.6 Cross Section along the Naidupuram block

2.3.3 Gandhipuram block

The Gandhipuram block is located to the east of Kodaikanal Lake. This is one of the highly urbanized block in the study area (Fig 2.8). The area has a consistent cover of a thin layer of debris cover, generally less than 4m. The cut slopes exposes fairly fresh charnockite rocks. The joints seen in the area were observed and plotted in a stereonet (Fig 2.7). The plotting of structural discontinuities indicates 3 sets of joints in the area. The joints are tight with no fillings. At places, there are wet patches seen on the rock exposures. Brown to red stains can be observed in some of the joint surfaces indicating seepage of water during the monsoon. In addition to the heavy urbanization, pockets of cultivated land and moderate vegetation are also noted. The lower reaches of the slope is mostly covered by agricultural fields. The irrigation to the cultivated land and the roots of the vegetation retain the moisture content of the soil. The area is damp even in the summer. Apart from these, another major source of water seepage in these slopes is the improper drainage system.

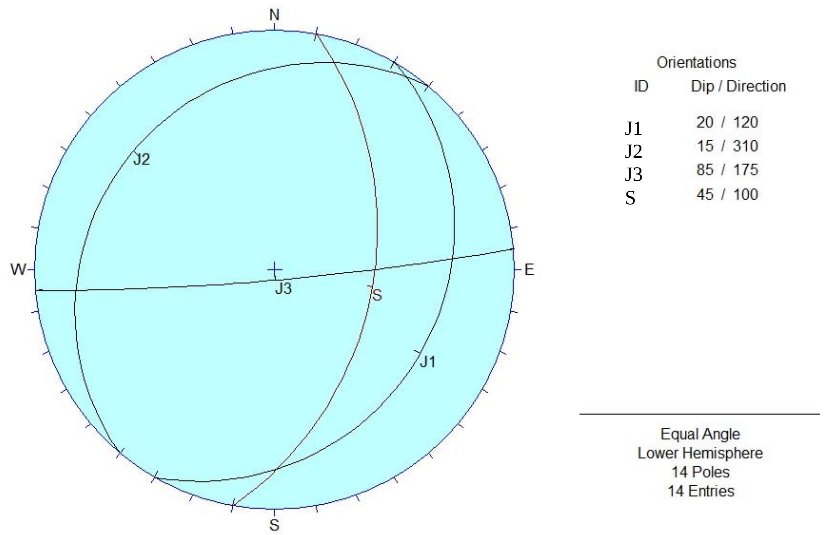


Fig 2.7 Stereoplot of discontinuities in Gandhipuram block

The domestic waste water is drained out directly at many places on the slope rather than through a proper drainage network. This causes wet patches at many places on the slope. Cracks in civil structures are commonly seen at many buildings indicating signs of instability in the area (Fig 2.9). The Palar River borders the upper reaches, taking a 90° turn from the eastern side and towards a roughly north-east direction. The State Highway road, SH156 connects Kodaikanal to Dindigul and Vattalagundu, cuts across this block thrice. Steep cut slopes are made for the construction of this highway making it all the more vulnerable to landslides. The midslope is steeper in comparison to the ridge top and lower portion where the slope is gentler. In spite of the steepness of the slope, it is packed with civil structures.

Joint, J_1: Strike – N300°; Dip - 20º towards N120º; dipping towards the valley
Joint J_2 : Strike – N130°; Dip-15º towards N310º; dipping into the hill
Joint J_3: Strike – N355°; Dip-85º towards N175º; dipping towards the valley
Slope: Dip-45° towards N100°

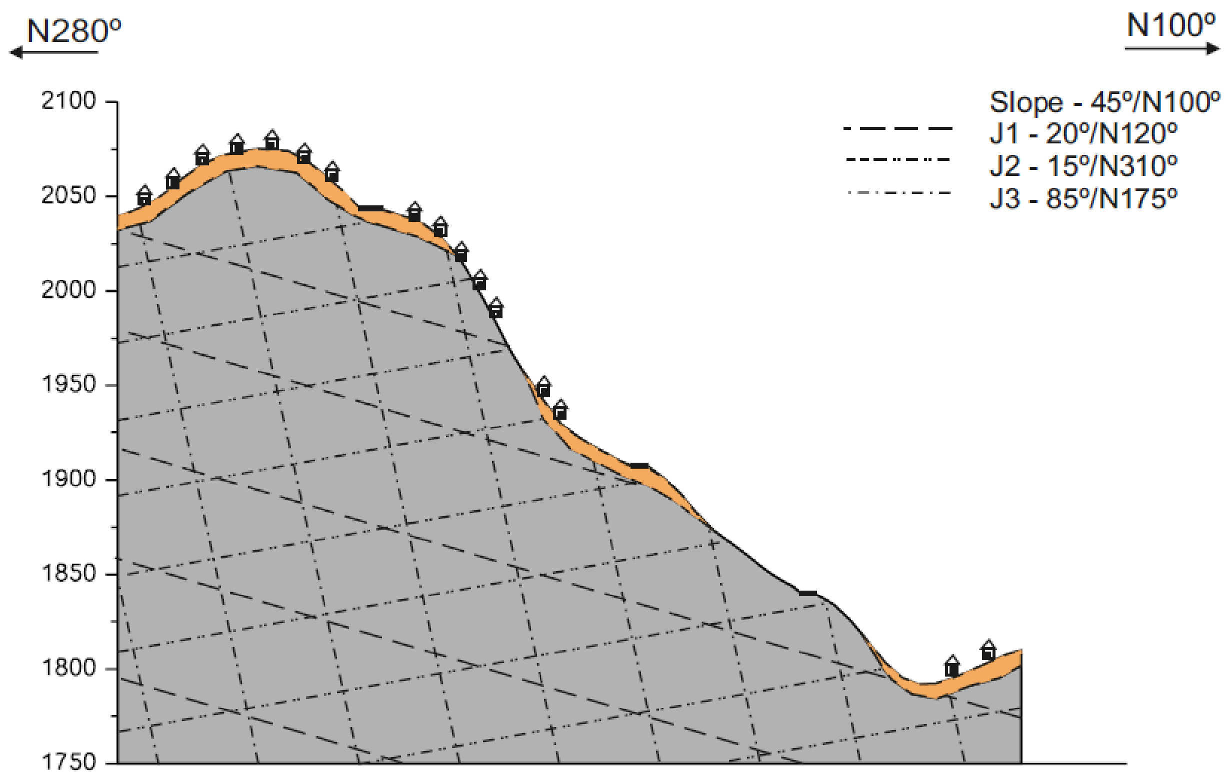


Fig 2.8 Cross Section along the Gandhipuram block

Fig. 2.9 Crack found in a house at Gandhipuram Slope

2.3.4 Shenbaganur block

The Shenbaganur block is located in the far eastern part of the Kodaikanal town. The block has a blanket cover of thick debris for more than 5 m. In the southern parts of Shenbaganur block, barren rock exposures could be seen at many locations. The gentle to very gentle slopes (15° to 25°) seen in the northern part of this block has thick overburden cover which is being used for agricultural purpose. However, the rock slopes seen in the southern part have steep to very steep slopes of more than 45° with rock cliffs at many places. The Charnockite rocks of the area are dark grey colored, medium to coarse grained, moderately weathered, and well jointed in nature, though rocks are highly weathered at places. The observed attitudes of the discontinuities are plotted in a stereonet (Fig 2.10).

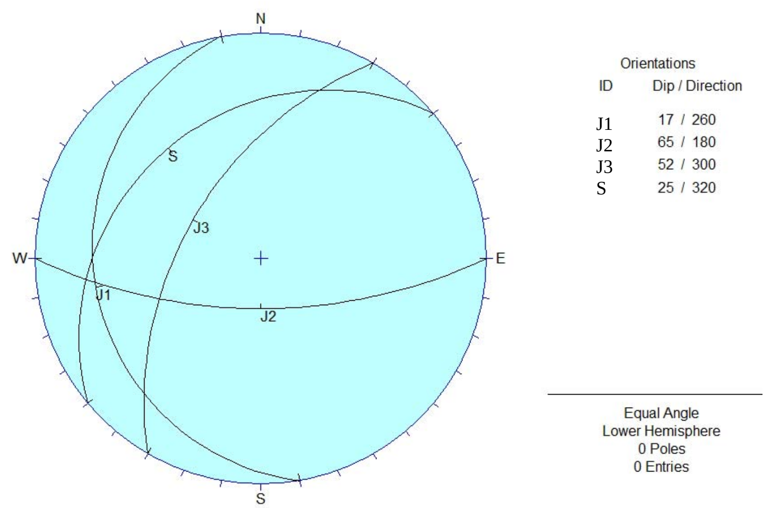


Fig. 2.10 Stereoplot of discontinuities in Shenbaganur block

The plotting indicates two sets of well developed discontinuities and the same have been projected in the cross section (Fig 2.11). In the top reaches where the hill is undulating in nature, several small segregations of urbanized area are seen. Scattered constructions are seen in the lower reaches of the hill. In view of dominant cultivation activities the area is damp in many locations with exception being rock slopes in lower reaches where the slopes are dry. The lower reaches of the area is inaccessible due to the steepness of the slope.

Joint, J_1: Strike – N310°; Dip - 80º towards N130º; dipping into the hill

Joint J_2 : Strike – N120°; Dip-52º towards N300º; dipping towards the valley

Slope: Dip-30° towards N265°

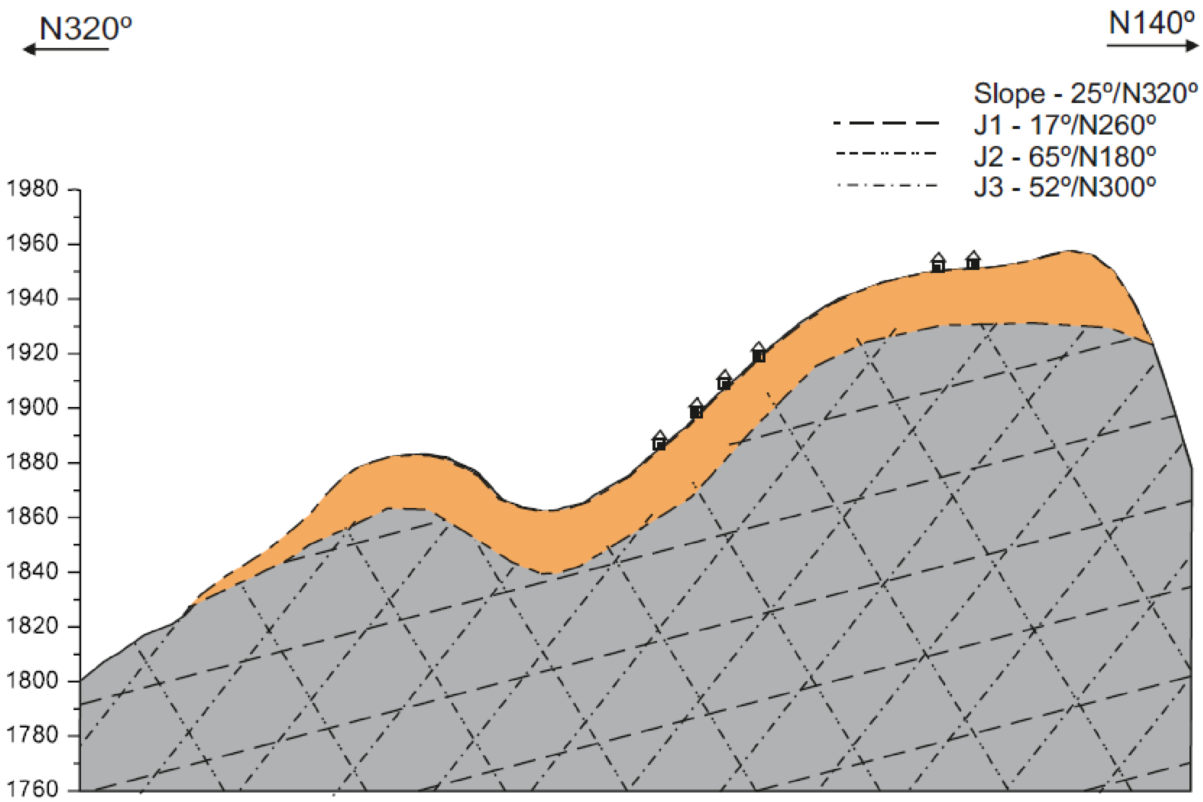


Fig. 2.11 Cross Section along the Shenbaganur block

2.3.5 Pudukkad block

The Pudukkad or the Observatory block is situated in the upper portion, i.e., the south western part of the Kodaikanal Lake. This block has a moderate to steep slope with inclination towards southeast. It is an undulating hill slope with debris occupying most parts of gentle slope, particularly the middle and upper reaches. Fairly thick (3m - 4m) debris are seen on the cut faces adjoining the stream over weathered charnockite (Fig 2.13). The rocks are exposed on the cut faces of the stream as well as in the lower reaches where steep slopes (>45°). The district road passes through the middle of the area with a bifurcation in such a way that the roads travel on either side of the lake. The cut slopes of the roads expose highly dissected (Fig 2.14) charnockite rocks below the debris cover (3m - 4m) which are generally moderate to highly weathered. Fresh rock patches could be seen at deeper levels. Towards the observatory, the rocks seen on the cut slopes are fairly fresh. At places, the rocks are so heavily weathered resembling soil. The fresh charnockite shows the characteristic dark grey color but as the weathering increases discoloration is noted. The color of the rock reduces to light grey and then to a brown color for heavily weathered charnockite. A minimum of 4 sets of joints are observed (Fig 2.12). It is noted that the slopes in this area are generally gentle to moderate. There is a mixed pattern of land used that is observed. A major portion is covered by agricultural lands with urbanization intermittently. Occurrences of landslides have been reported in the past in this area (Fig 2.15). Along with it, moderate and dense vegetation is also seen towards the west. In the lower reaches, it is bordered by the Levinge stream which flows towards the southeast direction and joins the Kodaikanal Reservoir. The Fairy Falls is also situated in this block. In some of the rock outcrops water seepage is observed to such extent that it is dripping or wet constantly.

Joint, J_1: Strike – N305°; Dip-20º towards N125º; dipping towards the valley
Joint J_2 : Strike – N220°; Dip-65º towards N040º; dipping into the hill
Joint J_3: Strike – N90°; Dip-10º towards N270º, dipping into the hill
Joint J_4: Strike – N170°; Dip-70º towards N350º; dipping into the hill
Slope: Dip-30 towards N130°

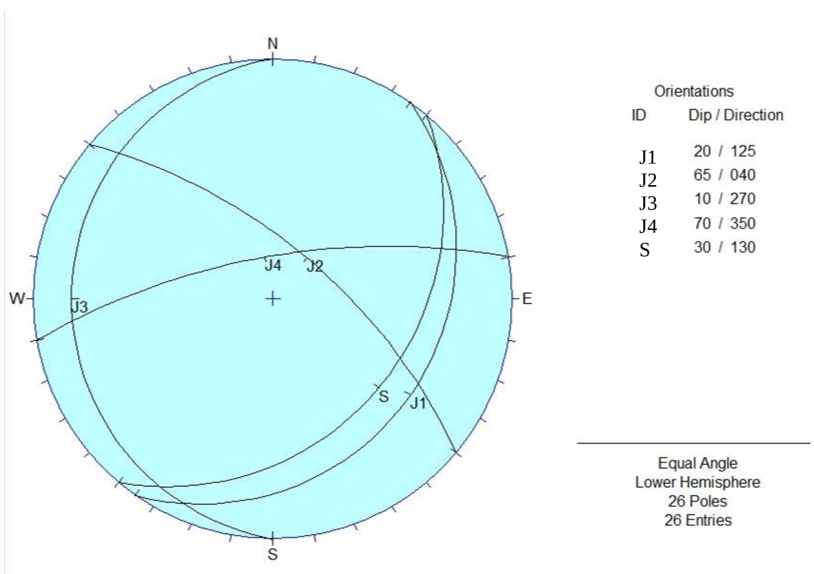


Fig. 2.12 Stereoplot of discontinuities in Pudukkad block

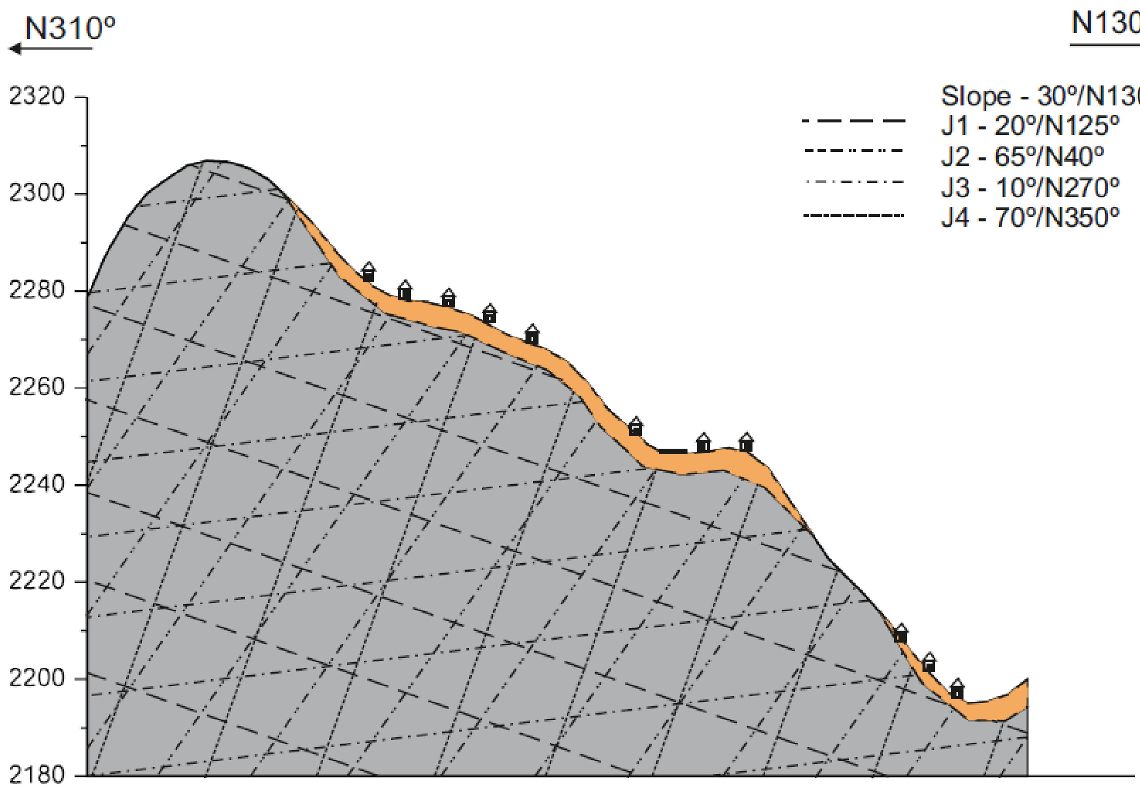


Fig. 2.13 Cross Section along the Pudukkad block

Fig 2.14 Highly dissected rock exposure seen along the Observatory Road showing water seepage along the joints

Fig 2.15 A slide along the Observatory road, below the houses

2.3.6 Vattaparai block

Located in the lower reaches of the Levinge stream, the Vattaparai block consists mostly of the Palani Hill Forest Conservation. The lower edge of the area is bordered by rock outcrops with varying degrees of weathering. Debris cover of thickness more than 20m is carpeted in this area (Fig 2.16). Since it falls in forest conservation it has dense vegetation in the block. Monstrous pine trees and eucalyptus trees could be seen in the entire region. As seen in the Guna Cave, the roots of these trees are also large and cover the slopes effectively. Dense vegetation and lack of sunlight makes the area damp throughout the year and at places wet patches are also observed on the rock exposures. The lower reach where Guna Cave and Pillar Rocks are located, charnockite is well exposed. The slope is steep where rock outcrops are spotted. A minimum of 3 sets of discontinuity is exposed (Fig 2.17). At Guna Cave area, as much as 5 sets of discontinuities are observed. There is sparse urbanization observed in the eastern margin of this block. Trees with tilted trunks are indicative of the stability problem this area is facing (Fig 2.18).

Joint J1: Strike – N315°; Dip-75º towards N135º; dipping towards the valley

Joint J2: Strike – N120°; Dip-60º towards N300º, dipping into the hill

Joint J3: Strike – N2500°; Dip-50º towards N070º. dipping into the hill

Slope: Dip-30 towards N122°

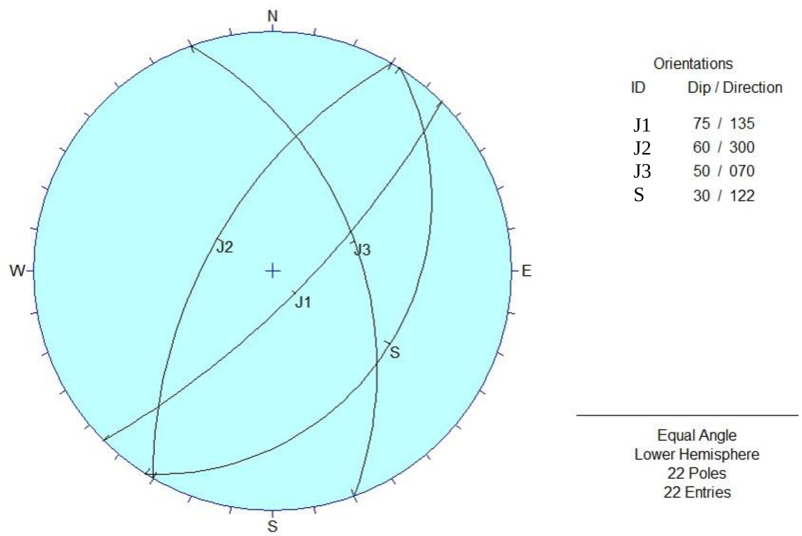


Fig 2.16 Stereoplot of discontinuities in Vattaparai block

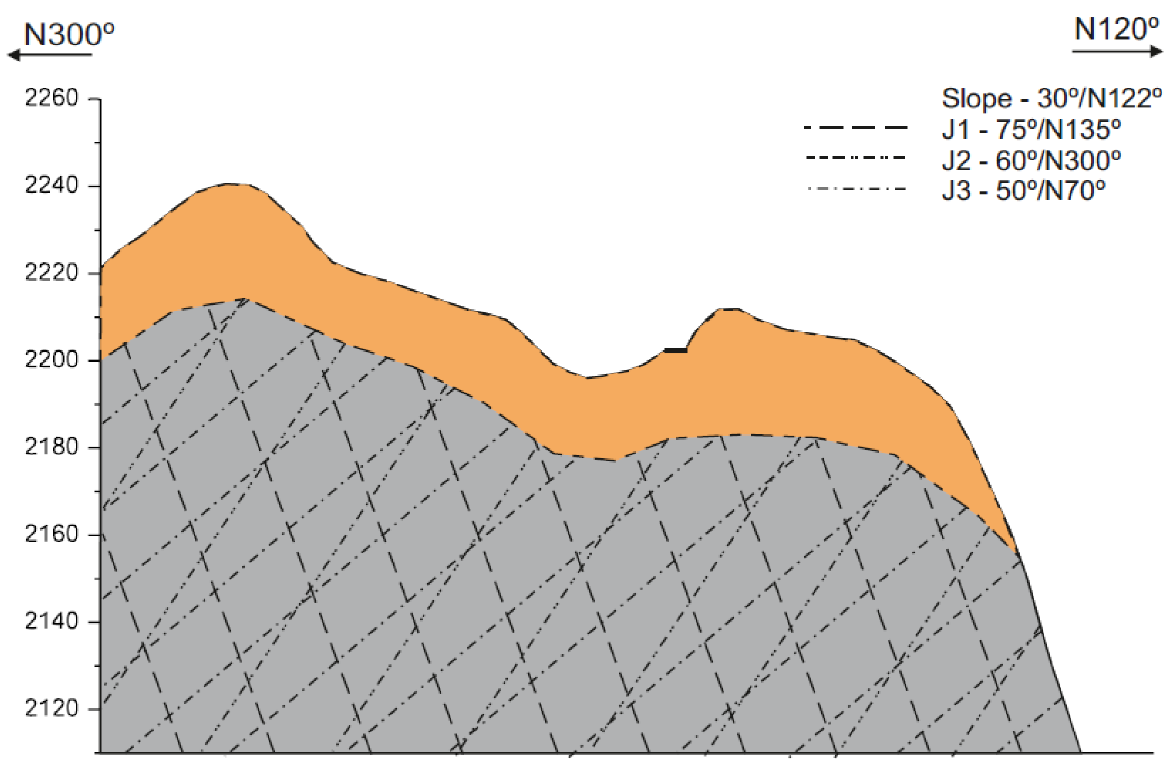


Fig 2.17 Cross Section along the Vattaparai block

Fig 2.18 Tilted Trees along the Pillar Rocks Road

Chapter 3
METHODOLOGY

In the present research, a systematic approach was followed in order to achieve the desired objectives. The Kodaikanal Township area as a whole was taken up for evaluating the probability of landslide hazards. On the basis of Geological mapping and preparation of LHZ map, individual hazardous slopes were identified and studied in detail for arriving at appropriate control measures. The topographical and geological conditions were studied in and around Kodaikanal area in order to identify suitable slopes for future urbanization. In this context, the initial study was carried out to prepare landslide hazard zonation (LHZ) on meso scale, 1:10,000. The detailed study of potentially unstable slopes was carried out on 1:1,000 – 2,000 scale. The following methodology was adopted to achieve the objective of the research work:

- Preparation of Geological Map
- Preparation of thematic maps to generate a LHZ map
- Field Investigations of unstable slopes identified from LHZ map
- Preparation of Cross Sections and Stereographic analysis for Rock Slopes
- Identification of Mode of Failure
- Estimation of shear strength parameters
- Calculation of Factor of Safety
- Evaluation of topographical and geological conditions for locating areas for future urbanization

3.1 Landslide Mapping

Landslide mapping is usually carried out by incorporating two important aspects namely theme and scale. The scale of the map and theme are chosen depending upon purpose of the map, required accuracy, time factor and other such parameters. Based on scale, landslide mapping can be done under four categories - mega-regional mapping on 1:1,00,000 to 2,50,000 scales, regional mapping on 1: 25,000 to 50,000 scales, semi-detailed mapping on 1: 5,000 to 10,000 scales and detailed mapping on 1:1,000 to 2,000 scales. Based on theme, there are generally three types of map viz. danger map, hazard map and risk map. When danger maps only indicate the existence of a landslide, Hazard map indicates the probability and occurrence of a hazard and a risk map indicates the nature of damage likely to be caused if a failure occurs. Danger maps, also termed as landslide inventory maps, only indicate the location of a landslide and do not show anything about its nature of activity, size, type, failure probability and possible damage. Depending upon the requirements, the maps are prepared in different scales. Danger maps can be prepared in mega-regional, regional and semi-detailed scales. Hazard and risk maps, on the other hand, become more meaningful when prepared in regional and semi-detailed scales. Detailed mapping of landslides is usually carried out on 1:1000 – 2000 scale after identifying the mode of failure.

3.2. Landslide Hazard Zonation (LHZ) mapping technique

Landslide hazard zonation mapping is an empirical approach, where the experience and knowledge gained from the previous landslides studies are used to relate to the present day conditions. The qualitative nature of field conditions is quantified based on a relative rating scheme. It is very useful for Planners, Engineers and Geologists during the preliminary stage planning of development schemes and the highlight of this method is the cost effectiveness. The LHZ maps can be prepared in mega-regional, regional and semi-detailed scales. In town level mapping, the semi-detailed or meso-scale (1:5000 to 1:10,000) LHZ map helps in town planning and expansion in order to decide the locations of various civil structures such as schools, offices, markets, houses, colonies and hotels in addition to demarcate areas for future urbanization.

A Landslide Hazard Zonation (LHZ) map divides the land surface into zones of varying degrees of stability, based on the estimated significance of causative factors in inducing instability. The meso-scale LHZ technique used in this research is a modified form of LHZ mapping by Anbalagan, 1992 (adopted as Indian National Standard Code No. - IS: 14496 (Part 2): 1998). The meso-scale technique incorporates more details of individual causative factors, with suitable modifications to fit in the purpose of systematic town planning in addition to incorporating the effects of external factors as correction parameters.

The landslide hazard zonation map of an area is prepared on a slope facet map prepared based on the inherent causative factors such as geology, slope morphometry, relative relief, land use and land cover and groundwater conditions and the external factors like seismicity and rainfall (Anbalagan, 1992). A facet is part of hill slope which has more or less similar characters of slope, showing consistent slope inclination and direction. The slope facets are generally bordered by ridges, break in slope, spurs, streams, gullies, rivers and other such features (Anbalagan 1992 and BIS, 1998). The facet map is prepared by demarcating the boundaries on the Survey of India toposheets. The study area falls in toposheet Nos. 58F/7SE, 58F/8NE, 58F/11SW and 58F/12NW on 1:25,000 scale (Fig 4.1). These maps were blown up to 1:10,000 scale to match Kodaikanal Town boundary map obtained from the local municipality.

The inherent causative factors were assessed facet wise and appropriate ratings were given, taking into consideration the existing field conditions (Table 3.1). The thematic maps were prepared using field inputs and satellite imageries in ArcGIS. The LHZ mapping of the Kodaikanal area was carried out on 1:10,000 scale.

Table 3.1 Maximum LHEF rating for different causative factors

Causative Factors		Maximum LHEF rating
Inherent Factors	Lithology	2.0
	Structure	2.0
	Slope Parameter	2.0
	Land use and land cover	2.0
	Groundwater conditions	1.0
External Factors	Seismicity + Rainfall	1.0
Total		10.0

3.2.1. LHEF ratings for different Causative factors

a) Lithology

i) Rock Slopes: The erodibility, erosion and weathering response of the rocks are the main criteria in awarding the ratings for subcategories of Lithology. The igneous rock types are generally hard and massive and are more resistant to weathering. In comparison sedimentary rocks are more vulnerable to weathering and erosion. Accordingly the LHEF rating shall be awarded. (Table 3.2) A correction factor on the status of weathering of rocks shall also be incorporated. (Table 3.3)

Table 3.2. LHEF rating for rock types

Category	**Rock types**	**Ratings**
Type-I	Basalt, Quartzite and Massive Limestone & Dolomite	*0.2*
	Granite, Gabbro and Dolerite	*0.3*
	Massive Granite Gneiss and Metavolcanics	*0.4*
Type-II	Thickly bedded calcareous rock with intercalations of argillaceous rocks	*0.8*
	Well-cemented terrigenous sedimentary rocks (dominantly sandstone) with minor beds of clay stone and Gneissic rocks	*1.0*
	Poorly-cemented terrigenous sedimentary rocks (dominantly sandstone) with intercalations of clay or shale beds	*1.3*
Type-III	Foliated gneiss	*1.0*
	Fresh to moderately weathered Shale & Slate	*1.2*
	Fresh to moderately weathered argillaceous rocks like Siltstone, Mudstone and Claystone	*1.4*
	Fresh to moderately weathered Phyllite	*1.6*
	Fresh to moderately weathered Schistose rocks	*1.7*
	Highly Weathered Shale and all other argillaceous rocks, Phyllite and Schistose rocks	*2.0*

Table 3.3. Correction factors for weathering

Weathering condition	Description	Rating	
		Rock type-I	**Rock type-II**
Completely weathered	Rock totally decomposed/ disintegrated to soil, no or minor existence of initial rock structure (*Correction factor* C_1)	$C_1 = 4.0$	$C_1 = 1.5$
Highly weathered	Rock totally discolored, discontinuity planes show weathering products, rock structure altered heavily with minor soil formation near surface (*Correction factor* C_2)	$C_2 = 3.5$	$C_2 = 1.35$
Moderately weathered	Rock prominently discolored with remnant isolated patches of fresh rock, weathering and alteration prominent along discontinuity planes, considerable alteration of rock structure (*Correction factor* C_3)	$C_3 =3.0$	$C_3 =1.25$
Slightly weathered	Rock partially discolored along discontinuity planes indicating weakening of rock mass, rock structure is slightly altered *(Correction factor* C_4*)*	$C_4 =2.5$	$C_4 = 1.15$
Faintly weathered	Rock slightly discolored along discontinuity planes which may be moderately tight to open in nature, intact rock structure with or without minor surface staining (*Correction factor* C_5)	$C_5 =2.0$	$C_5 =1.0$

ii) Soil slopes: Some hill slopes may be composed of loose soils and debris material. So, in slopes comprised of loose overburden materials, genesis and relative age are considered as the main criteria while awarding ratings. Older alluvial soil is generally well compacted and characterized by high shear strength and also resistant to weathering. On the other hand slide debris and younger incompact residual soil are generally loose with low shear strength. They are also more prone to weathering and erosion. LHEF rating for different types of soil types are shown in Table 3.4.

Table 3.4. LHEF rating for Soil types

Description		**Rating**
Older well compacted fluvial fill material (alluvial)		*0.8*
Clayey soil with naturally formed surface		*1.0*
Sandy soil with naturally formed surface (alluvial)		*1.4*
Debris comprising mostly rock pieces mixed with clayey or sandy soil (colluvial)	Older well compacted	*1.2*
	Younger loose material	*2.0*

b) Structure

Structure includes primary and secondary discontinuities in the rocks such as bedding planes, joints, foliations, faults and thrusts. The discontinuities in relation to the slope inclination direction have greater influence on the stability of slopes (Table 3.5). The relationship between the slope and discontinuity is considered for awarding the rating. (Table 3.6, Table 3.7 and Table 3.8)

Table 3.5. LHEF rating for relationship between structure and slope

Condition	**Rating**	**Total rating of all conditions**
1. Parallelism between slope and discontinuity	0.5	2.0
2. Relationship between slope inclination and dip/ plunge of discontinuity	1.0	
3. Dip of discontinuity/ plunge of wedge line	0.5	

Table 3.6. LHEF ratings for Structure

Description	Factor	Category	Rating	Slope condition
Relationship of parallelism between the slope and discontinuity	I	>30°	*0.20*	Very Favorable
	II	21 - 30°	*0.25*	Favorable
	III	11 - 20°	*0.30*	Fair
	IV	6 - 10°	*0.40*	Unfavorable
	V	≤ 5°	*0.50*	Very Unfavorable
Relationship of dip of discontinuity and inclination of slope	I	> 10°	*0.30*	Very Favorable
	II	0 - 10°	*0.50*	Favorable
	III	0°	*0.70*	Fair
	IV	0 – (-10°)	*0.80*	Unfavorable
	V	> -10°	*1.00*	Very Unfavorable
Dip of discontinuity	I	< 15°	*0.20*	Very Favorable
	II	16 - 25°	*0.25*	Favorable
	III	26 - 35°	*0.30*	Fair
	IV	36 - 45°	*0.40*	Unfavorable
	V	> 45°	*0.50*	Very Unfavorable

Table 3.7. Structure class of facets based on their LHEF ratings

Structure Class	LHEF rating (out of 2)	Description
I	Rating ≤ 0.7	Very Favorable
II	0.7 < Rating ≤ 1.05	Favorable
III	1.05 < Rating ≤ 1.4	Fair
IV	1.4 < Rating ≤ 1.75	Unfavorable
V	Rating > 1.75	Very Unfavorable

Table 3.8. Ratings for structure category in loose soil/ debris slope

A. Slope angle > 35°; slope angle, criteria for awarding rating		
Slope Angle	**Probable mode of failure**	**Rating**
36 - 45º	Probability of slope instability increases with increasing slope angle, whatever be the failure mode	1.0
46 - 60º		1.5
> 60º		2.0
B. Slope angle ≤ 35°; thickness of overburden, criteria for awarding rating		
Overburden thickness	**Probable mode of failure**	**Rating**
< 5m	Dominantly Planar Debris slide	0.65
5 – 10m	Planar Debris slide and sometimes Circular	0.85
11 – 15m	Circular and Planar Debris slide	1.30
16 – 20m	Dominantly Circular, though some times slip circle may non-circular type	1.50
> 20m		2.00

c) Slope Parameter

Slope parameter basically includes slope morphometry, i.e. slope angle and relative relief of individual facets. In meso-zonation approach, the impact of these two factors have been considered together to assess their significance in inducing instability. In this context it is their combined significance in a matrix form is considered, which is shown in Table 3.11. The maximum LHEF rating for slope parameter is 2.0.

i) Slope Morphometry:

Slope morphometry map defines slope categories on the basis of frequencies of occurrence of particular angles of slope. An average slope angle for the whole facet is judiciously selected. Five categories representing the slopes of escarpment/cliff, steep slope, moderately steep slope, gentle slope and very gentle slope have been classified on the basis of slope angle (Table 3.9)

Table 3.9. Slope morphometry classes based on slope angle

Slope type	Slope Angle	Probable type of failure	Class
Very gentle slope	< 15°	Slides with probable creep movement	A
Gentle slope	16 – 25°		B
Moderate slope	26 - 35°	Slides	C
Steep slope	36 - 45°		D
Very steep slope	46- 65°	Slides and falls	E
Escarpment/Cliff	> 65°	Falls & topples	F

ii) Relative relief:

The relative relief map represents the local relief within an individual facet, i.e., the maximum height between the ridge top and the valley floor. It is calculated by counting the difference between the bottom most point to top most point of a slope facet along the same direction (Table 3.10).

Table 3.10. Relative relief classes based on slope height

Relief classes	Relative relief (m)	Class
Very low	< 50	I
Low	50 - 100	II
Medium	101 – 200	III
High	201 - 300	IV
Very high	> 300	V

Table 3.11. LHEF rating for slope parameter classes

Slope parameter		a) Slope morphometry classes					
		A (<15º)	B (16–25°)	C (26-35°)	D (36-45°)	E (46-65°)	F (>65°)
b) Relative relief classes	I (<50m)	0.5	0.9	1.3	1.5	1.8	1.9
	II (50 -100m)	0.6	1.0	1.4	1.6	1.9	2.0
	III (101-200m)	0.7	1.1	1.5	1.7	1.95	2.0
	IV (201-300m)	0.8	1.2	1.55	1.75	2.0	2.0
	V (>300m)	0.9	1.3	1.6	1.8	2.0	2.0

From Table 3.11 it can be inferred that slopes with high slope angle (>35°) and high relief (>100m) are usually not favorable for civil constructions. However, the slopes with gentle angle and low relief are very favorable. Hence on the basis of the rating values, the slope parameters have been categorized into five classes (I to V) indicating the suitability of slopes for construction purpose (Table 3.12).

Table 3.12. Slope parameter class based on ratings

Rating (R)	**Description**	**Class**
R < 0.8	Very favorable	I
0.8 < R ≤ 1.2	Favorable	II
1.2 < R ≤ 1.6	Moderately favorable	III
1.6 < R ≤ 1.8	Unfavorable	IV
R > 1.8	Very unfavorable	V

d) Land use and land cover

One of the important factors governing slope stability is land use and land cover pattern. The nature of land cover is an indirect indication of the stability of hill slopes. A well spread root system increases the shearing resistance of the slope material. The barren and sparsely vegetated areas yield to faster erosion and greater instability. Based on the criteria of intensity of vegetation cover, the ratings shall be awarded (Table 3.13).

Table 3.13. Ratings for land use and land cover types

<table>
<tr><th colspan="2">Land use & land cover types</th><th>Rating</th></tr>
<tr><td colspan="2">Agricultural land or populated flat land (≤ 15°)</td><td>0.65</td></tr>
<tr><td colspan="2">Thickly vegetated forest area</td><td>0.80</td></tr>
<tr><td colspan="2">Moderately vegetated area</td><td>1.20</td></tr>
<tr><td colspan="2">Sparsely vegetated area with thin grass cover</td><td>1.50</td></tr>
<tr><td colspan="2">Sparsely urbanized</td><td>1.20</td></tr>
<tr><td colspan="2">Moderately urbanized</td><td>1.50</td></tr>
<tr><td rowspan="2">Heavily urbanized</td><td>With proper surface & subsurface drainages – no wet patches on slope</td><td>1.60</td></tr>
<tr><td>Inadequate drainage – wet patches left on slope</td><td>1.80</td></tr>
<tr><td colspan="2">Barren land – without anthropogenic activity</td><td>1.70</td></tr>
<tr><td colspan="2">Barren land with slope excavation (cut slopes for rail and road routes, construction terraces, mining activities, etc) incurring blasting damage to slope</td><td>2.00</td></tr>
</table>

e) Hydrogeological conditions

As groundwater in hilly terrain is generally channeled along structural discontinuities of rocks so it will provide valuable information on the stability of hill slopes for hazard mapping purposes. Therefore for purposes of quick appraisal the nature of surface indications of water such as damp, wet, dripping and flowing has been used for rating purposes (Table 3.14)

Table 3.14. Ratings for Hydrogeological conditions

Hydrogeological condition on slope	Rating
Dry	*0.0*
Damp	*0.2*
Wet	*0.5*
Dripping	*0.8*
Flowing	*1.0*

f) External factors

As external factors like seismicity and rainfall often initiate slope movements they are called triggering factors. India has been seismically divided into four zones, Zone II to Zone V. Similarly, annual rainfall has been classified into 4 categories. In areas with high annual precipitation, reduces the shear strength property of the slope material leading to instability (Table 3.15)

Table 3.15. Ratings for external factors

Seismic zone	Rating	Average annual rainfall of the area	Rating
II	*0.2*	≤ 50 cm	*0.2*
III	*0.3*	51 – 100cm	*0.3*
IV	*0.4*	101 – 150cm	*0.4*
V	*0.5*	> 150cm or history of cloud burst	*0.5*

3.2.2. Calculation of Total Estimated Hazard (TEHD) from LHEF ratings

Total estimated hazard (TEHD) indicates the overall condition of instability and shall be calculated facet wise by adding the LHEF ratings of all five inherent parameters along with external parameters, i.e. seismicity and rainfall (∑LHEF ratings for inherent and external parameters = TEHD) (Table 3.16). Ratings for external parameters will vary depending on the location of study area. The final value thus obtained is called TEHD value, which can vary widely from one facet to another depending on the condition of instability of the respective facets.

Total Estimated Hazard (TEHD) = LHEF Ratings for [(lithology + structure + slope morphometry + relative relief + land use and land cover + hydrogeological conditions + External parameters (seismicity and rainfall)]

Table 3.16. Landslide hazard zones based on corrected Total Estimated Hazard values

Hazard zone	Range of corrected TEHD value	Description of zone
I	TEHD < 3.5	Very Low Hazard (VLH) zone
II	3.5 ≤ TEHD < 5.0	Low Hazard (LH) zone
III	5.0 ≤ TEHD ≤ 6.5	Moderate Hazard (MH) zone
IV	6.5 < TEHD ≤ 8.0	High Hazard (HH) zone
V	TEHD > 8.0	Very High Hazard (VHH) zone

The LHEF rating scheme takes into consideration the net effect of all inherent and external causative factors responsible for slope instability. The maximum LHEF ratings for different categories are determined on the basis of their estimated significance in causing instability. The number 10 indicates the maximum value of the total estimated hazard (TEHD). Based on the obtained value, the slope was classified into different zones of stability such as Very High Hazard (VHH), High Hazard (HH), Moderate Hazard (MH), Low Hazard (LH) and Very Low Hazard (VLH). Taking these parameters into consideration, facetwise information was collected and analyzed to prepare a LHZ map of Kodaikanal area incorporating the field data on 1:10000 scale.

3.3 Detailed slope stability study

After identification of hazard prone slopes, the next phase of landslide investigation comprises of detailed slope stability study of potentially unstable hill slopes. The scale of detailed study, followed in the present work was 1:1,000 – 2,000. To assess the status of stability of the hazard prone slopes, representative geological plan and sections were prepared. From field studies and geological sections, the nature of slope failure was identified. For the purpose of stability assessment, analytical approach had been followed. The present study, which is a deterministic approach follows the concept of '2-D limit equilibrium' to get the value of Factor of Safety (F) of respective slopes. Here, the slope is considered to be made up of Mohr-Coulomb type of material whose shear strength is expressed in terms of cohesion (c) and friction angle (Φ). The condition of "limiting equilibrium" for any block resting on a slope exists, when driving (mobilizing) forces acting along the plane of separation is exactly counter balanced by resistive (restraining) forces exerted by the block and only in this case the F value of that block is considered as 1. The systematic procedure for obtaining the F value by 2-D slope stability analysis is discussed below.

3.3.1 Identification of dominant modes of slope failures and their stability analysis

The slope forming materials can be broadly divided into two categories – a) in-situ rock and b) transported overburden soil. Type of failure primarily depends on the type of material involved. By mapping the area and taking observations related to geological structures, the dominant mode of failure is identified. In the study area, the observed modes of failure include rotational failure, plane failure and talus failure.

3.3.1.1. Major types of failure observed on rock slopes

The slope failures in rock mass are governed by geological discontinuities and movement occurs along the surface(s) formed by one or several sets of geological discontinuities. In the study area, six potential rock slopes were evaluated and all of them fall under the category of plane failure.

i) Concept of Plane Failure

Plane failure is a type of translational failure, which occurs when a geological discontinuity, such as a joint, dips towards the valley with strike almost parallel to that of the slope but amount of dip less than slope inclination (day-lighting condition).

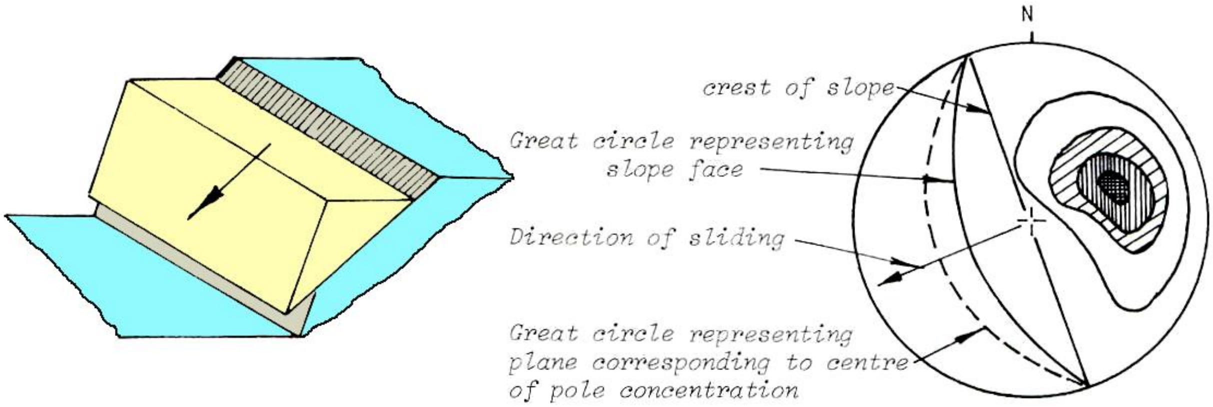


Fig 3.1. Schematic diagram of plane failure (Hoek & Bray, 1981)

ii) Markland test for plane failure

a) The plane on which sliding occurs (failure plane) must strike parallel or nearly parallel (±20°) to the strike of slope.

b) The dip of failure plane (ψp) must be less than inclination of slope (ψf) i.e. ψp < ψf. It means that failure plane must get 'day lighted' on the slope.

c) The dip of failure plane must be greater than angle of internal friction (φ) along the failure plane i.e. ψp > φ. Hence the conditions for plane failure can be denoted as ψf > ψp > φ.

d) Release joints/surfaces provide negligible resistance to sliding, may be present on both the sides of sliding mass as well as in crown portion.

iii) Stability Analysis of Plane Failure

The important considerations for 2-D stability analysis of plane failure are briefly discussed below.

iv) Slope Geometry

The geometry of the slope, which is prone to failure, may be classified into two categories based on position of tension cracks.

a) A slope having tension crack on the top of upper surface.

b) A slope having tension crack on the slope face.

Determination of Factor of Safety (F)

As per the condition of 'limiting equilibrium', F value for any slope is calculated as the ratio of total force resisting sliding to the total force tending to induce sliding. Therefore for slopes showing plane failure mode, the factor of safety (F) is given by the following equation (Wylie and Mah, 2004).

$$F = \frac{cA + \left(w\, cos\psi_p - U - sin\psi_p\right) tan\phi}{W \sin\psi_p + V \cos\psi_p} \qquad \text{Eq. 3.1}$$

3.3.1.2. Major types of failure observed on slopes composed of overburden materials

(a) Rotational or Slip-Circular Failure

Circular failure often occurs on hill slopes characterized by thick overburden soil and debris. The failure surface here is not controlled by any preexisting weak plane and as such it is independent to find the line of least resistance through the slope material. Such type of slope failures usually takes the form of a circular profile (Fig 3.10). Even hill slopes composed of crushed rocks as well as highly weathered and altered rocks may behave like soil and tend to fail in a circular failure mode.

i) Conditions for rotational/ circular failure

The general conditions responsible for a circular type of failure are as follows.

a) Slopes composed of unconsolidated and loose soil and debris or highly weathered and altered rocks of considerable thickness, where the failure surface is not guided by any predefined plane and hence it is free to take it in own course. Generally the failure surface takes a circular shape and hence called rotational/ circular failure.

b) Presence of excess water decreasing shear strength of slope material.

ii) Stability Analysis of Rotational (Slip-Circular) Failure

In the present work three methods of stability analysis for rotational failure has been adopted. These are – i) Circular Failure Chart Method (Hoek and Bray, 1981 and Wyllie and Mah, 2004), ii) Bishop's simplified method of Slices (Wyllie and Mah, 2004) and iii) Computer Program SARC (Singh and Goel, 2002). All the three methods are briefly discussed below and their details can be found in corresponding reference literatures.

iii) Stability analysis using Bishop's simplified method of slices

Bishop's simplified method of slices is one of the widely followed techniques for calculation of factor of safety by analytical methods. Bishop's method assumes a circular slide surface and that the side forces are horizontal. The analysis satisfies vertical forces and overall moment equilibrium (Wyllie and Mah, 2004). In this method the soil mass is symmetrically divided into vertical slices whose dimensions are fixed on the basis of slope geometry. These dimensions are defined as slice parameters which include width of the slice (Δx), height (h) of individual slices from centre and base angle (α).

To determine the slice parameters, at first on a suitable scale an accurate profile of the slope should be made. Field visits are also required to ascertain the local hydrogeological condition. Other input parameters are same as in the CFC method. Fig 3.2 is used to define the geometry of failure plane and to draw the critical failure circle. The procedure for determination of number of slices has been described in detail in Hoek and Bray, 1981.

The equation for determining F value is given in Fig 3.3. In this method the F value is calculated by iteration process. Initial value of F = 1 is assigned in the right hand side of the equation (Fassumed) and a value of F is obtained (Fderived). The iteration process is continued till the difference between two values is less than 0.001 (Anbalagan et al., 2007). The process for determination of F value is given in detail in Hoek and Bray (1981) and Wyllie and Mah (2004).

In Fig 3.3, the equation for deriving factor of safety is given as;

$$F = \sum\{X/\ (1+Y/\ F)\}\ /\sum Z + Q \quad \text{.............................. (Eq. 3.2)}$$

Where $X = [\{c + (\gamma h - \gamma_w h_w)\tan\Phi\}\Delta x]/\ \cos\alpha$

$Y = \tan\alpha.\tan\Phi$

$Z = \gamma h\ \Delta x\ \sin\alpha$

$Q = 0.5\gamma_w z^2.\alpha/R$ (R = Radius of curvature of critical circle)

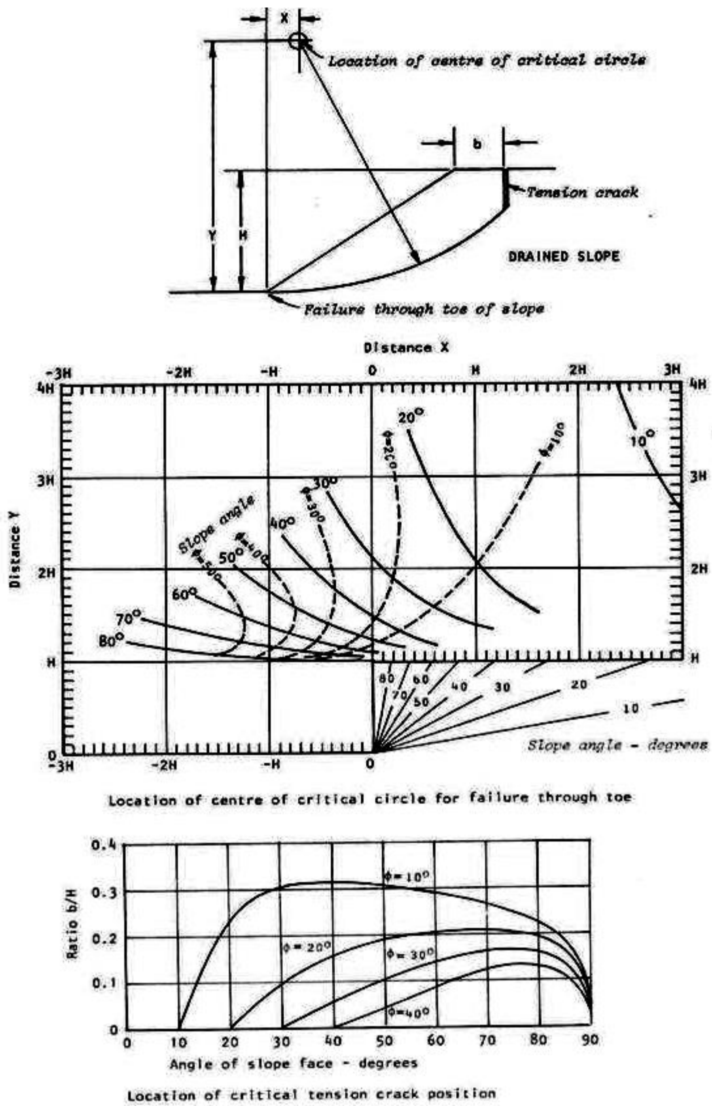


Fig 3.2. Locating critical failure surface and critical tension crack for drained slopes using charts of Hoek and Bray, 1981

iv) Stability Analysis using SARC program

This computer program is essentially based on Bishop's method of slices (Singh and Goel, 2002). The program hypothetically segments the slope into vertical strips of almost equal thickness and calculates the total force exerted by individual segments towards the toe of slope. Failure condition is established when the cumulative outward force of these slope segments exceeds the shear strength along most critical plane of failure. The failure surface in this approach is supposed to pass through the toe of the slope.

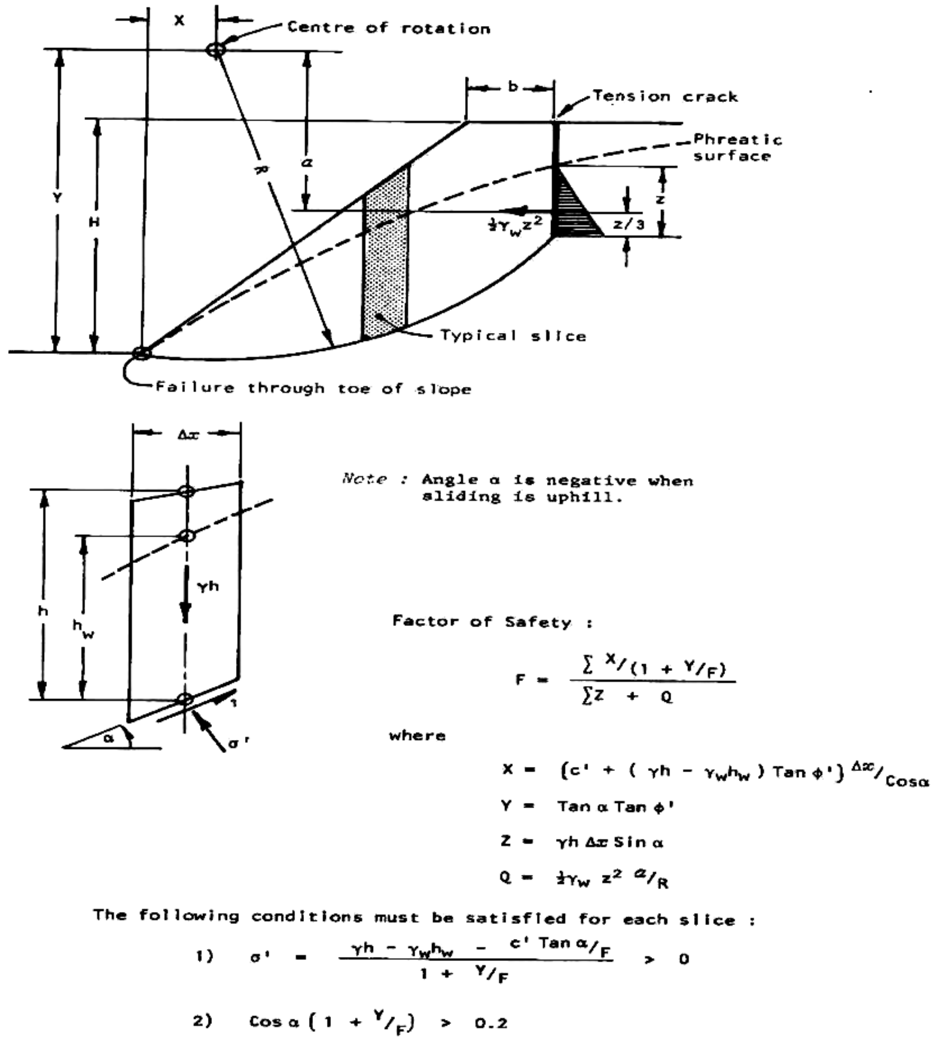


Fig 3.3. Bishop's simplified method of slices for analysis of circular failure in slopes cut into materials, in which failure is defined by Mohr-Coulomb Failure Criterion (Hoek and Bray, 1981

Accordingly this program seeks various combinations of failure surfaces based on the relative position of tension crack behind the crown (on top) and the exit points at the toe of slope and finally selects one combination which gives lowest F value, i.e. instability condition along the most critical failure surface. Hence, SARC program helps to draw the possible failure surface as it gives the radius of curvature and coordinates of centre of rotation with respect to slope face.

b) Planar Debris Slide or Talus Failure

Planar debris slide or talus slide (Anbalagan et. al., 2007) refers to down slope movement of thin overburden soil and debris layer, lying over in-situ rock with the attitude of rock surface dipping roughly towards valley side at an angle less than the inclination of general slope. The mechanism of talus slide is nearly similar to planar failure, with difference that rock – debris contact acts as plane of movement. Loose debris/ scree materials/ slope wash/ colluvium get deposited on lower reaches of hill slope due to past slide activities. A long spell of heavy rainfall on these materials results in the formation of a temporary phreatic surface / water charged zone at the contact of in-situ rocks with debris. As a result, a layer of water charged debris may slide down due to high pore water pressure along its contact with underlying in-situ rock and this phenomenon is referred as talus failure or planar debris slide. This kind of failure condition is observed in the soil slopes of the Kodaikanal area.

i) Conditions for planar debris slide

This type of slide is generally observed along cut slopes of roads and rail lines in hilly terrains. The following conditions are considered favorable to initiate this phenomenon.

a) Gentle to moderately steep dip of the rock slope (15º - 35º) towards valley side acting as zone of accumulation of debris coming from upper reaches. In some cases this type of failure is also noticed in hill slopes with steep (>45º) slope angle.

b) Shallow thickness of accumulated debris, usually ranging between 1m to few meters (≈ 5m). But sometimes this type of failure is also seen when slope has sufficient thickness of debris.

c) Heavy rainfall for a considerable period of time may act as a triggering factor to accentuate this phenomenon. Rain water accumulates over relatively impermeable underlying in-situ rock, due to which the phreatic surface rises sharply and comes close to ground level, creating huge pore water pressure within the accumulated debris (Fig 3.14) and thus initiating a planar debris slide.

i) Stability Analysis of Planar Debris (Talus) slide

Analysis of planar debris slide was done by Coates (1970) and the equation of F is given below.

$$F = \frac{c.sec^2\Psi_f/\gamma.Z + tan\varphi\,[1-(1-Z_w/Z).\gamma_w/\gamma]}{tan\Psi_f} \quad \text{Eq. 3.3}$$

where,

c = cohesion,

Φ = friction angle,

g = unit weight of talus material,

gw = unit weight of water,

Ψf = average slope gradient,

Z = average depth of overburden and

Zw = average depth of phreatic surface from slope face (Fig 3.4).

The equation 3.3 is derived considering the following assumptions.

i) Talus material is supposed to have constant thickness (Z). In practice, average thickness of non-uniform debris layer is considered.

ii) During long spell of rains, groundwater level starts rising up to a depth Zw below slope surface.

iii) Surcharge is usually taken into account by increasing Z by equivalent soil cover and decreasing Zw in the same manner.

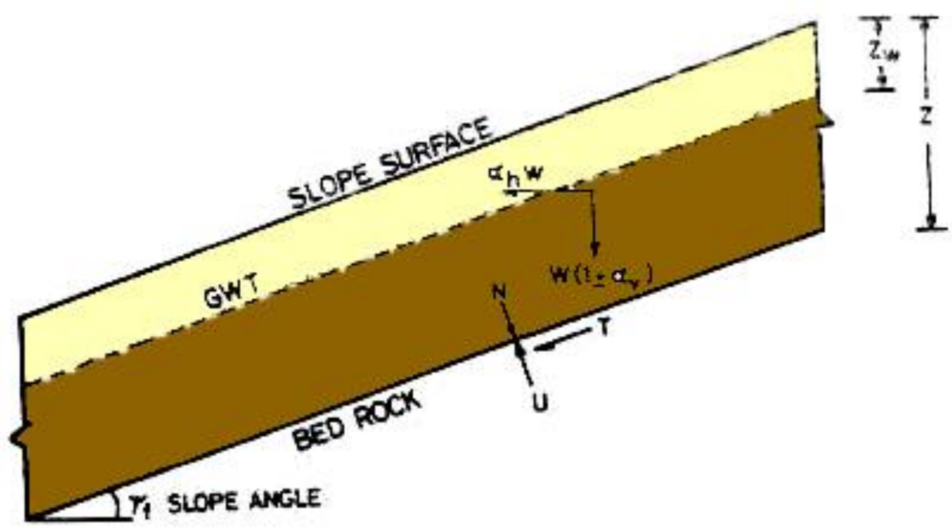


Fig 3.4. Schematic condition for a Planar Debris (Talus) Failure indicating the stresses acting on debris mass

Note: Slope surface and Slope angle are considered parallel in the analysis (Anbalagan et al., 2007). Symbols used in the above figure: W = Weight of Unstable Mass, α_v = Vertical component of ground acceleration, α_h= Horizontal component of ground acceleration, N = Normal stress, U = Uplift stress and τ = Shear stress acting on debris mass

It is important to note that talus slide may take place at slope angle much less than Φ value of the slope forming material. This may happen in case of thin cover of talus material with water table reaching close to the slope surface during long spell of rains.

3.4 Determination of shear strength parameters for slopes

The geotechnical investigations are carried out to understand the engineering properties of the rock mass. Any engineering project requires quantitative data for planning and designing. The engineering rock mass classification helps to assess the quality of hard rock such as strength and modulus of deformation. The analyses are done by classifying the rock into following two categories;

Intact rock: Intact rocks are small representative sample of the rock mass, which is devoid of any discontinuities but may with micro types. The intact rock samples are basically used for determination of modulus of deformation and uniaxial compressive strength.

Rock mass: It refers to a mass of in-situ rock sample that all inherent anisotropic characters like fault, joint and fractures are present on it and it also exhibits wide range of compositional and mechanical properties.

Soil Slopes: Laboratory test (Direct shear test) – this test is generally conducted on in-situ soil sample in laboratory. If the slope is dominantly consisted of fine fraction (maximum upto sand size) which is homogenous in nature, shear strength parameters estimated from direct shear test gives nearly accurate value. Even if disturbed samples are tested, the values obtained may not differ much from the former case.

Rock Slopes: For estimating the shear strength parameters of rock slopes two approaches were followed in the present work. Rock Mass rating Scheme (Bieniawski, 1979). The value obtained is represents the shear strength of rock mass.

3.4.1 Rock Mass Rating (RMR) System

Rock Mass Rating is an easy and economical approach uses to assess the strength properties of a rock, is introduced by Bieniawski in 1973; based on his experience in the tunneling fields. This empirical approach is based on six parameters, which can be obtained from both laboratory and field conditions. Each parameter is assigned with ratings based on its importance to the rock strength. The final RMR value of rock will be the summation of ratings of all six parameters. The six parameters for the calculation of RMR value are:

a) Uniaxial Compressive Strength (UCS) of the Intact Rock Material
b) Rock Quality Designation
c) Spacing of Discontinuity
d) Condition of Discontinuity
e) Groundwater Condition
f) Orientation of Discontinuities

However, the Bureau of Indian Standards [Code No. CED4848 (4107) August, 1989], modified the Geomechanics classification. This new modification was done keeping in view the analysis of slope stability. In the BIS code of 1989 version, the RMR for the adverse joint orientation with respect to slope orientation was eliminated as the slope stability analysis separately takes into account the orientation of joints with respect to the slope. Thus in the BIS format of Geomechanics classification, the last parameter i.e. orientation of discontinuities is excluded and this is called RMRbasic. The BIS modified Geomechanics classification is given in Table 3.17.Based on the five parameters rock mass are rated and finally added up to get the RMRbasic value. From the obtained values of RMRbasic one can classify the rock mass and can obtain corresponding values for cohesion (c) and angle of internal friction (Φ) (Table 3.18).

3.4.1.1 Determination of RMR and strength parameters

The rating for the each parameter is given carefully during the field work and by laboratorial experiments. The lump samples of appropriate size were brought into the laboratory. From these data the RMRbasic and engineering properties of rock were determined.

(a) Uniaxial Compressive Strength (UCS)

The strength of the rock to withstand the maximum stress without failure. In the UCS, the both ends of the sample exposes to the atmosphere and the loading done from one end, thus it is called Uniaxial. The UCS is calculated by noting down the load at which the sample breaks. Due to the non-availability of UCS machine, the values are calculated indirectly from Point Load Lump Strength Index, by using the following formula:

$$IL_{50} = [P/\{(W\times D)0.75\}\times\sqrt{5}] \quad \text{Eq. 3.4}$$

IL50 - Point Load Lump Strength Index

W – Width of specimen

D – Depth of specimen

And hence, UCS = (15× IL50) Eq. 3.5

(b) Rock Quality Designation (RQD)

RQD accounts the core losses and fracturing of rocks. It can be expressed as the sum of core pieces greater than or equal to 10 cm to the total run of bore hole.

$$RQD = (\sum \text{lengths of core pieces} \geq 10\text{cm} / \text{total core run}) \times 100$$

In absence of core, the RQD can be found from the following equation, proposed by Barton et al. (1974)

$$RQD = 115 - 3.5Jv \quad \text{Eq. 3.6}$$

Where, Jv– volumetric joint count

In this work, Barton's formula has been followed for all lithounits.

c) Spacing of Discontinuities

The mean distance between the discontinuities or between the planes of weakness in a rock mass is measured perpendicular to the strike of discontinuity by a graduated table.

d) Condition of Discontinuity

This parameter includes roughness of discontinuity surfaces, their separation, length or continuity, weathering of the wall rock or the planes of weakness. and infilli ng (gauge) material.

(e) Groundwater Condition

The ground water condition has greater impacts on strength and engineering properties of rock mass. The various conditions are dry, damp, wet, dipping and flowing are assessed from field visually.

Table 3.17 RMR$_{basic}$ ratings (Modified after Bieniawski, 1979 and Bureau of Indian Standards, 1989)

<table>
<tr><th colspan="2">Parameters</th><th colspan="7">Ranges of Values</th></tr>
<tr><td rowspan="2">1. Strength of intact rock material</td><td>Point Load strength Index</td><td>>10 MPa</td><td>4-10 MPa</td><td>2-4 MPa</td><td>1-2 MPa</td><td colspan="3">For this low range Uniaxial Compressive test is preferred</td></tr>
<tr><td>Uniaxial Compressive strength</td><td>>250 MPa</td><td>100-250 MPa</td><td>50-100 MPa</td><td>25-50 MPa</td><td>5-25 MPa</td><td>1-5 MPa</td><td>< 1 MPa</td></tr>
<tr><td colspan="2">Rating</td><td>5</td><td>12</td><td>7</td><td>4</td><td>2</td><td>1</td><td>0</td></tr>
<tr><td colspan="2">2. Drill Core Quality RQD</td><td colspan="2">90-100</td><td colspan="2">75-90</td><td>50-75</td><td>25-50</td><td><25</td></tr>
<tr><td colspan="2">Rating</td><td colspan="2">20</td><td colspan="2">17</td><td>13</td><td>8</td><td>3</td></tr>
<tr><td colspan="2">3.Spacing of discontinuities</td><td colspan="2">> 2 m</td><td colspan="2">0.6-2 m</td><td>200-600mm</td><td>60-200 mm</td><td>< 60mm</td></tr>
<tr><td colspan="2">Rating</td><td colspan="2">20</td><td colspan="2">15</td><td>10</td><td>8</td><td>5</td></tr>
<tr><td colspan="2">4. Condition of discontinuities</td><td colspan="2">Very rough surface, not continuous, no separation, unweathered wall rock</td><td colspan="2">Slightly rough surface, separation <1mm, slightly weathered walls</td><td>Slightly rough surfaces, separation <1mm, highly weathered walls.</td><td>Slickensided surfaces, or Gouge <5mm thick, or separation 1-5 mm, continuous</td><td>Soft Gouge>5 mm or separation >5mm , continuous</td></tr>
<tr><td colspan="2">Rating</td><td colspan="2">30</td><td colspan="2">25</td><td>20</td><td>10</td><td>0</td></tr>
<tr><td colspan="2">5. Groundwater in joints</td><td colspan="2">Completely dry</td><td colspan="2">Damp</td><td>Wet</td><td>Dripping</td><td>Flowing</td></tr>
<tr><td colspan="2">Rating</td><td colspan="2">15</td><td colspan="2">10</td><td>7</td><td>4</td><td>0</td></tr>
</table>

The ratings for UCS, RQD, spacing of discontinuities, condition of discontinuity and hydrogeological condition were referred from Table 3.17 (Bieniawski, 1989).

RMRbasic = Σ Ratings of (UCS + RQD + Discontinuity Spacing + Discontinuity Condition + Groundwater Condition + Orientation of Discontinuity) Eq. 3.7

Finally the representative values of shear strength parameters were obtained using the formulae –

c (MPa) = 0.005 × RMRbasic d Eq. 3.8

Φ (degree) = [(0.5× RMRbasic) + 5] Eq. 3.9

Table 3.18 RMR Classes and values of shear strength parameters as determined from total RMR_{basic} rating (Bieniawski, 1990)

RMR_{basic} rating	**100-81**	**80-61**	**60-41**	**40-21**	**<20**
Class	***I***	***II***	***III***	***IV***	***V***
Description	Very Good Rock	Good Rock	Fair Rock	Poor Rock	Very Poor Rock
Cohesion (c) value of Rock Mass (K. Pascal)	>400	300-400	200-300	100-200	<100
Friction angle (Φº) of Rock Mass	>45	35-45	25-35	15-25	<15

3.4.2 SMR System

The Slope Mass Rating system uses application of Beinawski's Rock Mass Rating system to assess the stability of the slope. The SMR is modified by the Romana (1985) (Table 3.19 and Table 3.20). This approach used plane and toppling failure. Anbalagan (1992) considered wedge failure as a special case of plane failure and analyzed with respect to the orientation of slope and line of intersection between two discontinuities (wedge line). This modification accepted as IS code (IS: 13365(Part 3):1992). SMR can be numerically explained as,

SMR = RMRbasic + (F1×F2×F3) + F4 Eq. 3.10

F1 is the parallelism between the slope and the discontinuity, it ranges from <5 to >30. As the parallelism increases the possibility of slope failure increases.

F2 is depends on amount of dip of discontinuity plane or plunge of wedge line. It ranges from 0.15 for < 20^0 to 1.00 for >45^0.

F3 is the parallelisms between the dip/plunge of the discontinuity to the dip of slope face. The condition is favorable when the slope face and the discontinuity dips at equal angle and the condition gets worse when the slope dip is greater than that of discontinuity.

F4 is the correction factor depends on the nature of excavation on the slope.

Table 3.19 Adjustment rating for joints, using modified SMR approach (Romana,1985)

Case	**Very favorable**	**Favorable**	**Fair**	**Unfavorable**	**Very unfavorable**
P:αj-αs T:(αj-αs)-180 P/T : F1	>30 0.15	30-20 0.40	20-10 0.70	10-5 0.85	<5 1.00
P : βj P : F2 T : F2	<20 0.15 1	20-30 0.40 1	30-35 0.70 1	35-45 0.85 1	>45 1.00 1
P : βj- βS P/T : F3	>10 <110 0	10-0 110-120 -6	0 >120 -25	0-(-10) -- -50	<-10 -- -60
P = Planar failure	T = Toppling failure	αs = slope dip direction	αj= joint dip direction	βj=joint dip amount	βS=slope dip amount

Table 3.20 Description of SMR classes (Romana,1985)

Method	Natural slope	Pre-splitting	Smooth Blasting	Mechanical blasting	Deficient blasting
F4	+15	+10	+8	0	-8

Class	SMR	Description	Stability	Failures	Support
I	81-100	Very good	Completely stable	None	None
II	61-80	Good	Stable	Some blocks	Occasional
III	41-60	Normal	Partially stable	Some joints or many	Systematic

				wedges	
IV	21-40	Bad	Unstable	Planar or big wedges	Importance /corrective
V	0-20	Very bad	Completely unstable	Big planar or soil like	Re-excavation

3.4.3 Barton and Brandis Criterion

The Barton-Bandis failure criterion is an empirical relationship widely used to model the shear strength of rock discontinuities Rock joint shear strength is one of the key properties used in the stability analysis and design of engineering structures in rock mass, e.g. slopes, tunnels and foundations (Hoek and Brown, 1980). The conventional method currently used to determine the joint shear strength is the direct shear testing which can be performed in the field and in the laboratory. Several criteria have been proposed in the past to identify the strength of a rough rock joint. The simplest peak-shear strength model for rock joints is perhaps Patton's model (Patton, 1966). Based on the Coulomb friction law, this model characterizes the joint behavior by a single surface parameter that is the average roughness angle.

Coulomb criterion represents the relationship between the peak shear strength and normal stress by

$$\tau = c + \sigma n \tan\varphi \qquad \text{Eq. 3.11}$$

where τ is joint shear strength,

σn is normal stress,

c is the cohesive strength, and

φ is angle of friction.

This linear relationship by Coulomb was adopted as the simplified method to calculate the shear strength but it does not reflect the reality. A natural discontinuity surface in hard rock is never as smooth as the ground surface of the type used for determining the basic friction angle. The undulations and asperities on a natural joint surface have a significant influence on its shear behaviour. Patton (1966) demonstrated this influence by means of an experiment in which he carried out shear tests on 'saw-tooth' specimens.

The shear strength of Patton's saw-tooth specimens can be represented by:

$$\tau = \sigma n \tan(\phi b + i) \qquad \text{Eq. 3.12}$$

where ϕb is the basic friction angle of the surface and

i is the angle of the saw-tooth face.

While Patton's approach has the merit of being very simple, it does not reflect the reality that changes in shear strength with increasing normal stress are gradual rather than abrupt. Barton (1973, 1976) studied the behaviour of natural rock joints and proposed that equation (4) could be

re-written as:

$$\tau = \sigma_n \tan\left(\varphi_r + JRC\, log_{10}\left(\frac{JCS}{\sigma_n}\right)\right) \qquad \text{Eq. 3.13}$$

where τ is peak shear strength

σn is the effective normal stress

JRC is the joint roughness coefficient and

JCS is the joint wall compressive strength, and

Φb is the basic friction angle

Barton and Choubey (1977), on the basis of their direct shear test results for 130 samples of variably weathered rock joints, revised this equation to:

$$\tau = \sigma_n \tan\left(\varphi_b + JRC\, log_{10}\left(\frac{JCS}{\sigma_n}\right)\right) \qquad \text{Eq. 3.14}$$

where φr is the residual friction angle

Barton and Choubey suggest that φr can be estimated from

$$\varphi r = (\varphi b - 20) + 20(r / R) \qquad \text{Eq. 3.15}$$

where r is the Schmidt rebound number wet and weathered fracture surfaces and

R is the Schmidt rebound number on dry unweathered sawn surfaces

Equations 6 and 7 have become part of the Barton-Bandis criterion for rock joint strength and deformability (Barton and Bandis, 1990).

3.4.3.1 Joint Roughness Coefficient (JRC)

The joint roughness coefficient JRC is a number that can be estimated by comparing the appearance of a discontinuity surface with standard profiles published by Barton and others. One of the most useful of these profile sets was published by Barton and Choubey (1977) (Fig 3.5) The appearance of the discontinuity surface is compared visually with the profiles shown and the JRC value corresponding to the profile which most closely matches that of the discontinuity surface was chosen.

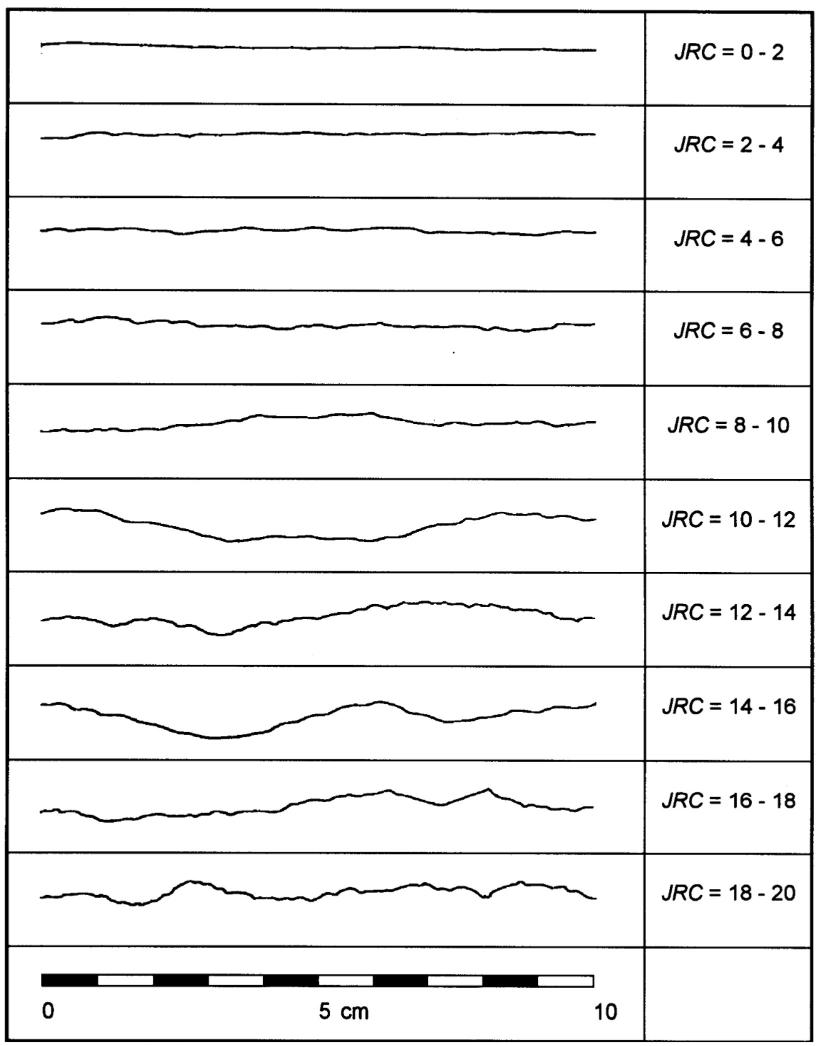


Fig 3.5. Roughness profiles and corresponding JRC values (After Barton and Choubey 1977).

3.4.3.2 Joint Wall Compression Strength (JCS)

The measurement of this parameter is of fundamental importance in rock engineering since it is largely the thin layers of rock adjacent to joint walls that control the strength and deformation properties of the rock mass as a whole. The depth of penetration of weathering into joint walls presumeably depends on rock type, in particular on its permeability. The Correlation relating the rock density, compressive strength and rebound number of the Schmidt hammer is given in Fig 3.6.

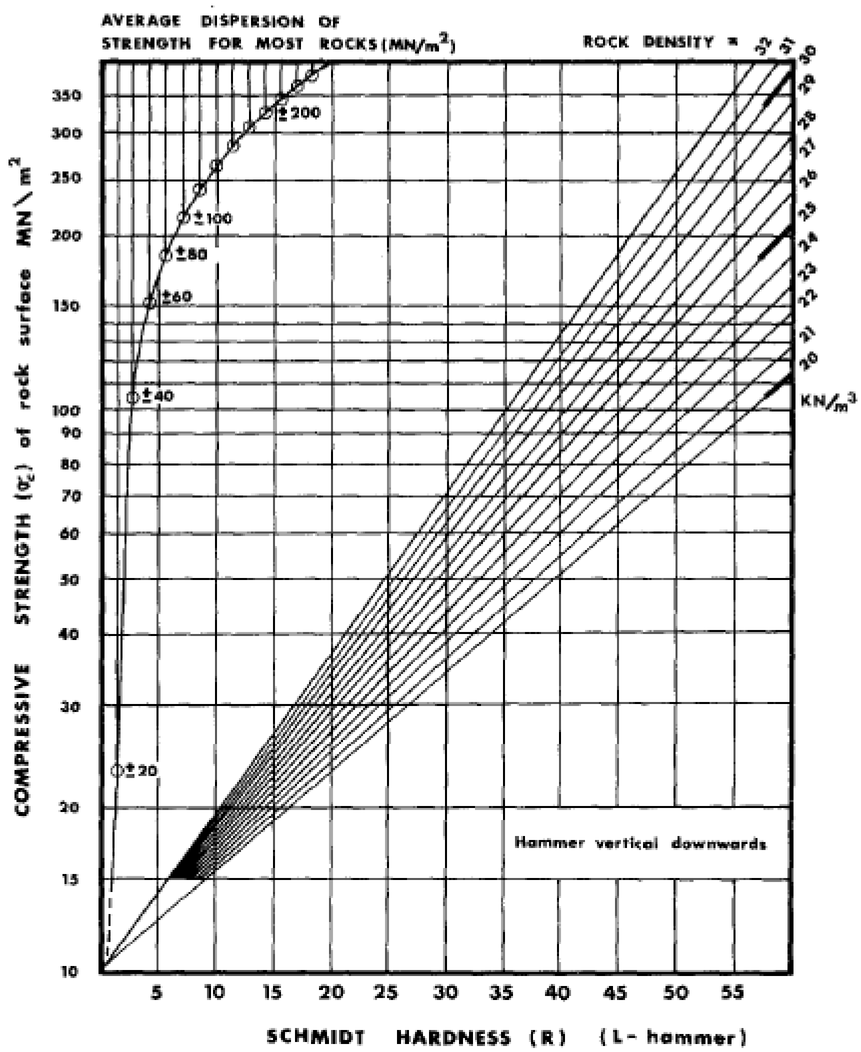


Fig 3.6. Correlation chart for Schmidt (L) hammer, relating rock density, compressive strength and rebound number, after Miller (1965)

CHAPTER 4
LANDSLIDE HAZARD ZONATION MAPPING OF KODAIKANAL TOWN

4. 1 Landslide Hazard Zonation

A landslide hazard zonation map divides the land surface into zones of varying degrees of stability, based on the estimated significance of causative factors in inducing instability. To carry out the landslide hazard zonation map of Kodaikanal area, the modified macro-zonation approach of Anbalagan et al (2008) has been used in the present research work. The details of this modified approach have been discussed in Chapter 3. This chapter describes various work components involved during the preparation of landslide hazard zonation (LHZ) map of Kodaikanal.

4.2 Data set used and preparation of thematic maps

The thematic maps of the study area are prepared using the Survey of India Toposheet 58F/7SE, 58F/8NE, 58F/11SW and 58F/12NW of 1:25,000 scale (Fig 4.1), DEM prepared by Shuttle Radar Topography Mission (SRTM, September, 2014) 1 Arc-Second Global(USGS), Google Earth Satellite Imageries and available geological maps (Fusch,1978). These base topographic maps were used as reference map for field survey, identification of land use/land cover patterns, landslides, and other related analysis.

4.3 Facet map

The slope facet map provides the base for the preparation of various thematic maps of the study area. A facet is a part of hill slope, which has more or less similar slope characteristic such as consistent slope direction and inclination (Anbalagan, 1992). The facet map is prepared using the Survey of India toposheets. The slope facets are generally delineated by ridge break in slope, stream, spurs and other geomorphic features.

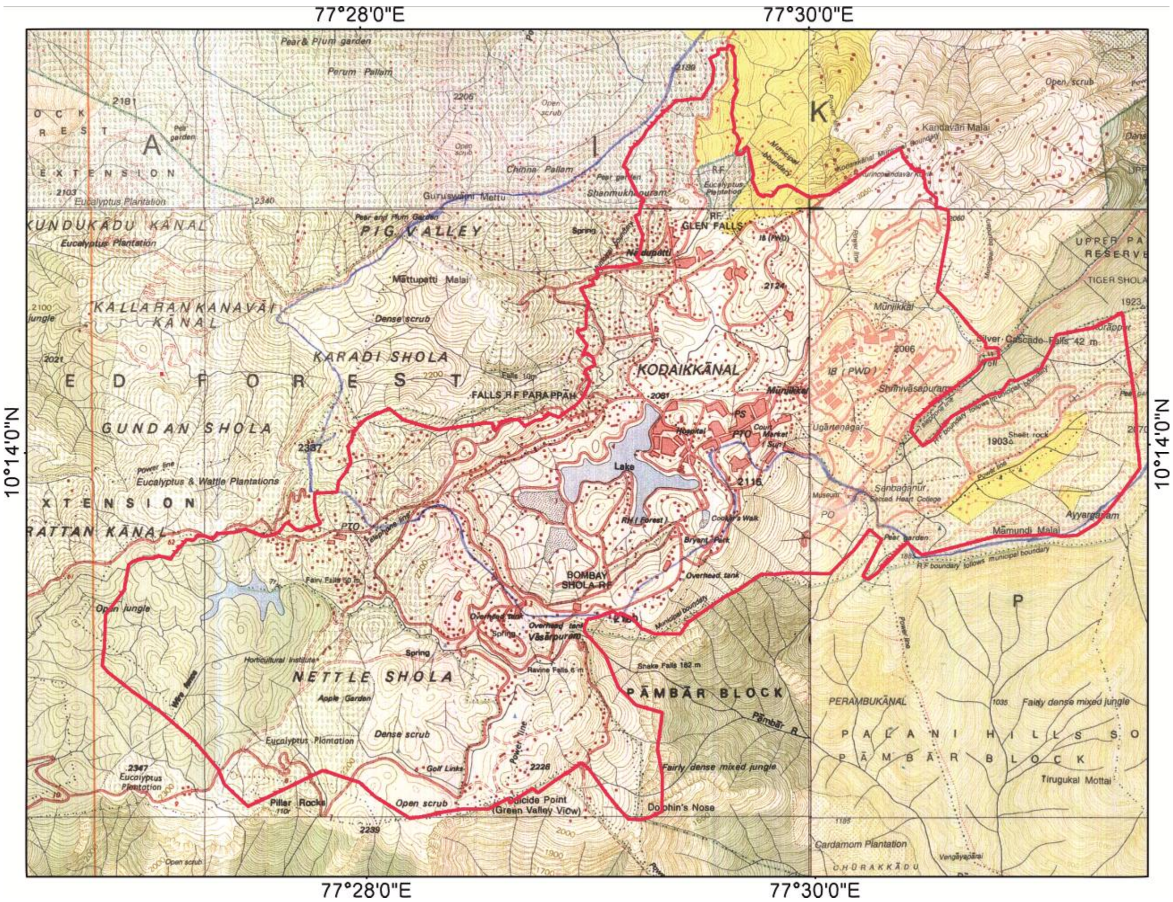


Fig 4.1 Survey of India Topographic map of Kodaikanal Region with demarcated study area

Out of the total 96 facets identified in the study area, 23 facets are rock slopes and the remaining 73 facets are soil slopes (Fig 4.2). The data related to various causative factors such as lithology, structure, slope morphometry, relative relief, land use land cover, hydrogeological condition and other related factors were collected facet wise and given the ratings according to field conditions.

4.4 Lithological Map

The lithology map shows the distribution of rock types and soil present in the study area (Fig 4.3). The Kodaikanal township is situated in the central part of the Kodaikanal Taluk. Charnockite rocks with overburden cover at many places are exposed within Kodaikanal township area. The thickness of the overburden debris varies from place to place. An area of about 60% is covered by debris ranging thickness from 1m to 5m. Rock with thin overburden cover is exposed in the remaining 40% of the area.

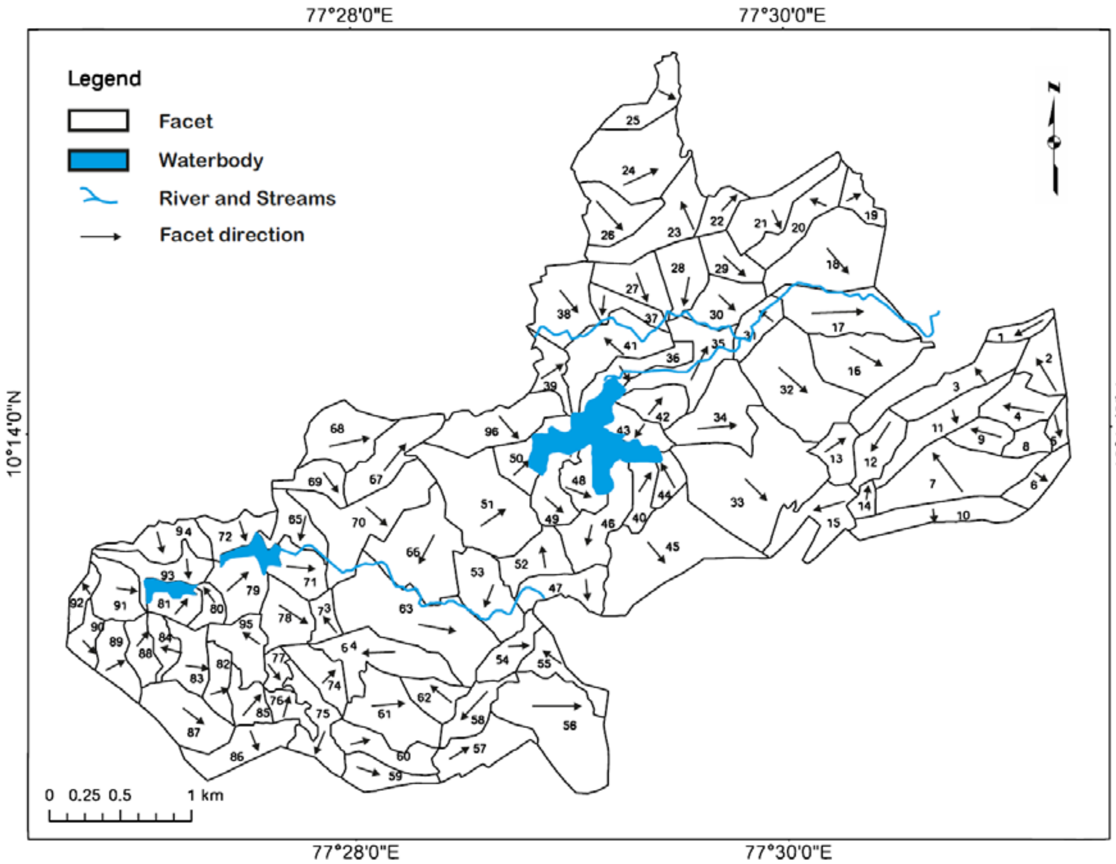


Fig 4.2 Facet map of the study area showing individual facet direction

The southern boundary of the study area consists of a linear ridge which extends from Shenbaganur to Moir Point and it exposes charnockite rock with least overburden cover. The rocks are fairly fresh to moderate weathered in the area surrounding the Guna Cave whereas fresh to slightly weathered rocks are seen in the Coalkers Walk area. The rocks are fairly fresh in general in cut slopes of roads and terraces. Rock exposures are seen on ridge top along the Fairy Fall, Fern hill and Bear shola hills. Slightly weathered to fairly fresh rocks could be seen on valley cut faces as well as along the water courses. The Palani hills forest conservation area located in the southern part supports thick lush green trees with old and well compacted colluvial debris. Similar type of debris materials are seen in areas adjoining the Kodaikanal Lake in Bear Shola, Pudukkad and Gandhipuram blocks, as well as Kurinji Nagar and Shenbaganur area. The nature of weathering differs at different locations and the ratings have been accorded as per the site conditions.

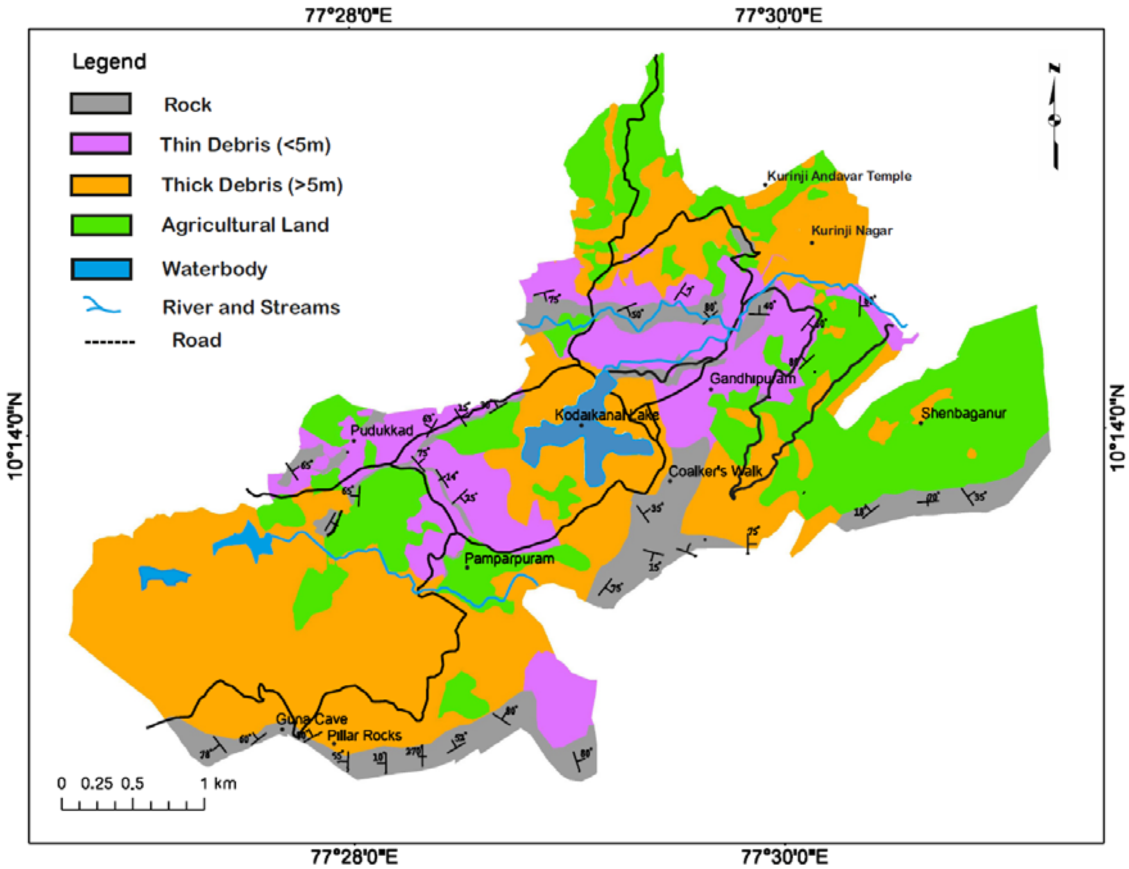


Fig 4.3 Geology map of Kodaikanal area

4.5 Structure Map

The dominant structural features in the area are joint planes with feebly developed foliations at places. The rocks in general show three well developed joint sets with concoidal fractures. The joints have good strike continuity. The joints are undulating; rough and showing iron stains at places. The joints were observed in different facets and the data had been used to prepare the structure favorability map. The joints are tight with no fillings inside. For assigning LHEF rating for structure, all the discontinuities of individual facets were plotted on a stereonet and on the basis of kinematic analysis, the most unfavorable discontinuity was identified.

4.6 Slope Morphometry

Slope morphometry map indicates the nature of steepness of the slope facets, within study area. The slopes were classified into six categories (Table 3.11) from very gentle slope (< 15º) to escarpment or cliff (> 65º). STRM DEM and Survey of India toposheets were used for the purpose. This obviously indicates the average slope angle in view of local undulations within a facet. The slope morphometry map (Fig 4.4) of Kodaikanal shows that 75% of the area falls under the category of very gentle (<15°) to gentle slope (25°). At places, the Particularly slopes, which encompasses old and compacted debris, in areas adjoining Fairy Falls and Vattaparai, Fern Hill and Shenbaganur are generally having gentle slopes. The Ananthagiri area, Vilpatti and Pamparpuram area has moderate slopes with an angle of 26°-35°. The cliff edge of the Vattaparai area, bordering the southern end of the study area falls under the steep slope (36°-45°) along with areas surrounding Kurinji Nagar and Gandhipuram.

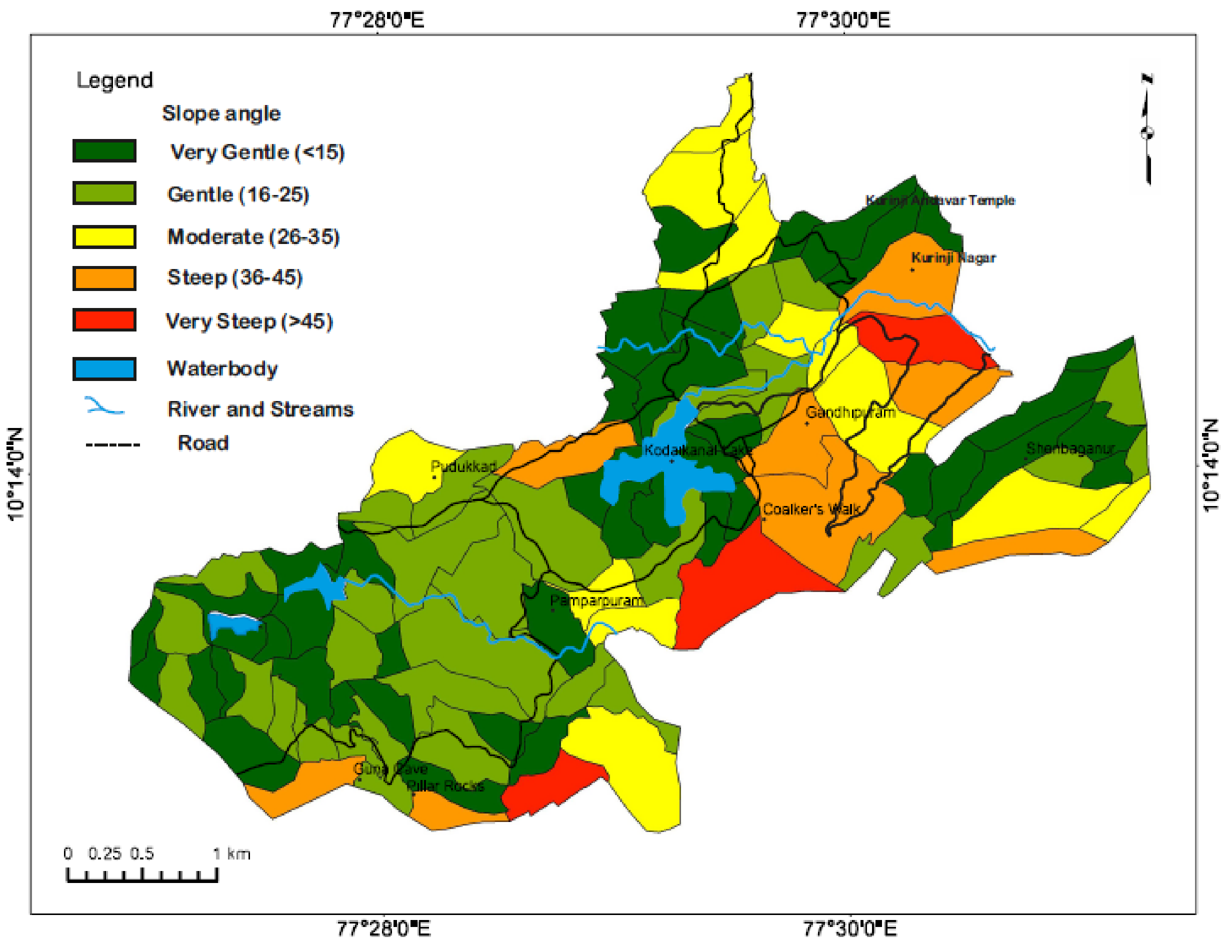


Fig 4.4 Slope morphometry map of Kodaikanal area

4.7 Relative Relief

Relative relief map indicates local height of slopes from ridge top to valley bottom. The local height of the facet is estimated by counting the difference between highest and lowest contour lines, passing through the facet. On the basis of local height, slopes are classified into five categories (Table 3.12) from very low (<50m) to very high (>300m). Accordingly the final thematic map of relative relief in Kodaikanal area had been prepared (Fig 4.5).

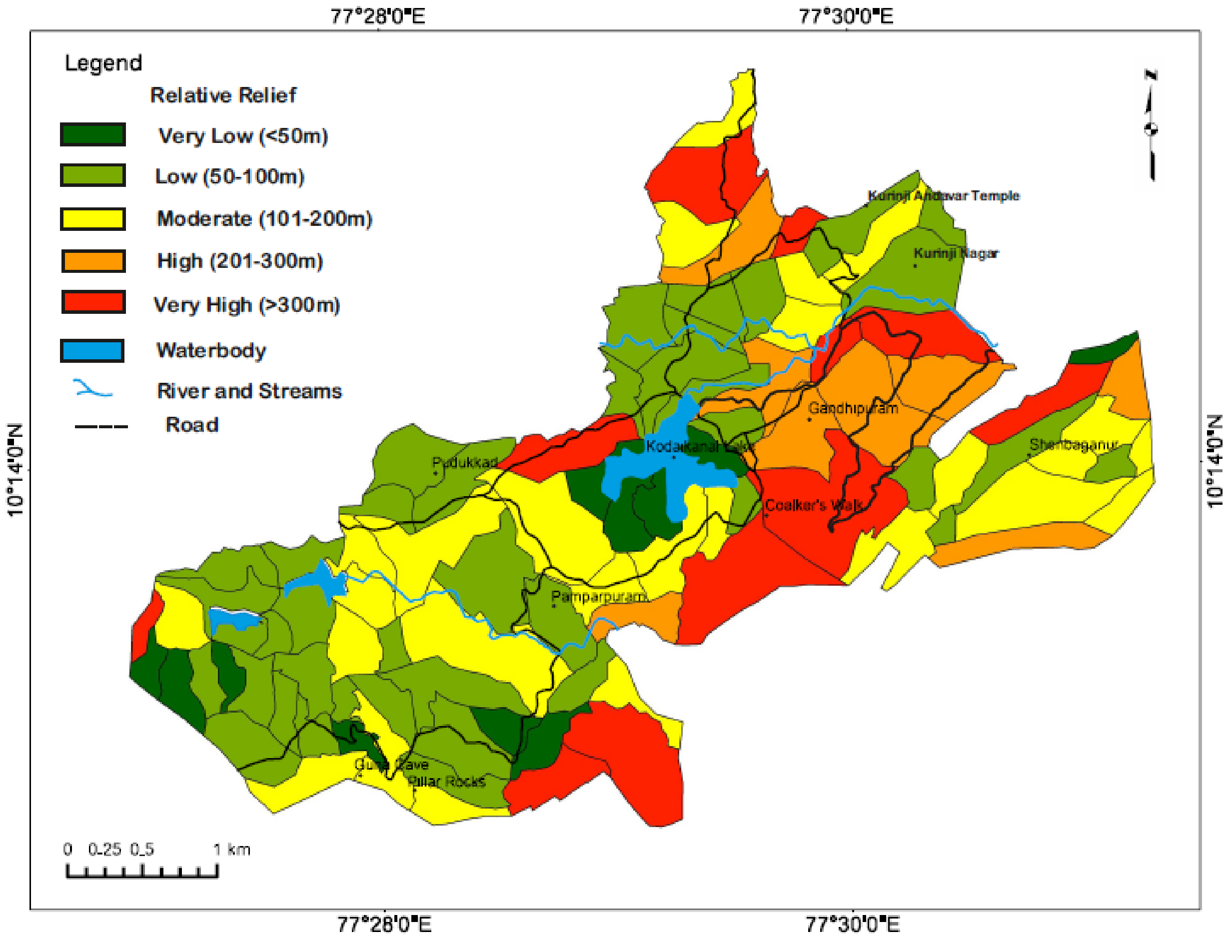


Fig 4.5. Relative relief map of Kodaikanal area

The map shows that the study area has a wide range of heights, from very low to very high. It is observed that in areas surrounding Vattaparai, Pamparpuram, Kurinji Nagar and Shenbaganur have slope heights varying from low to moderate, whereas Ananthagiri and Coalker’s walk has a dominance of high and very high relief. It is noted that debris slopes range from very low to moderate relief, while in case of rock slopes, the relief is mostly high to very high (>200m). Information obtained from the slope morphometry map and the relative relief map were combined (Table) to form a slope parameter map (Fig 4.6).

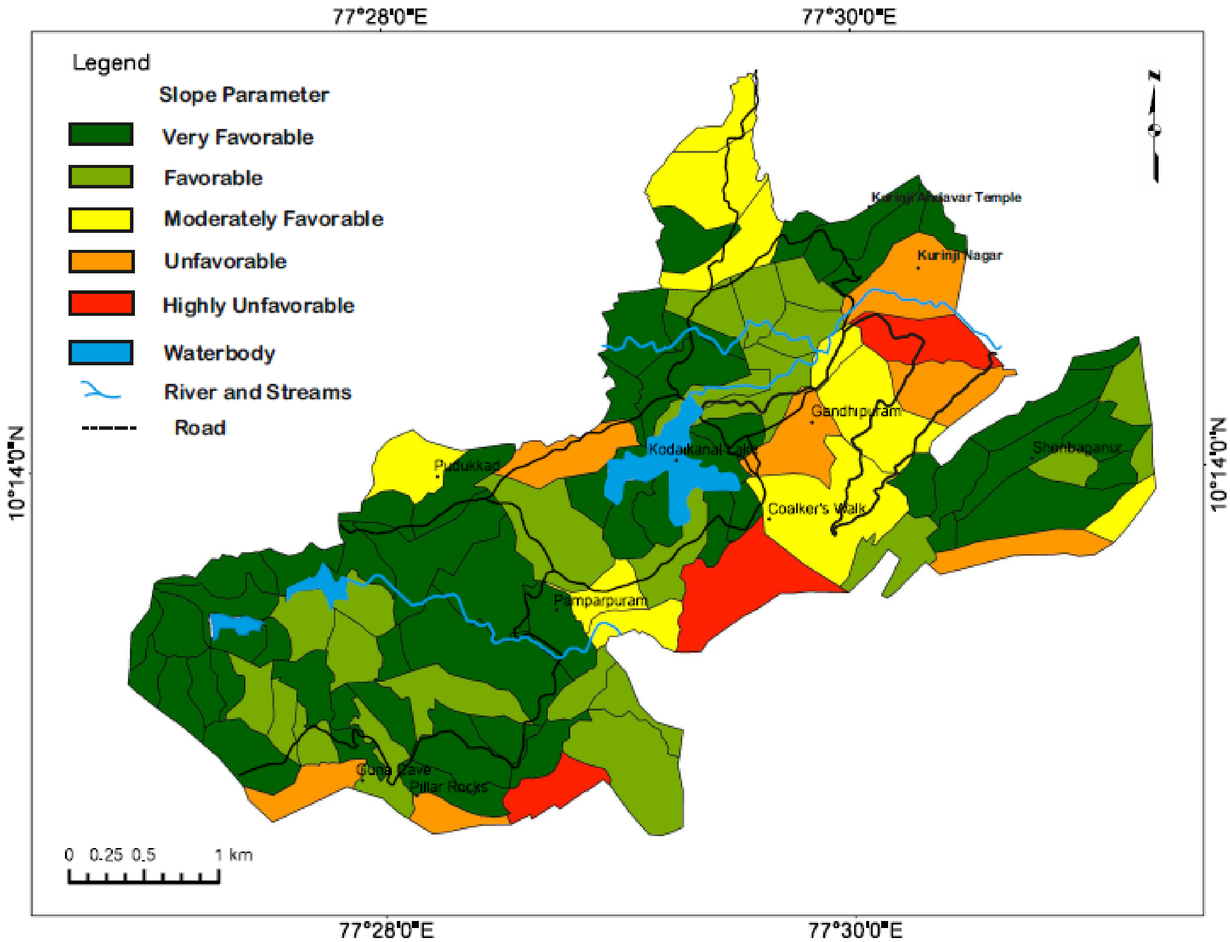


Fig 4.6. Slope Parameter map of Kodaikanal area

4.8 Land Use Land Cover

Land use and land cover pattern of a terrain is an indirect indications of the stability of hill slopes, as the roots of plants penetrate through the soil and increase the shear strength of the slope. A land use and land cover (LULC) map (Fig 4.7) was prepared dividing the area is into five categories viz (1) Agricultural cum inhabited land, (2) Moderately covered forest land, (3) Sparsely vegetative land cover, (4) Barren land, (5) Road and (6) Water bodies.

The star shaped Kodaikanal Lake is situated in the middle of the study area. The LULC map shows that dense vegetation and cultivated land covers an approximately equal distribution of the study area. The Ananthagiri area, Kurinji Nagar and Fairy Fall area have a heavy concentration of urban structures with intermittent pockets of cultivated land within. The urbanized areas include civil structures such as hotels, private residential buildings, colleges, markets and other government offices. Vattaparai area is part of the Palani hills forest conservation area and hence is composed of humungous pine forest and eucalyptus trees forming a dense vegetation pattern. Areas in the immediate surrounding of the Kodaikanal lake has moderate vegetation with spots of urbanization within them. Shenbaganur and the areas adjoining the Observatory are marked by cultivated land of carrots, garlic, cabbages, etc. Barren rocks are seen bordering the southern part of the study area. Urbanisation is observed to be distributed throughout the area sporadically.

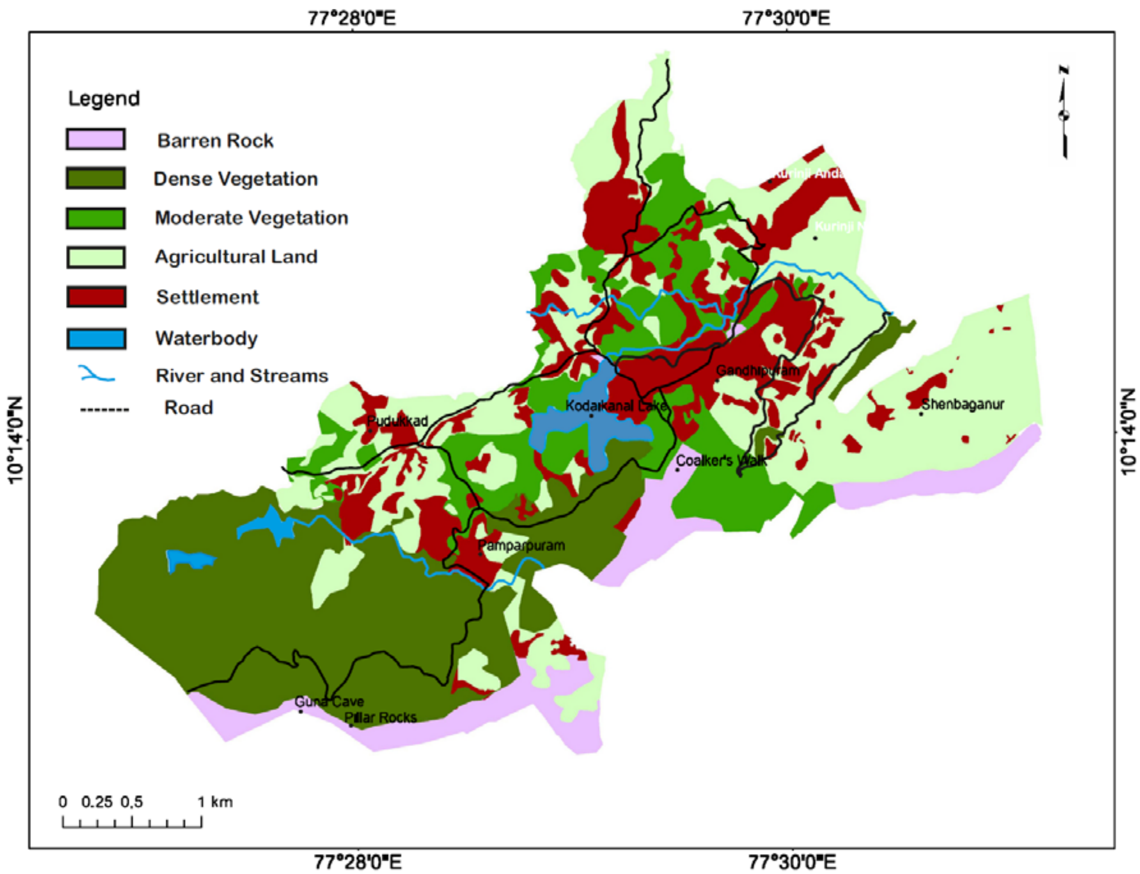


Fig 4.7. Land use land cover map of Kodaikanal area

4.9 Hydrogeological Condition

Hydrogeological condition map of the study area points out the extent to which a slope is saturated in individual facets. Since hill slopes usually represent drained condition (unless water logged) the worst possible condition from hazard point of view can only be estimated if extent of slope saturation is visually assessed after the monsoon. As the ground water in hilly terrain is generally channelized along structural discontinuities of rocks, it does not have uniform flow pattern. Out of five condition of soil saturation, two conditions namely dry and damp are dominantly seen in many parts of the study area. The thematic map of hydrogeological condition in study area is shown in Fig 4.8.

The map illustrates that dampness persists in almost all the slope facets in Kodaikanal area. Apart from barren areas in the southern part of the study area where rocks are exposed, the rest of the area is mostly damp. Within the damp slopes, some wet patches were also observed at places. In areas adjoining the Ananthagiri area, pockets of wet to dripping condition were noted. The dripping condition was noted in the Observatory area also. Dry conditions are because of the self-draining slope materials. LHEF ratings were appropriately given and the hydrological map prepared.

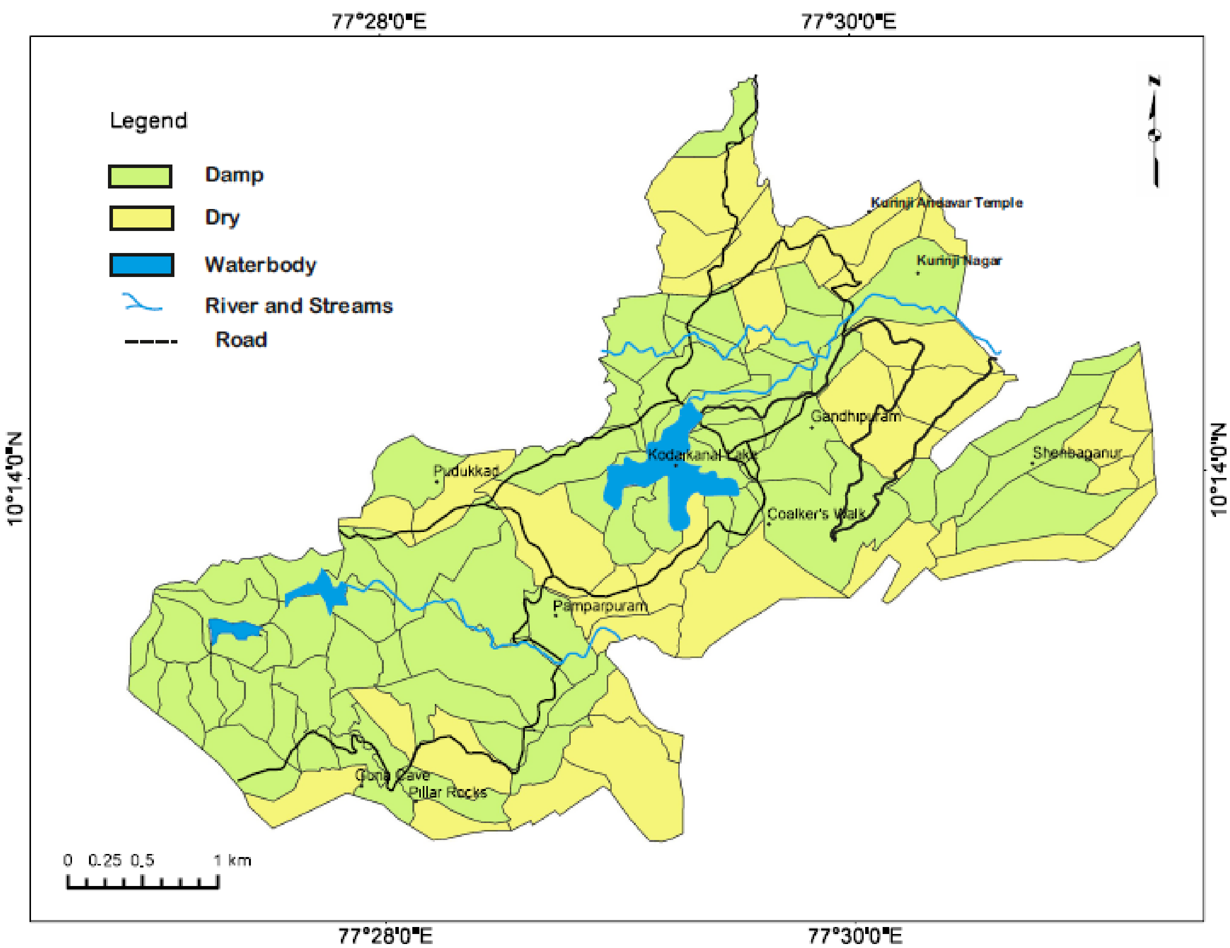


Fig 4.8. Hydrogeology map of Kodaikanal area

4.10 Landslide Hazard Zonation (LHZ) Map

The inherent causative factors were assessed facet wise and appropriate ratings were given taking into consideration the existing field conditions. After preparing the thematic maps of all inherent parameters based on the LHEF ratings for all of the 96 facets, rating for the external parameters were added. Since the study area falls in seismic zone IV (IS 1893, (Part 1): 2002) with average annual precipitation of the order of 150 cm, the LHEF rating for external factors for all facets were assigned as 0.8. The thematic maps were prepared using field inputs and satellite imageries in ArcGIS. The LHZ mapping of the Kodaikanal area was carried out on 1:10,000 scale.

After adding the LHEF ratings for inherent as well as external factors the TEHD value of individual facets were determined (Table 4.3). The hazard classes were then transferred to the slope facet map to generate the Landslide Hazard Zonation or LHZ map of Kodaikanal.

Table 4.1 LHEF ratings for causative parameters for individual facets

Facet No.	Lithology	Structure	Slope Parameter	LULC	Hydro cond.	Rainfall	Seismic zone	Total	Zone
1	0.8	0.65	0.5	0.65	0.2	0.4	0.3	3.5	VL
2	1.2	0.85	1.2	0.65	0.2	0.5	0.3	4.9	L
3	0.8	0.65	0.5	0.65	0.2	0.4	0.3	3.5	VL
4	1.2	0.85	0.7	0.65	0.2	0.5	0.3	4.4	L
5	1.2	0.85	1.1	0.65	0.2	0.5	0.3	4.8	L
6	0.6	0.7	1.5	1.7	0.2	0.5	0.3	5.5	M
7	0.8	0.65	0.5	0.65	0.2	0.4	0.3	3.5	VL
8	1.2	0.85	0.6	0.65	0.2	0.5	0.3	4.3	L
9	1.2	0.85	1.1	0.65	0.2	0.5	0.3	4.8	L
10	0.6	0.75	1.75	1.7	0.2	0.5	0.3	5.8	M
11	1.2	0.85	0.6	1.8	0.2	0.5	0.3	5.45	M
12	1.2	0.85	0.7	1.8	0.2	0.5	0.3	5.55	M
13	2	0.85	0.6	0.65	0.2	0.5	0.3	5.1	M
14	1.2	0.85	0.6	0.65	0.2	0.5	0.3	4.3	L
15	1.2	0.85	1.1	1.2	0.2	0.5	0.3	5.35	M

Facet No.	**Lithology**	**Structure**	**Slope Parameter**	**LULC**	**Hydro cond.**	**Rainfall**	**Seismic zone**	**Total**	**Zone**
16	2	0.65	1.2	1.8	0.5	0.5	0.3	6.95	H
17	1.2	0.85	2	1.5	0.5	0.5	0.3	6.85	H
18	1.2	0.65	1.6	0.65	0.2	0.5	0.3	5.1	M
19	1.2	0.85	0.6	1.8	0	0.5	0.3	5.25	M
20	1.2	0.85	0.7	1.8	0	0.5	0.3	5.35	M
21	1.2	0.85	0.5	1.8	0	0.5	0.3	5.15	M
22	1.2	0.65	0.6	1.8	0.2	0.5	0.3	5.25	M
23	1.2	0.65	1.55	1.2	0.2	0.5	0.3	5.6	M
24	1.2	0.85	1.6	0.65	0.2	0.5	0.3	5.3	M
25	1.2	0.85	1.5	0.65	0.2	0.5	0.3	5.2	M
26	1.2	0.85	0.7	1.8	0	0.5	0.3	5.35	M
27	2	0.85	1	1.8	0.2	0.5	0.3	6.65	H
28	1.2	0.65	1	1.2	0	0.5	0.3	4.85	L
29	1.2	0.65	1.1	1.2	0.2	0.5	0.3	5.15	M
30	0.9	1.05	1.1	1.8	0.8	0.5	0.3	6.45	H
31	0.75	0.9	1.55	1.2	0.5	0.5	0.3	5.7	M
32	0.9	1.1	1.6	1.8	0.8	0.5	0.3	7	H
33	0.9	1.3	1.6	1.8	0.5	0.5	0.3	6.9	H
33	0.8	0.65	1.6	1.2	0.5	0.5	0.3	5.7	M
34	1.2	0.65	1.65	1.8	0.5	0.5	0.3	6.6	H
35	1.05	1	1.2	1.5	0.2	0.5	0.3	5.75	M
36	1.2	0.85	1	1.2	0.2	0.5	0.3	5.25	M
37	2	0.65	0.5	1.2	0.2	0.5	0.3	5.35	M
38	0.6	1.05	0.6	1.8	0.8	0.5	0.3	5.65	M
39	1.2	0.65	0.6	1.2	0.2	0.5	0.3	4.65	L
40	1.2	0.85	0.6	0.8	0.2	0.5	0.3	4.45	L
41	1.2	0.65	0.6	1.5	0.2	0.5	0.3	4.95	L
42	2	0.65	0.6	1.8	0	0.5	0.3	5.85	M
43	2	0.65	0.5	1.8	0	0.5	0.3	5.75	M
44	2	0.85	0.6	1.2	0.2	0.5	0.3	5.65	M

Facet No.	Lithology	Structure	Slope Parameter	LULC	Hydro cond.	Rainfall	Seismic zone	Total	Zone
45	0.75	0.8	2	1.7	0.8	0.5	0.3	6.85	H
46	1.2	0.85	1.1	0.8	0.2	0.5	0.3	4.95	L
47	1.2	0.65	1.55	0.8	0.2	0.5	0.3	5.2	M
48	2	0.65	0.5	1.2	0	0.5	0.3	5.15	M
49	2	0.65	0.5	1.2	0	0.5	0.3	5.15	M
50	2	0.65	0.5	1.5	0.2	0.5	0.3	5.65	M
51	1.05	1.25	1.1	1.5	0.2	0.5	0.3	5.9	M
52	1.2	0.85	1.5	0.8	0.2	0.5	0.3	5.35	M
53	0.8	0.65	0.5	0.65	0.2	0.4	0.2	3.4	VL
54	1.2	0.65	1	0.8	0.2	0.5	0.3	4.65	L
55	1.2	0.65	1.1	0.8	0.2	0.5	0.3	4.75	L
56	0.9	1.1	1.3	0.65	0.8	0.5	0.3	5.55	M
57	0.9	1.5	1.3	0.65	0.5	0.5	0.3	5.65	M
58	1.2	0.65	0.5	1.2	0.2	0.5	0.3	4.55	L
59	0.9	1.25	1.1	1.5	0.3	0.5	0.3	5.85	M
60	1.2	0.85	0.5	0.8	0.2	0.5	0.3	4.35	L
61	1.2	0.65	1	0.8	0.2	0.5	0.3	4.65	L
62	0.8	0.65	0.5	0.65	0.2	0.4	0.3	3.5	VL
63	1.2	0.85	1.1	0.8	0.2	0.5	0.3	4.95	L
64	1.2	0.85	1	0.8	0.2	0.5	0.3	4.85	L
65	1.2	0.85	0.7	0.8	0.2	0.5	0.3	4.55	L
66	0.9	0.95	0.6	1.5	0.2	0.5	0.3	4.95	L
67	1.05	1	0.6	1.5	1	0.5	0.3	5.95	M
68	0.9	1.2	1	1.5	0.5	0.5	0.3	5.9	M
69	0.9	0.85	1	1.5	0.2	0.5	0.3	5.25	M
70	0.9	0.9	0.7	0.65	0.5	0.5	0.3	4.45	L
71	1.2	0.85	1.1	0.8	0.2	0.5	0.3	4.95	L
72	1.2	0.85	0.6	0.8	0.2	0.5	0.3	4.45	L
73	1.2	0.85	0.6	0.8	0.2	0.5	0.3	4.45	L
74	1.2	0.85	0.6	0.8	0.2	0.5	0.3	4.45	L

Facet No.	Lithology	Structure	Slope Parameter	LULC	Hydro cond.	Rainfall	Seismic zone	Total	Zone
75	0.9	1	1.1	1.5	0.5	0.5	0.3	5.8	M
76	1.2	0.85	0.9	0.8	0.2	0.5	0.3	4.75	L
77	1.2	0.85	0.6	0.8	0.2	0.5	0.3	4.45	L
78	1.2	0.85	1.1	0.8	0.2	0.5	0.3	4.95	L
79	1.2	0.85	1	0.8	0.2	0.5	0.3	4.85	L
80	2	0.85	0.6	0.8	0.2	0.5	0.3	5.25	M
81	2	0.85	0.6	0.8	0.2	0.5	0.3	5.25	M
82	1.2	0.85	1	0.8	0.2	0.5	0.3	4.85	L
83	1.2	1.3	1	0.8	0.2	0.5	0.3	5.3	M
84	1.2	0.85	0.6	0.8	0.2	0.5	0.3	4.45	L
85	1.2	1.3	1	0.8	0.2	0.5	0.3	5.3	M
86	0.9	1.3	1.1	1.5	0	0.5	0.3	5.6	M
87	1.2	1.3	0.6	0.8	0.2	0.5	0.3	4.9	L
88	1.2	1.3	0.6	0.8	0.2	0.5	0.3	4.9	L
89	1.2	1.3	0.5	0.8	0.2	0.5	0.3	4.8	L
90	1.2	1.3	0.5	0.8	0.2	0.5	0.3	4.8	L
91	1.2	0.85	1	0.8	0.2	0.5	0.3	4.85	L
92	1.2	1.3	0.5	0.8	0.2	0.5	0.3	4.8	L
93	1.2	1.3	0.6	0.8	0.2	0.5	0.3	4.9	L
94	1.2	1.3	1	0.8	0.2	0.5	0.3	5.3	M
95	1.2	0.85	0.6	0.8	0.2	0.5	0.3	4.45	L
96	0.9	1.05	1.8	1.5	0.8	0.5	0.3	6.85	H

A Landslide Hazard Zonation (LHZ) map (Fig 4.9) divides the land surface into zones of varying degrees of stability, based on the estimated significance of causative factors in inducing instability. The map shows that about 50% of the areas fall under very low and low hazard zones, which are dominantly seen in areas of Vattaparai, Fairy fall area and Shenbaganur area. It is noted that the slopes falling under the low hazard and very low hazard zones have dominant land use patterns such as dense vegetation and cultivated land. The Pamparpuram, Kurinji Nagar, Fern hill and Vilpatti areas fall under the moderate hazard zone catergory. The Ananthagiri and Coalker's walk areas, which fall under high hazard zone are the highly urbanized parts of the Kodaikanal Township. From the Landslide Hazard Zonation (LHZ) map, out of the total 96 facets, 8 slopes were found to be in HH zone.

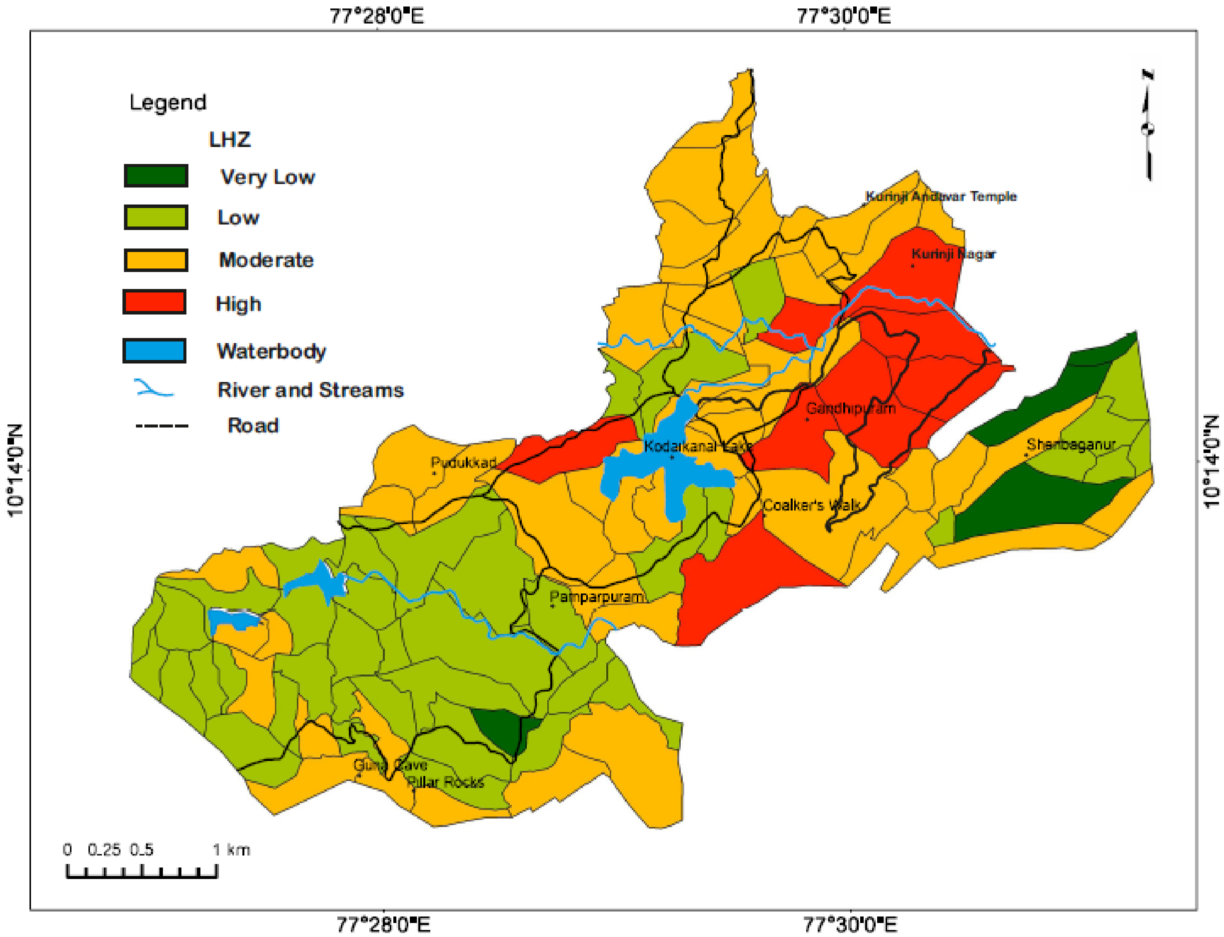


Fig 4.9. Landslide hazard zonation map of Kodaikanal area

CHAPTER 5
DETAILED LANDSLIDE INVESTIGATIONS IN KODAIKANAL

Landslide hazard zonation is the first step to identify potentially unstable zones. The Landslide Hazard Zonation (LHZ) map of Kodaikanal Township indicates the distribution of landslide hazards of the study area as a whole. From this map, the high hazard (HH) slopes (Fig 5.1) are of interest for taking up for the detailed investigations. Accordingly, the detailed investigations were carried out within the unstable slopes of four blocks namely Gandhipuram Block, Kurinji Block, Naidupuram Block and the Pudukkad Block. The Shenbaganur block is dominated by agricultural land with gentle slopes and as such stable in nature. Similarly the Vattaparai Block is also stable, which consists mostly of dense forest vegetation. The identified unstable slopes were taken up for detailed studies adopting the following steps – a) preparation of cross sections, b) collection of samples for laboratory testing, c) understanding the mechanism of failure and kinematic analysis for rock slopes, d) assessment of shear strength properties and e) calculation of factor of safety.

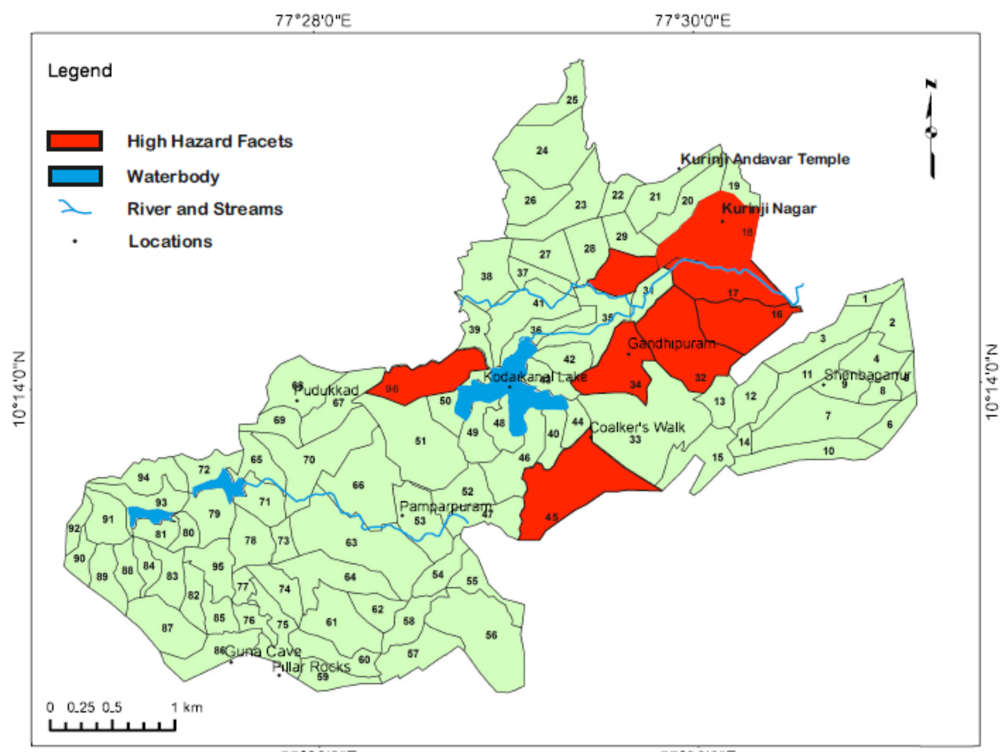


Fig 5.1 Map showing distribution of high hazard slope facets in various blocks of the study area

Field detailed investigations of these potentially unstable slopes were carried out to understand geological setting, causative factors, and mode of failure. Based on the pattern of failures such as rock slope failure, rotational failure or talus failure (planar debris failure), the detailed stability analysis of the identified unstable slopes was carried out on 1:1,000 – 2,000 scale. If a slope indicates a FOS of less than unity, it is in an unstable condition and it requires remedial measures. Based on stability analysis and depending on site condition, the control measures were judiciously evolved.

5.1 Input Parameters for stability analysis

5.1.1 Engineering properties of Charnockite Rocks –

1. Unit weight of slope material - Charnockite rocks of the Charnockite Group are present in the whole of Kodaikanal Township as basement rock though the rock exposures are obscured by the presence of debris at many places. The bluish grey charnockites are coarse-grained and characterized by orthopyroxene-bearing granitic mineral assemblages. As such, the variation in unit weight was found to be insignificant. The unit weight of lump samples collected from different locations of the study area are indicated in Table 5.1.

Table 5.1 Unit weight values of Charnockite rock in the study area

Rock Type	**Unit weight (g/cm^3)**
Charnockite Rock	2.75
	2.62
	2.52
	2.64
	2.70
	2.60
Average Value	2.64

2. Uniaxial Compressive Strength:

Due to absence of drill cores, UCS values had been determined from Point load Index (PLI) values. For that purpose lump samples were collected and their PLI values had been determined using the` formula as given in BIS Code (IS 8764: 1998) (Eq. 3.4 and Eq. 3.5).

Table 5.2 Estimation of Uniaxial Compressive Strength for different blocks of the study area

Block	Uniaxial Compressive Strength (MPa)
Gandhipuram	110
Naidupuram	136
Pudukkad	122
Vattaparai	142

3. Estimation of shear strength parameters of rocks –

For the purpose of slope stability study using limiting equilibrium approach, cohesion and friction angle of the rocks are considered as important input parameters. There are many methods by which the shear strength parameters can be assessed. In the present research two methods have been followed. The first one pertains to obtaining shear strength from RMR_{basic}, which is a widely used rock mass classification scheme. This provides shear strength parameters for the rock mass as a whole. The scheme generally provides a conservative value. The other approach is related to Barton and Brandis Criterion, which had been followed.

The RMR parameters were collected from the field at various sites of stability analysis. The values pertaining to all the 6 parameters were collected and presented in Table 5.3. A perusal of the table indicates that the values of RMR_{basic} ranges from 50 to 71 with most of the values above 65 indicating that the rocks on an average fall in the category of good. The corresponding shear strength parameters are as follows:

Cohesion: 300-400kPa

Angle of Internal Friction: 35°-45°

Table 5.3. Estimation of shear strength parameters of charnockite rocks in different blocks of the study area using RMR_{basic}

Block	Facet No.	Rating values of five input parameters					RMR_{basic}	Description	c (MPa)	Φ (°)
		UCS	RQD	Spacing.	Cond.	HGC				
Kurinji	16	4	13	10	16	7	50	Fair	.25	30
Gandhipuram	17	7	17	15	16	10	65	Good	.325	37.5
	31	12	17	8	24	10	71	Good	.35	40
	32	12	13	10	25	7	67	Good	.33	38.5
	33	4	17	10	21	10	62	Good	.31	36
	34	7	17	15	20	7	66	Good	.33	38
	45	12	17	15	19	7	70	Good	.35	40
Naidupuram	30	12	20	10	20	7	69	Good	.345	39.5
Pudukkad	96	12	13	8	21	4	58	Fair	.29	34
Vattaparai	57	15	17	8	14	7	61	Good	.305	35.5
	59	12	13	8	19	7	59	Fair	.295	34.5
	86	12	13	8	12	7	52	Fair	.26	31
List of abbreviations presented in header row of Table 5.3 are indicated below; UCS – Uniaxial Compressive Strength, RQD – Rock Quality Designation, Spacing. – Spacing of discontinuity, Cond. – Condition of discontinuity and HGC – Hydrogeological condition.										

Barton and Brandis Method for determination of shear strength parameters

For the calculation of shear strength parameters using the Barton and Brandis method (Eq. 3.14), the parameters that were collected from the field were Joint Roughness Coefficient, JRC and Joint wall Compressive Strength. The appearance of the discontinuity surface is compared visually with the roughness profiles by Barton and Choubey, 1977 (Fig 3.11) and the JRC value corresponding to the profile which most closely matches that of the discontinuity surface was chosen to be 10-12. For calculating the JCS, according to Barton and Choubey, if the joints are completely unweathered then JCS will be equal to the unconfined compression strength of the unweathered rock. Since, the charnockite rocks of the study area are mostly fresh to fairly fresh in nature. The uniaxial compressive strength that was derived from the point load index has been used in the current study. The range of UCS varies from 90-150MPa.

Table 5.4 Estimation of shear strength parameters of charnockite rocks in different blocks of the study

Block	Cohesion, c (MPa)	Friction Angle, Φ (°)
Gandhipuram	.38	40
Naidupuram	38	41
Pudukkad	27	35
Kurinji	28	37

The values estimated from RMR gives the shear strength parameters of the rock mass as a whole whereas the Barton and Brandis method provides the same for that of the joint wall. Hence, the values (Table 5.4) obtained from the Barton and Brandis method would be more appropriate to use in case of stability analysis.

5.1.2 Determination of shear strength parameters of debris material

Debris materials mainly include loose, unconsolidated and assorted size fractions obtained from past landslides and weathered materials. They get accumulated over the rock surface. Their thickness varies from place to place but generally less than 5m. As such they are mostly involved in talus type of failures. Samples were collected from several locations of landslide significance for determination of shear strength parameters. Direct shear test was conducted under five different normal loads and corresponding values of shear stresses were determined. After plotting the data set on $\sigma - \tau$ axes, a range of shear strength parameters were obtained. Taking into consideration the geology and overall site condition the value of cohesion (c) and friction angle (Φ) were judiciously selected (Table 5.5). These values were considered for stability analysis of the given five locations.

Table 5.5 Estimation of shear strength parameters of soil in different blocks of the study area

Block	Cohesion, c (kPa)	Friction angle, φ (°)
Kurinji	37	35
Gandhipuram	25	34
Naidupuram	31	38
Pudukkad	28	37
Vattaparai	45	32

5.2 Kurinji Block

Kurinji Block is located in north direction of Kodaikanal Lake (Fig 5.1) and accordingly it forms the northern boundary of study area. The Palar River flowing at the toe of the Kurinji Nagar slope has been mainly responsible for the instabilities of the slope in the lower reaches. The river flows eastwards and further down, the Silver Cascade Falls can be seen close to the eastern border of the Gandhipuram Block. The block consists dominantly of thick debris material with intermittent rock exposures. The thickness of the debris varies from a minimum of 5m to more than 20m. The thick debris is seen particularly in the lower reaches. Charnockite rock exposures are seen on the steep valley slope just adjoining the Palar River and also along some of the road cut slopes. The fairly thick overburden cover with steep slopes in the Kurinji Nagar area is prone to circular failure. The Landslide Hazard Zonation map indicates the occurrence of only one high hazard slope which is the Kurinji Nagar slope (Facet No. 18) in the Kurinji block. The rest of the facets in the Kurinji Block are under moderate hazard zone of the LHZ map.

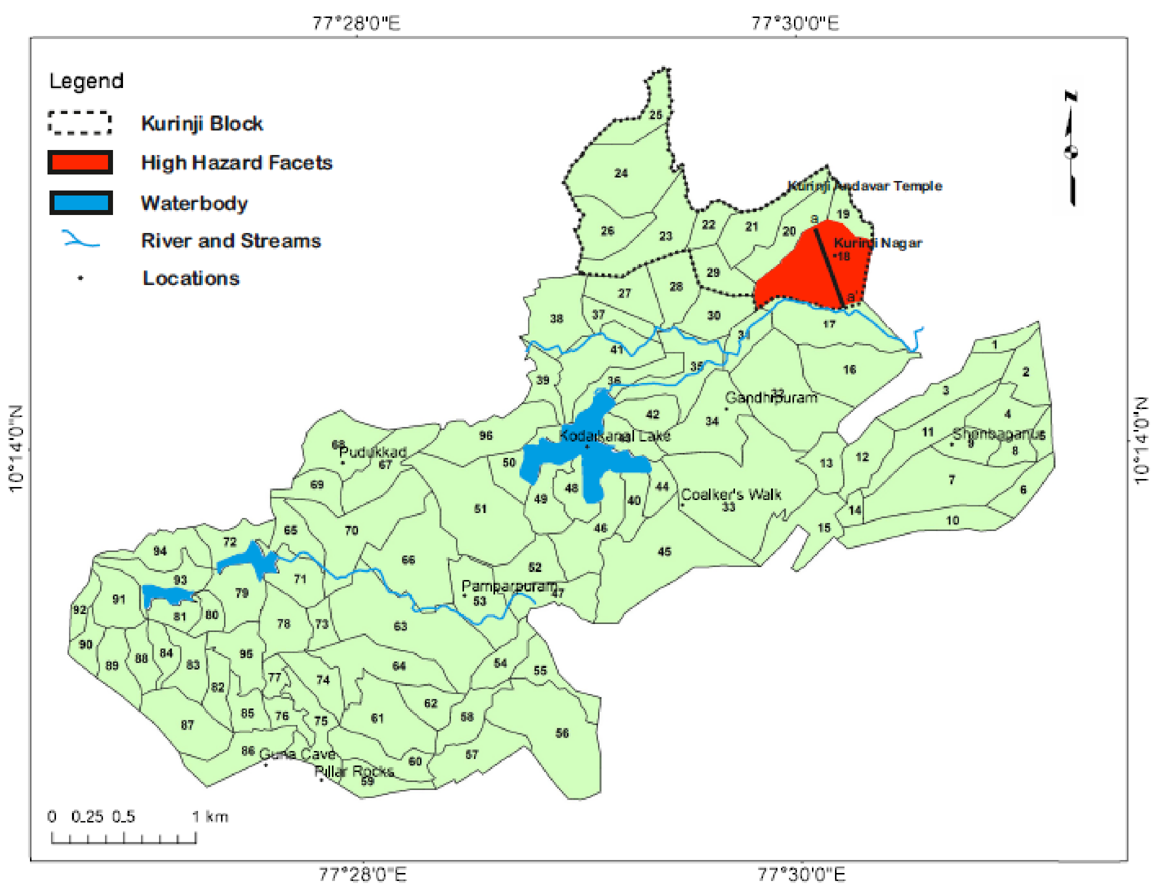


Fig 5.2 Map demarcating the Kurinji Block and the High Hazard Zone within the block

5.2.1 Kurinji Nagar Slope

Located in the eastern border of the Kurinji block, the Kurinji Nagar facet (Facet No. 18) has a steep slope with an angle of about 45°. The upper reaches of this slope has thick debris extending up to more than 20m with thick urbanization in the form of houses and other civil structures. In the lower reaches the density of the residential units are less with more areas occupied by agricultural land. Terrace cultivation method is followed throughout the study area. Closer to the river, moderate vegetation is noticed. The Palar River flowing towards the east, borders the facet on the southern side. Two roads namely the district road and a local road runs through the slope facet at two different levels and runs almost parallel to each other. The river also runs nearly parallel to these roads before taking an acute turn towards north close to eastern end of the facet. Due to round the year agricultural practices, the hydrogeological condition of the facet is observed to be damp even during summer.

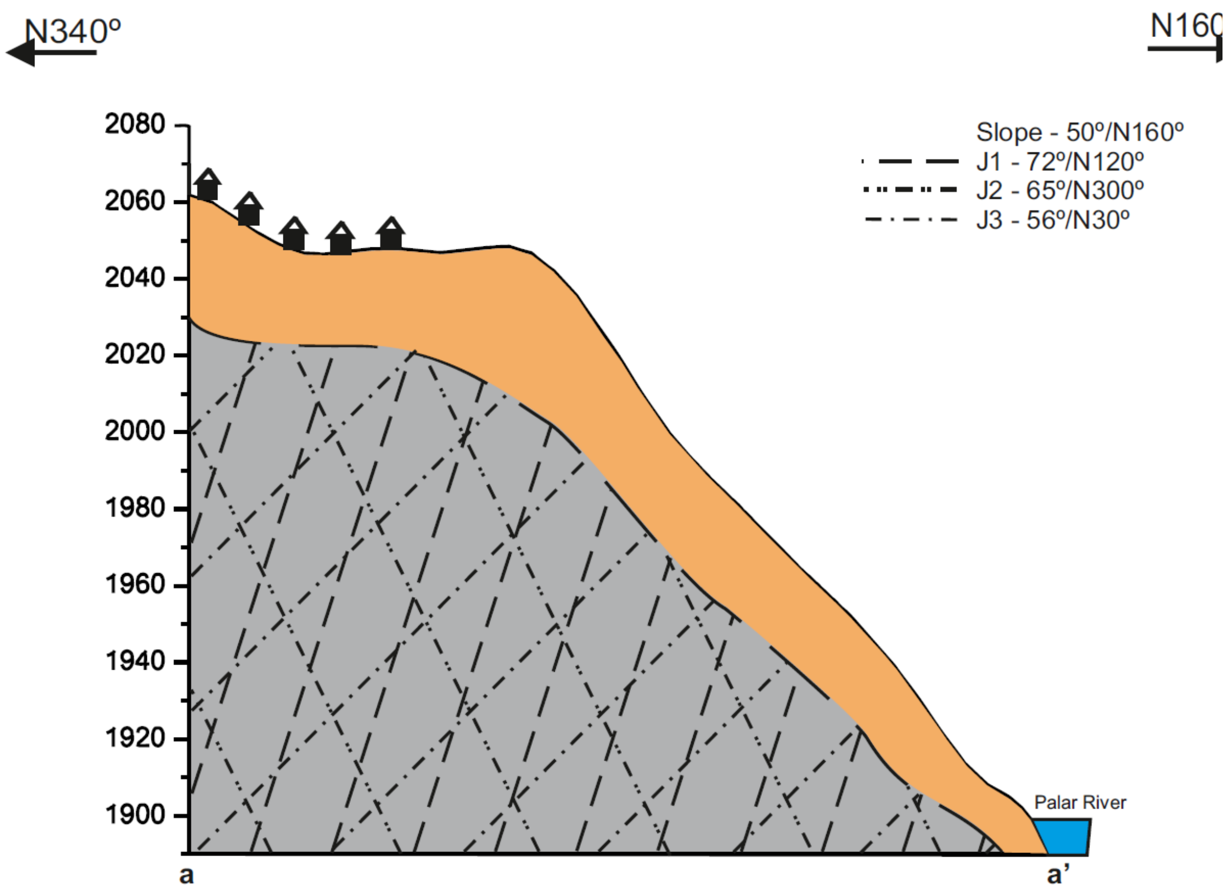


Fig 5.3 Geological cross section (a-a') along the Kurinji slope

A single profile (a-a') was taken in the Kurinji Nagar slope facet. The middle and lower parts of the slope have slope angles varying from 40° - 45° towards N160°, while the upper slope is very gentle. The section covers the entire width of the facet from the ridge to the stream at the toe. The slope gradient is steep (45^o) close to the stream. The agricultural terraces are located in the lower and middle reaches above the stream course. In this segment, on the basis of site observations, it is inferred that the thickness of debris cover may be approximately 15m or even more in the upper reaches and the thickness gradually gets reduced downwards. The thickness is of the order of about 5m just above the stream. Taking into consideration the thickness of debris and slope inclination, it is inferred that rotational failure may be the dominant mode of failure.

5.2.1.1 Slope Stability Analysis of Kurinji Nagar Slope

Rotational type of failure is the probable failure mode to occur in this slope. Since the slope has sufficiently thick debris cover of more than 15m and extending up to 25m in addition to having a fairly steep slope, the probability of a circular failure is very high. In view of this, the circular failure analysis was carried out using Circular chart method and later a more accurate analysis using Slide 2D software was done for the potentially unstable Kurinji Nagar slope facet.

a) Stability Analysis Using Circular Failure Chart (CFC) Method

The principle of derivation of Circular Failure Charts (CFC) and the methodology of their application has been discussed in Chapter 3. This method is basically a fast technique for estimating the Factor of Safety (F) value for probable circular mode of failure. The slope is found to be damp during most parts of the year. Taking into consideration the fact that it receives high annual precipitation, the analysis was carried out for dry as well as high saturation conditions. In fact, the actual analysis was done with 0% slope saturation (dry), 25% slope saturation (moderate) and 50% slope saturation (high) as the hill slope is predominantly composed of coarse grained debris namely well graded gravels. For dry condition, Circular Failure Chart No.1 was used. For 25% and 50% saturation, chart No.2 and 3 were respectively used. The following input parameters were used for the analysis.

These include – a) geo-mechanical properties like density and shear strength parameters of the slope material, b) slope geometry including its height and average slope inclination and c) soil moisture content for estimating the hydrogeological condition of the slope. From the geological section (Fig 5.4) height of the slope (H) was taken as 50m and slope inclination was taken as 45º. Samples were collected from different levels on the slope for conducting Direct Shear Test to calculate the shear strength parameters. The average unit weight (γ) of these gravely soil samples was ≈ 20kN/m^3. The values were plotted in normal stress (σ) – shear stress (τ) axis to obtain representative shear strength parameters. Among the many possible combinations derived from best fit lines, cohesion (c) value of these gravely soil was judiciously selected as 37 kPa and friction angle (Φ) value is selected as 35º. Input parameters for analysis

Height of the slope – 160m

Cohesion, c – 37kPa

Friction Angle, Φ – 35°

Unit weight of soil, γ - 18kN/m2

The dimensionless ratio (c/γ.H.tanΦ) which is a constant for all the three charts was calculated to be 0.025. Different values of F obtained with increasing slope saturation are indicated in Table 5.6.

Table 5.6 Factor of safety, FoS, values of the slope for different conditions of slope saturation

Factor of safety (F) as per the 'X' and 'Y' intercept in the chart.	**DIFFERENT SLOPE SATURATION CONDITIONS**		
	0%, i.e. Completely Dry (Chart No.1)	25% (Chart No.2)	50% (Chart No.3)
Y axis intercept (F_1)	1.20	1.10	0.928
X axis intercept (F_2)	1.14	1.08	0.624
$\mathbf{F_{avg}}$ = 0.5 x (F_1+ F_2)	**1.17**	**1.09**	**1.01**

II. Stability Analysis Using SARC (Bhawani Singh, 2002)

In addition to the input parameters, the coordinates of the profile of the slope were also given as an input for the analysis using SARC program. The detailed functioning of the program has been given in Chapter 3. The result of the analysis indicates that the slope is marginally stable with an FOS of 1.16. This result corroborates with the result of the Circular chart method and also the field conditions.

The Kurinji Nagar slope is stable under dry condition. During saturated condition, the FOS gets reduced. The analysis clearly indicates that subsurface seepage is the major reason for the slope instability. Since domestic water is major contributor. A well planned network of pipes to collect all the domestic waste water will help in a big way to reduce water charging of the slope. Moreover, open RCC surface drains at different levels will help to collect storm water efficiently. These measures will help the slope against the forces of destabilization.

5.3 Gandhipuram block

The Gandhipuram block is located to the east of Kodaikanal Lake. This is one of the highly urbanized blocks in the study area. The upper reaches of the Gandhipuram Block, which also marks the northern boundary, is bordered by Palar River which is flowing eastward. The area has a consistent cover of a thin layer of debris cover, generally less than 4m.

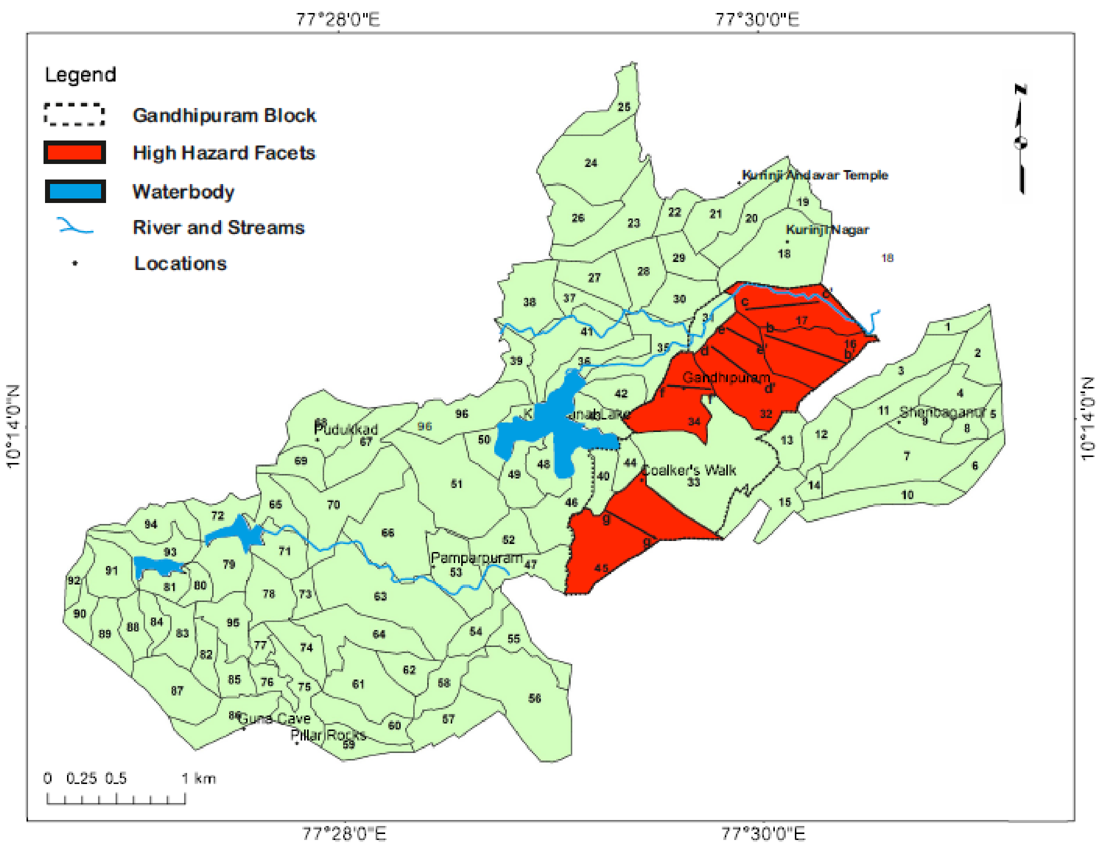


Fig 5.4 Map demarcating the Gandhipuram Block and the High Hazard Zone within the block

The cut slopes exposes fairly fresh charnockite rocks. The joints are tight with no fillings. At places, there are wet patches seen on the rock exposures. Brown to red stains can be observed in some of the joint surfaces. The area is damp even during summer. A major source of water seepage in these slopes is the improper drainage system. The upper slope of the block is gentle while the middle slope is steeper even in comparison lower portion of the slope. Still the density of construction is more in the middle and lower portions. Out of the 11 slope facets constituting this block, a total of 7 (Facet nos. 16, 17, 31, 32, 33, 34 and 45) fall under the category of high hazard zone (Fig 5.4). All these slopes have been separately taken up for the detailed stability analysis. A general description and stability analysis of these slopes are given below.

5.3.1 Srinivasapuram Slope:

The Srinivasapuram slope falling in facet no. 16 of Gandhipuram block is located close to its eastern margin. The slope is inclined towards N125^{o}, with a fairly steep slope angle of 37° (Fig. 5.6). Charnockite rock that is observed to be exposed with thin overburden of less than 1m in the mid slope is fairly fresh to moderately weathered in nature.

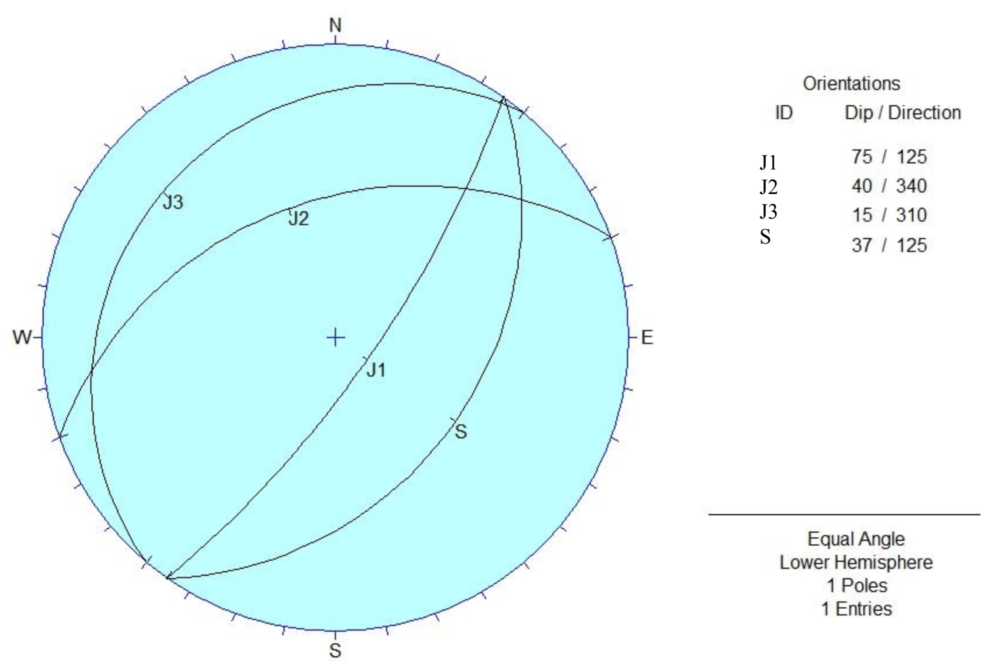


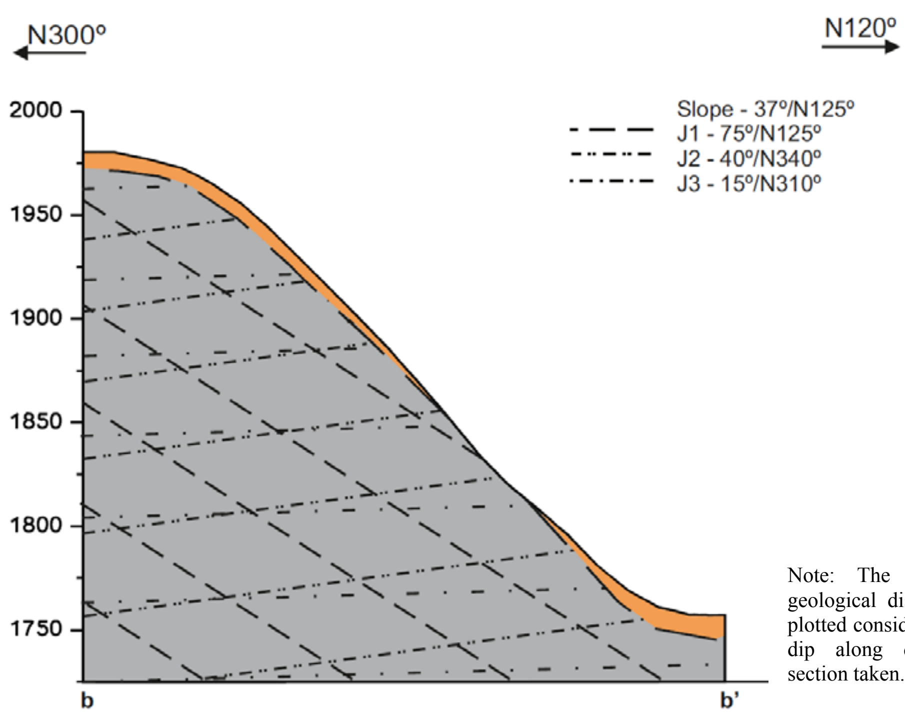
Fig 5.5 Stereoplot of geological discontinuities observed in the Srinivasapuram Slope of Gandhipuram Block

The thickness of the overburden material is seen to be 2m to 4m in the upper and lower reaches of the slope. In the upper reaches of the slope, where the slope is gentler, clusters of closely spaced residential buildings, hostels, resorts, offices and other civil structures are seen. In the lower reaches of the slope, the urbanization is sporadic and sparse within the agricultural land. It is noticed that along the state highway which passes through the facet in the upper reach, the overburden thickness is 3-4m and supports thick vegetation cover. Wide terraces are built in the lower reaches in order to carry out the cultivation. The soil is generally more silty at lower level and clayey at higher levels.

5.3.1.1 Stability Analysis of Srinivasapuram slope

a) Slope stability of rock slope

Most parts of the slope are covered by debris, which are seen in thin layers over the in-situ rocks. However, the in-situ rocks are seen in the middle part of the slope and hence, stability analysis of the rocks has been taken up for possible rock failure analysis. For that purpose, the geological discontinuities observed on the slope were plotted in a stereonet and the representative joint directions were obtained in addition to the slope direction (Fig 5.5).



Note: The attitude of the geological discontinuities were plotted considering the apparent dip along direction of the section taken.

Fig 5.6 Geological cross section along (b-b') the Srinivasapuram Slope

A perusal of the attitude of the joint planes indicates that the joint J1 only dips in the same direction as that of the slope but at a steep angle and hence, it does not satisfy the Markland test condition ($\psi_f > \psi_p > \phi$) for plane failure. Similar conditions were obtained for wedge failure also. Hence, both plane mode of failure and wedge mode of failure are eliminated as the possible modes of failure.

b) Slope stability of talus slope

The thickness of the debris observed in the upper slope on slope surface ranges from 2m to 4m, but generally more than 3m. Hence, the slope has been analyzed for a potential talus failure. The slope inclination varies from 30° to 35. Taking into consideration the geology and overall site condition, a cohesion (c) value of 5.2kPa and friction angle (Φ) = 35º were judiciously selected from the direct shear test (Table 5.7). These values were applied for stability analysis for a potential talus failure.

Table 5.7 Input Parameters and Result of stability analysis for talus slope of Srinivasapuram slope

Location	**Slope Angle (°)**	**Cohesion, c (t/m2)**	**Friction Angle, φ (°)**	**Height of Talus (m)**	**Υ (t/m^2)**	**Υ_w (t/m^2)**	**FOS (Dry)**	**FOS (Wet) ~25% Sat.**
Srinivasapuram	35	0.52	35	4	1.8	1	1.14	1.00

From the stability analysis, it is observed that the FOS of the talus slopes of the Srinivasapuram slope is 1.14, indicating that the debris slope is marginally stable under dry condition. The FOS of the slope becomes close to 1.0 under normal saturation during rains. However, during heavy rains when the saturation increases drastically the slope may become unstable. This observation corroborates with the site condition in the form of cracks seen in the buildings which were created during heavy rains.

5.3.2 Annanagar Slope (Facet no. 17):

The Annanagar slope which is located west of the Srinivasapuram slope also marks the eastern border of the Gandhipuram block. It is a rather steep slope with an angle of 46° towards N88°. The Annanagar area is highly urbanized with poorly designed stone/brick masonry structure located on terraces. The rock outcrops are seen close to the top of the ridge and the rest of the slope is covered with fairly thick debris cover ranging from 3m to 4m (Fig 5.8). The Palar River flows eastwards along the eastern margin of this slope in the upper half of the facet. The middle and lower reaches of the slope support agricultural terraces. The state highway runs within the slope facet in the upper part. The entire area has a no provision of domestic waste water disposal drain. Moreover, no surface drains or pipe drains are also seen in this area. Well-developed cracks could be observed in many houses in the area.

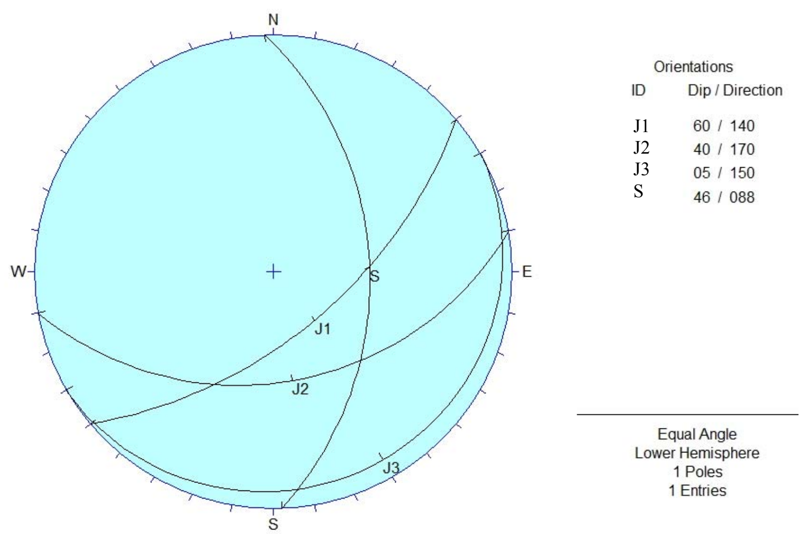


Fig 5.7 Stereoplot of geological discontinuities observed in the Annanagar Slope of Gandhipuram Block

<u>a) Slope stability of rock slope</u>

The slope is mostly covered by debris in the upper and lower reaches except for the middle region where in-situ rocks are exposed. The rock slope has been taken up for possible rock failure analysis. For that purpose, the geological discontinuities observed on the slope were plotted in a stereonet along with the attitudes of the slope (Fig 5.7). From the kinematic analysis of the attitude of the joint planes, it is observed that none of the joints J1, J2 or J3, satisfy the condition of parallelism between the slope and the discontinuity and hence, it does not satisfy the Markland test condition ($\psi_f > \psi_p > \phi$) for plane failure. Similar conditions were obtained for wedge failure also. Hence, both plane mode of failure and wedge mode of failure are eliminated as the possible modes of failure.

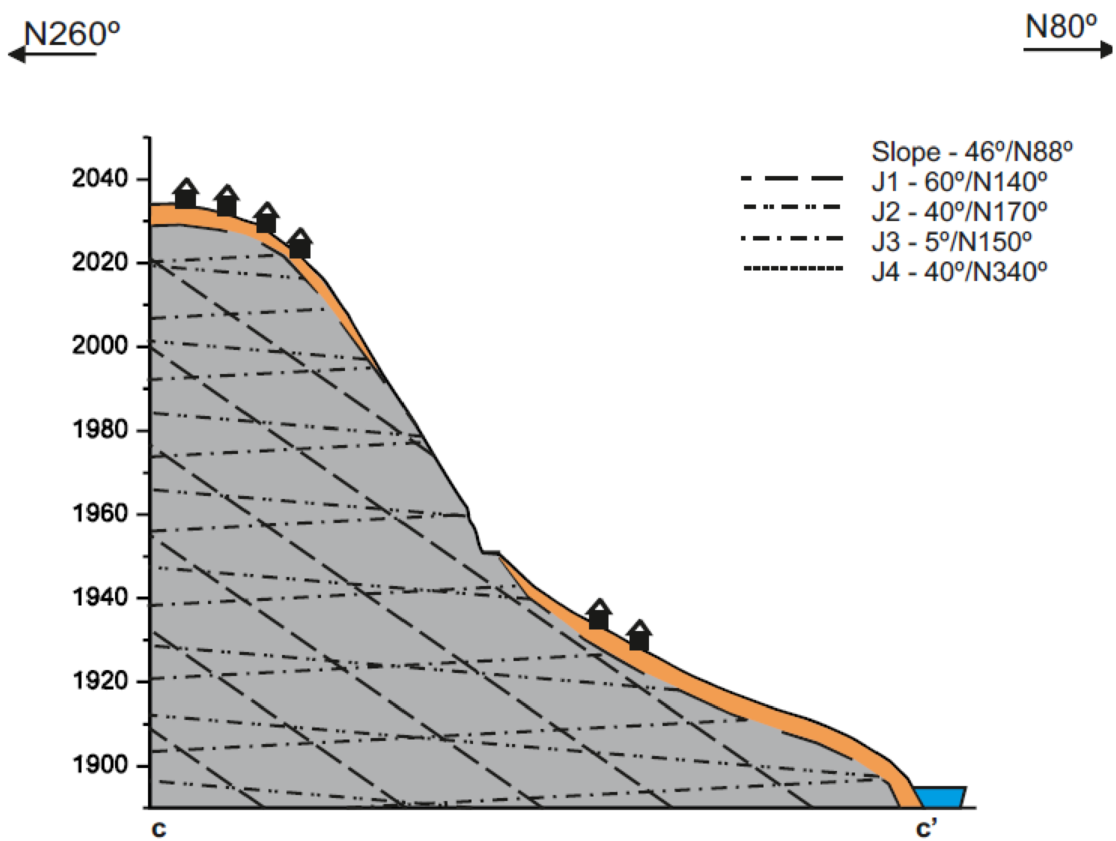


Fig 5.8 Geological cross section along (c-c') the Annanagar Slope

5.3.2.1 Stability Analysis of Annanagar slope

b) Slope stability of talus slope

The thickness of the debris seen on the upper slope above the slope surface ranges from 1m to 4m, but generally more than 3m. As the slope inclination of the upper slope ranges between 30° to 35°, the upper slope has been analyzed for a potential talus failure. Taking into consideration the geology and overall site condition where, the debris are associated with big angular boulders, a cohesion (c) value of 4 kPa and friction angle (Φ) = 34° were judiciously selected on the basis of direct shear test (Table 5.8). These values were applied for stability analysis for a potential talus failure.

Table 5.8 Input Parameters and Result of stability analysis for talus slope of Annanagar slope

Location	**Slope Angle (°)**	**Cohesion, c**	**Friction Angle, φ (°)**	**Height of Talus (m)**	**ϒ (t/m^2)**	**$ϒ_w$ (t/m^2)**	**FOS (Dry)**	**FOS (Wet)**
Annanagar	35	0.4	34	4	1.8	1	1.08	0.95

From the stability analysis, it is observed that the FOS of the talus slopes of the Annanagar slope is 1.08, indicating that the debris slope is marginally stable under dry condition. The FOS of the slope becomes close to unity under normal saturation during rains. However, during heavy rains when the saturation increases drastically the slope may become unstable. This observation corroborates with the site condition in the form of cracks seen in the buildings which were created during heavy rains.

5.3.3 Ananthagiri Slope:

The Ananthagiri slope (Facet no. 32) is located west of Srinivasapuram and Annanagar slopes. The slope has an average angle of 35° trending towards N138° with a small stream flowing in the middle of the slope along the southeastern direction. The slope is constituted of thin overburden cover in the top reaches over fairly fresh to moderately weathered charnockite rock. The thickness of the soil varies from 3 to 4m. The state highway cuts across the entire slope a total of 3 times at different levels. Apart from the state highway, various parallel running streets with residential and trade buildings in either side are also observed. The top reaches of this slope is crammed with urbanization. The Ananthagiri slope is one of the heavily urbanized slopes of the Gandhipuram block (Fig 5.11 and Fig 5.13). A break in slope is observed along the road located close to Kodai FM station. Above the road, the slope is moderate with angle of 30° but below the road the slope becomes steep up to an angle of 45°. The buildings are located on the slope particularly below the church shows minor settlement cracks. No major ground cracks are observed in this area. It was also observed that like the rest of the urbanized slopes, the domestic waste water was disposed directly on to the slope (Fig 5.14).

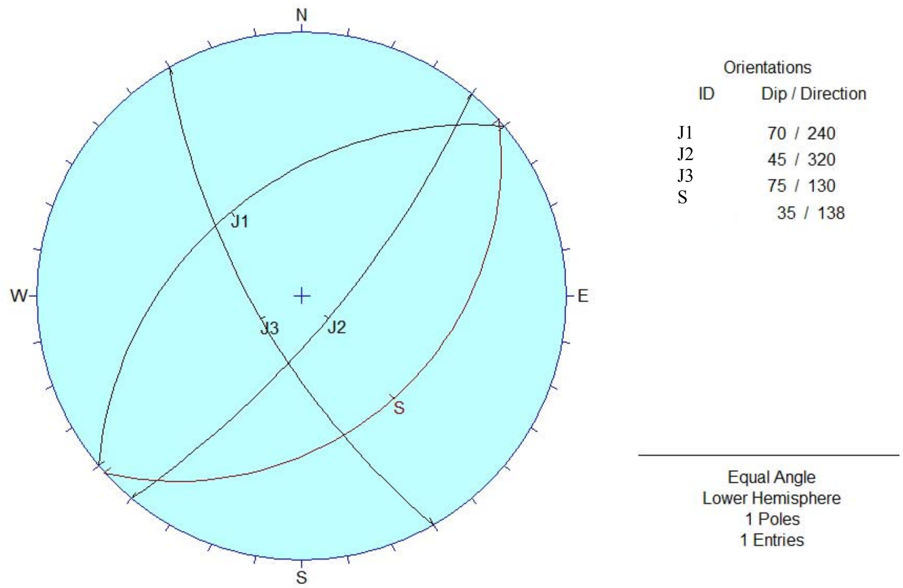


Fig 5.9 Stereoplot of geological discontinuities observed in the Ananthagiri Section 1 of Gandhipuram Block

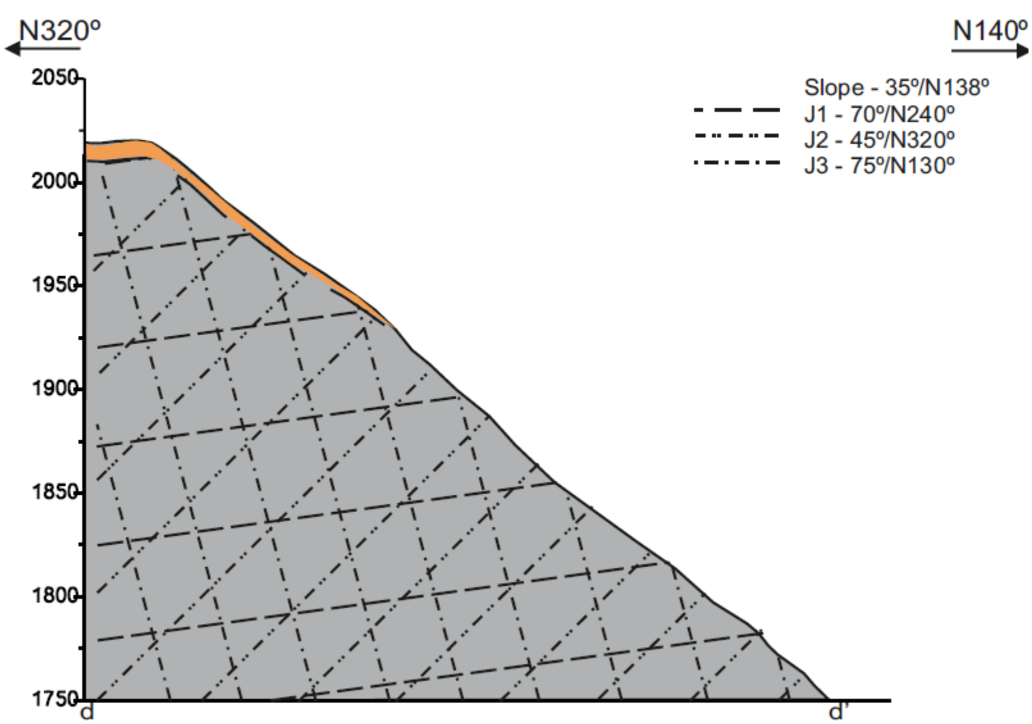


Fig 5.10 Geological cross section along (d-d') the Ananthagiri Section 1

5.3.3.1 Slope stability of Ananthagiri slopes

a) *Stability analysis of rock slope – Section 1 and 2*

For sections 1 and 2, two profile were taken along the Ananthagiri slope (Fig 5.10 and Fig 5.15). The rock slopes present along sections 1 and 2 were taken up for the stability analysis. For that purpose, the geological discontinuities observed on the slope were plotted in a stereonet along with the slope direction (Fig 5.9 and Fig 5.12). A perusal of the attitudes of the joint planes indicates that the joint J3 dips in the same direction as that of the slope but at a steep angle and hence, it does not satisfy the Markland test condition ($\psi_f > \psi_p > \phi$) for plane failure. Similar conditions were obtained for wedge failure also. Hence, both plane mode of failure and wedge mode of failure are eliminated as the possible modes of failure.

Fig 5.11 Ananthagiri Slope showing cramped building, both residential and commercial

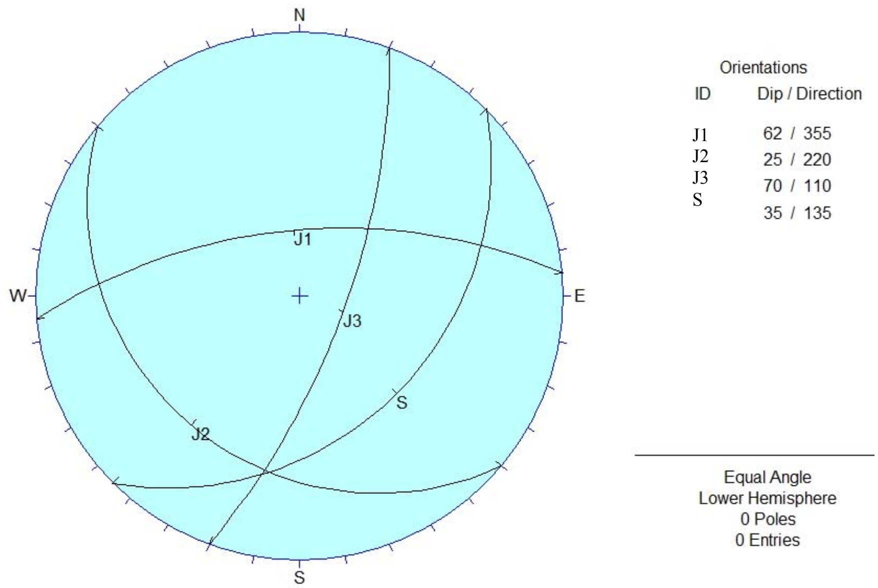


Fig 5.12 Stereoplot of geological discontinuities observed in the Ananthagiri Section 2

Fig 5.13 Ananthagiri Slope 1 showing heavy urbanization on the slope

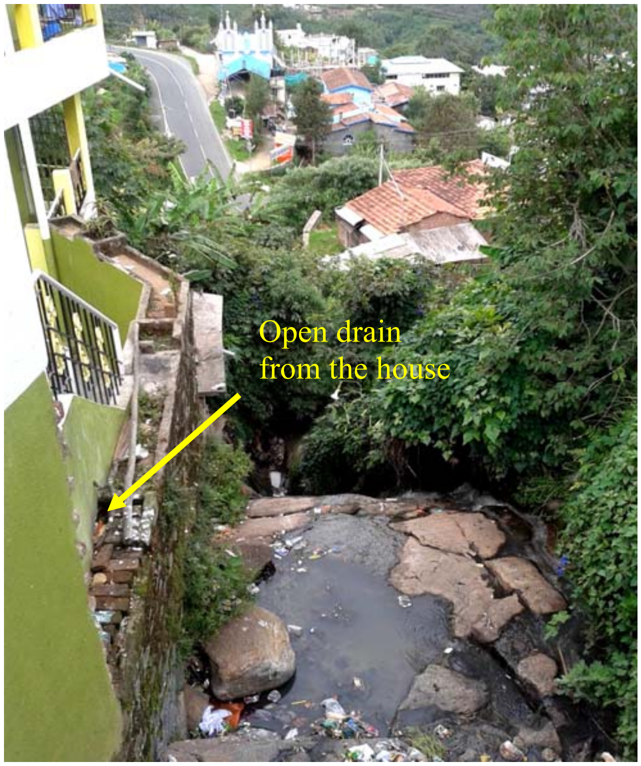


Fig 5.14 Improper waste water management seen at the slope

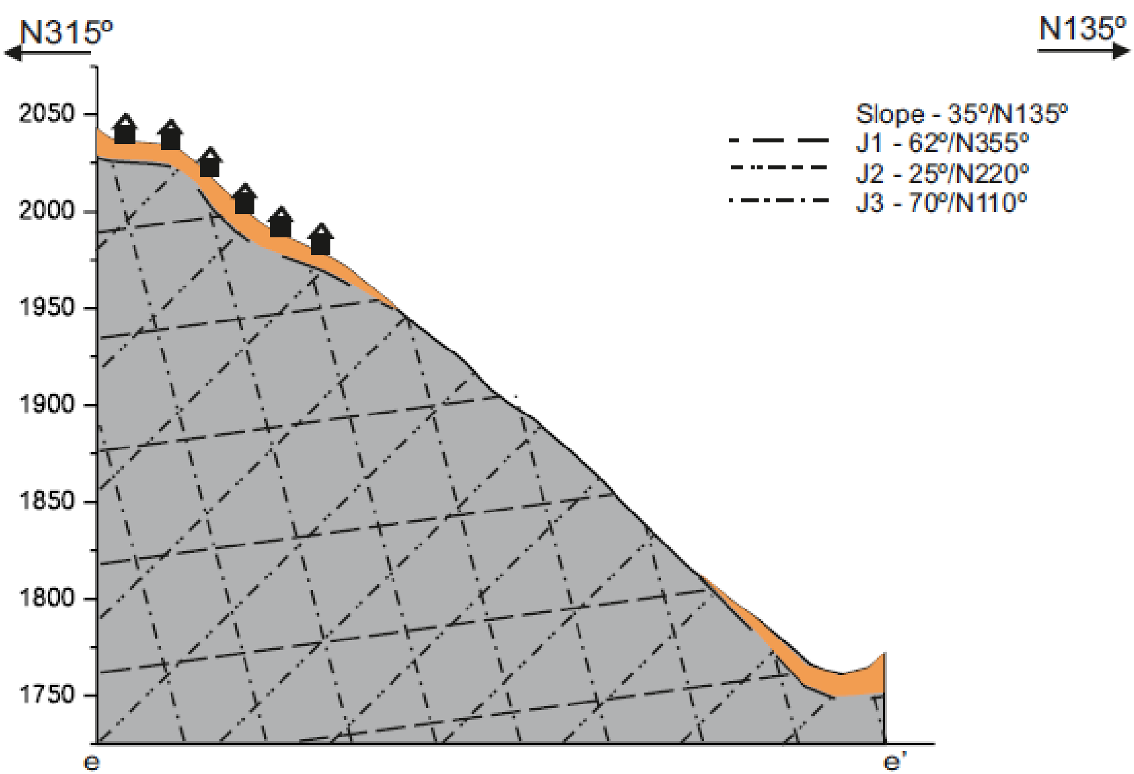


Fig 5.15 Geological cross section along (e-e') the Ananthagiri Section 2

b) Stability analysis of talus slope – Section 1 and 2

The top slope, which is highly urbanized has a debris deposit having thickness ranging between 3m to 4m in both the sections of the Ananthagiri slope. The slope angle of the section 1 is about 40º and that of section 2 is about 37º. In view of that fact, that slope materials have considerable fraction of big angular rock blocks, a judicial value of the shear strength parameters have been taken based on direct shear test, cohesion (c) value = 45kPa and friction angle (Φ) = 38º (Table 5.2). These values were used for the stability analysis of the talus slope.

Table 5.9 Input Parameters and Result of stability analysis for talus slope of Ananthagiri slope

Location	**Slope Angle (°)**	**Cohesion, c (t/m^2)**	**Friction Angle, φ (°)**	**Height of Talus (m)**	**ϒ (t/m^2)**	**$ϒ_w$ (t/m^2)**	**FOS (Dry)**	**FOS (Wet)**
Ananthagiri Slope1	40	0.5	38	3.5	1.8	1	1.07	1.00
Ananthagiri Slope2	37	0.45	38	3.5	1.8	1	1.17	1.09

The stability analysis (Table 5.9) of the talus slope indicates that the slope section along Ananthagiri Slope1 is stable with a FOS of 1.07 and Ananthagiri slope 2 is stable with a FOS of 1.17. Both the slopes are just stable under wet conditions also. However, during heavy rainfalls, the slopes may show conditions of instability.

5.3.4 Gandhipuram Slope

The Gandhipuram Slope (Facet No. 34) is located to the west of the Kodaikanal Lake. The slope is nearly concave with average slope angle being greater than 40° towards N100°. The upper slope is very steep, with a slope angle of 50° and exposes charnockite rock with varying thickness of overburden cover (Fig 5.19). The thickness of the debris in the upper slope is of the order of about 10m with very gentle to nearly flat slopes. Similar thickness of debris is seen at lower levels having gentle slopes. The charnockite rocks are well exposed in most parts of the inclined slope. The charnockite rocks below the overburden soil are moderate to highly weathered in nature (Fig 5.17). The joints observed have been plotted in a stereonet (Fig 5.18). The entire slope is packed with civil structures like residential buildings, shops and even a school (Fig 5.16). These buildings are very closely spaced. The houses are mostly of masonry type and without suitable column and beam supports. The residential buildings sometimes are even of two storeys level. The school is located at the ridge top of this slope and is a three storeys building. The state highway, SH156, borders the upper boundary of the Gandhipuram slope. Even though the areas between the buildings are very small, it is observed that even in these congested spaces agriculture is practiced. Vegetation/grass/banana tree/other bushes support the entire cut slope wherever possible.

No suitable surface and sub surface drainage exists throughout the slope. In addition to the irrigational uses, the domestic water wastage is spilled directly on the slope, increasing the infiltration of water into the slope. Geologically, the topsoil is more clayey in nature or clayey silt mixed with rock blocks. Thus, soil moisture is well retained.

Fig 5.16 Urbanization on the steep slope of the Gandhipuram Slope, Facet no. 34

Fig 5.17 Weathered rock exposure seen on the Gandhipuram Slope

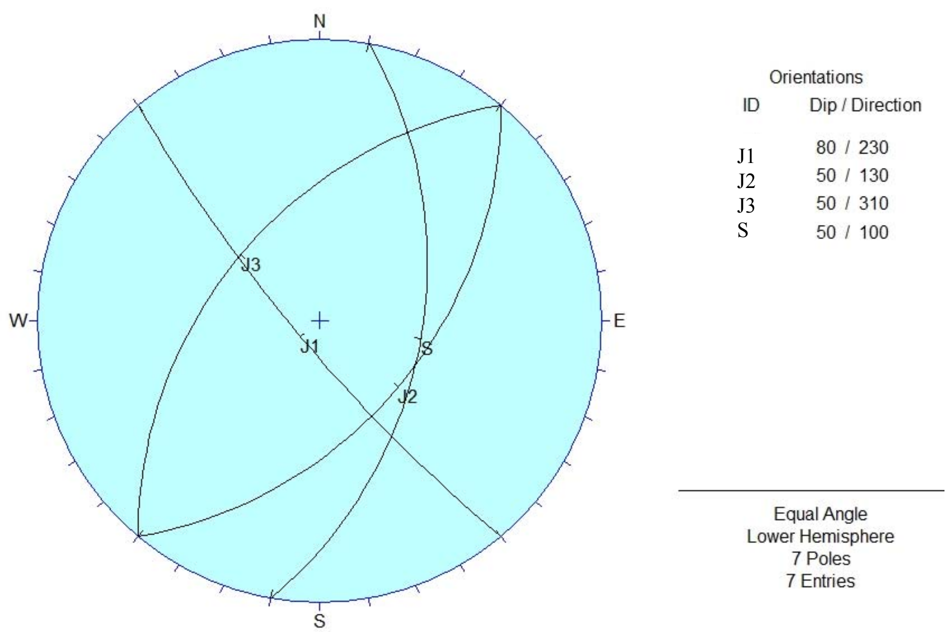


Fig 5.18 Stereoplot of geological discontinuities observed in the Gandhipuram Slope

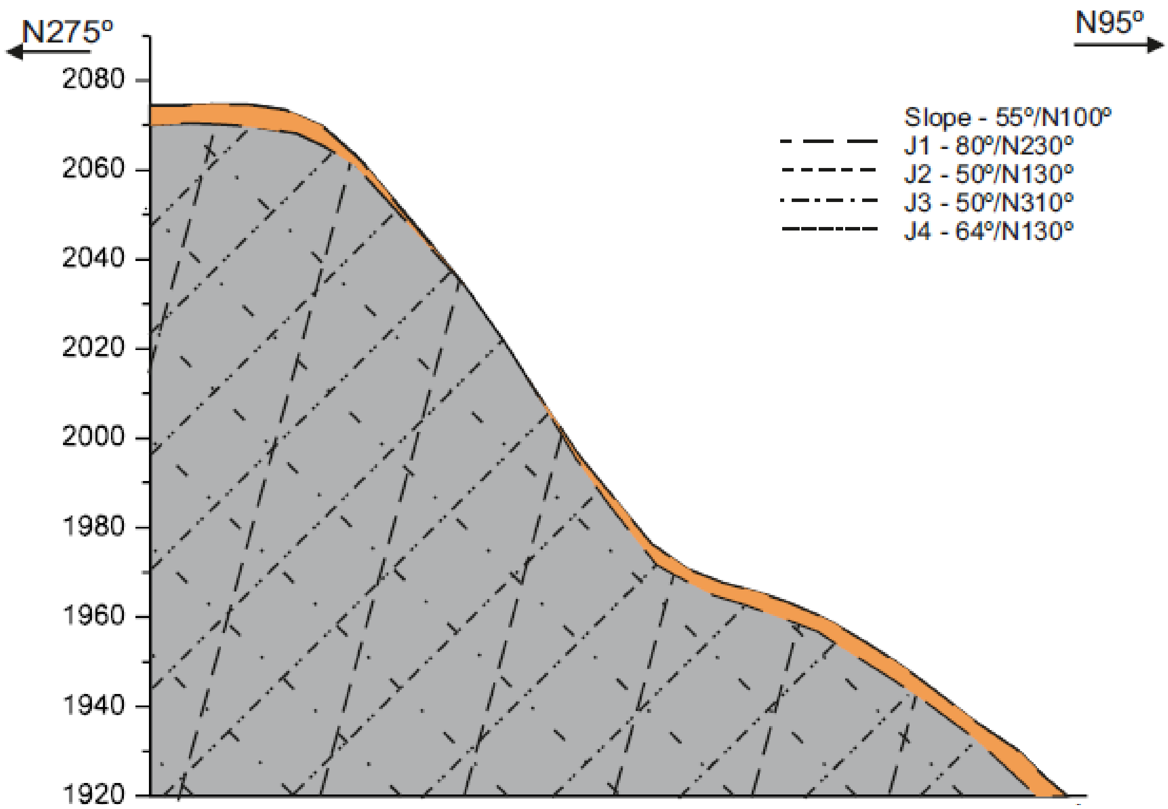


Fig 5.19 Geological cross section along (f-f') the Gandhipuram Slope

5.3.4.1 Slope stability of Gandhipuram slope

a) Stability analysis of rock slope

The values of cohesion, c, and friction angle,ϕ, satisfies the Markland test condition ($\psi_f > \psi_p > \phi$) for plane failure. The stability analysis was carried out using the SASP program by Bhawani Singh and the value of factor of safety was obtained as 2.42. This F value (Table 5.10) did not corroborate with the visible ground observations, regarding slope instability.

Table 5.10 Input Parameters and Result of stability analysis for rock slopes of Gandhipuram facet

Location	**Slope Angle, α (°)**	**Height, H (m)**	**Dip of Joint Plane, α (°)**	**Cohesion, c, (t/m^2)**	**Friction Angle, φ (°)**	**JRC**	**JCS (t/m^2)**	**FOS**
Gandhipuram	55	90	42	40	38	10	90	2.42

5.3.5 Coalkers Walk Slope

The Coalkers Walk, Facet no. 34, slope is located directly to the south of the Kodaikanal Lake. The slope is nearly concave with an average slope angle greater than 45° towards N147° (Fig 5.21). The Coalkers Walk slope is a rock cliff slope that makes a part of the southern boundary of the study area. The slope is constituted of charnockite rocks with thin overburden on the top. Fairly thick deposit of debris material is seen at the toe area. The Coalkers Walk is one of the major tourist attraction spot in Kodaikanal. The 1 km paved pedestrian path was constructed by Lt. Coalker in 1872, is running along the edge of steep rock slope. It provides a stunning panoramic view of the plains on the south. The slope has a total height of 1200m with continuous steep slope for a height 850m, on a clear day one can view as far as Dolphin's Nose in the south, the valley of the Pambar River in the southeast, Periyakulam town and even the city of Madurai. The steepness of the slope makes it impossible to access the lower reaches. A small cluster of urbanization is observed in the western part of the slope facet along with moderate vegetation. The slope also hosts one of the major hospitals in the township. The district road passes through the facet at the crest of the slope.

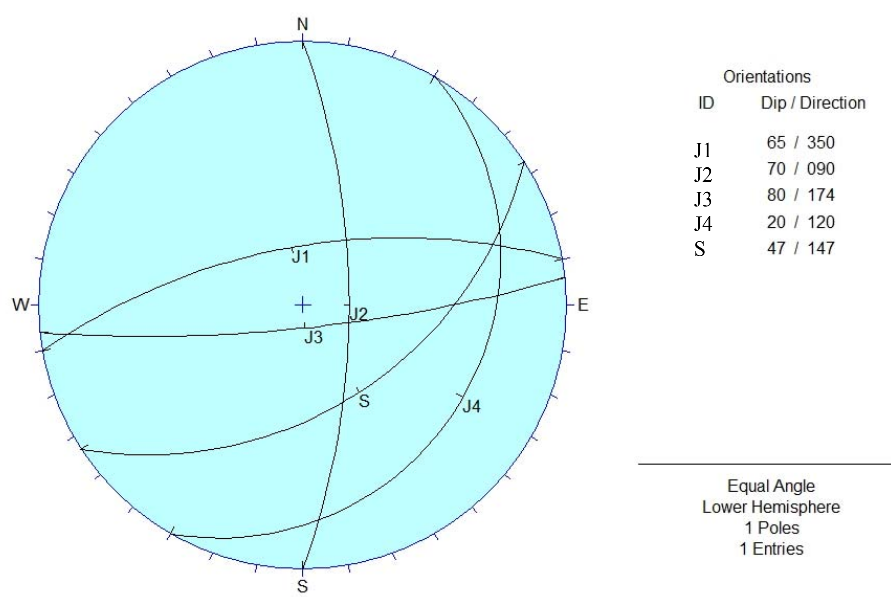


Fig 5.20 Stereoplot of geological discontinuities observed in the Coalker's Walk Slope

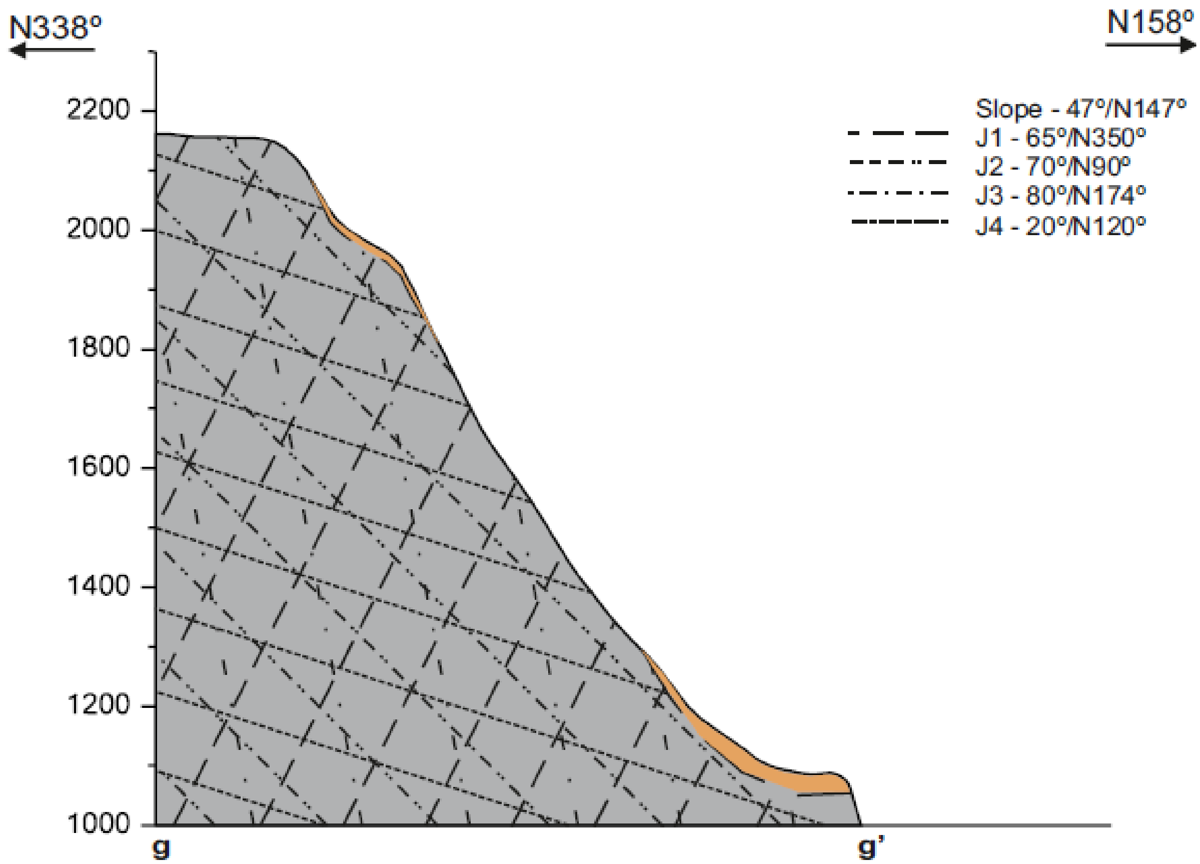


Fig 5.21 Geological cross section along (g-g') the Coalkers Walk Slope

5.3.5.1 Slope stability of Coalkers walk slope

a) Stability analysis of rock slope

The entire slope mostly consists of rock outcrop except at the toe region and a small portion in the upper portion where slope break is observed. The geological discontinuities were plotted in a stereonet along with the slope direction. From the kinematic analysis, it is observed that the joint, J4, satisfies the parallelism condition with the slope. The values of cohesion, c, and friction angle, ϕ, satisfies the Markland test condition ($\psi_f > \psi_p > \phi$) for plane failure. The stability analysis was carried out using the SASP program by Singh and Goel, 130, and the value of factor of safety (Table 5.11) was obtained as 1.59 suggesting that the slope is considerably stable.

Table 5.11 Input Parameters and Result of stability analysis for rock slopes of Coalkers Walk slope

Location	**Slope Angle, α (°)**	**Height, H (m)**	**Dip of Joint Plane, α (°)**	**Cohesion, c, (t/m^2)**	**Friction Angle, φ (°)**	**JRC**	**JCS (t/m^2)**	**FOS**
Coalker's Walk	60	850	20	35	40	12	120	1.59

b) Stability analysis of talus slope

As the incidence of overburden material in this slope is considerably less. Hence, the stability analysis of the talus failure has not been carried out as the possibility of failure of slope due to talus mode is rather low.

5.3.6 Control Measures

The slope stability analysis indicates that the slope are generally stable in dry condition (FOS – 1.07 to 1.14) but during extremely high rainfall (FOS - 0.98 to 1) there is a probability of failure particularly in urbanized talus slopes. Moreover, most of the localities lack a systematic drainage system for disposing of domestic waste water and storm water of the area. Since the slopes are sensitive to instability, if the water saturation increases, it is the immediate necessity to provide suitable subsurface drains in the form of suitably planned network of drainage pipes for disposing of domestic waste water. Moreover, a well-planned open drainage system with RCC drains shall be constructed to collect storm water and dispose it off suitably. This will substantially help to reduce sub surface seepage during of water.

In addition, a series of well-planned retaining walls shall be constructed at the edge of all the terraces used for agriculture or residential or commercial purposes.

5.4 Naidupuram Block

The Naidupuram block (Fig 5.22) is located north of the Kodaikanal Lake and south of the Kurinji Block. The block has well developed exposures of charnockite rock with thin (<5m) debris cover at places. The cut slopes exposes fairly fresh charnockite rocks. The Bear

Shola Stream flows towards eastwards in the middle of the area. The slopes in this block are generally moderately steep (30°-35°) to steep (>45°) in nature. Wet patches can be seen on the rock exposures at places. The block also supports the Bear Shola Falls on the western margin of the block. Urbanization is noticed in the upper reaches where the slope is gentle. The slope also supports agricultural lands and moderate vegetation throughout. Out of the 12 slope facets that make up this block, all of the slopes fall under the low hazard and moderate hazard zone of the LHZ map except one (Facet no. 30), which is named as M. M. Street slope. The detailed stability analysis of this high hazard slope has been carried out.

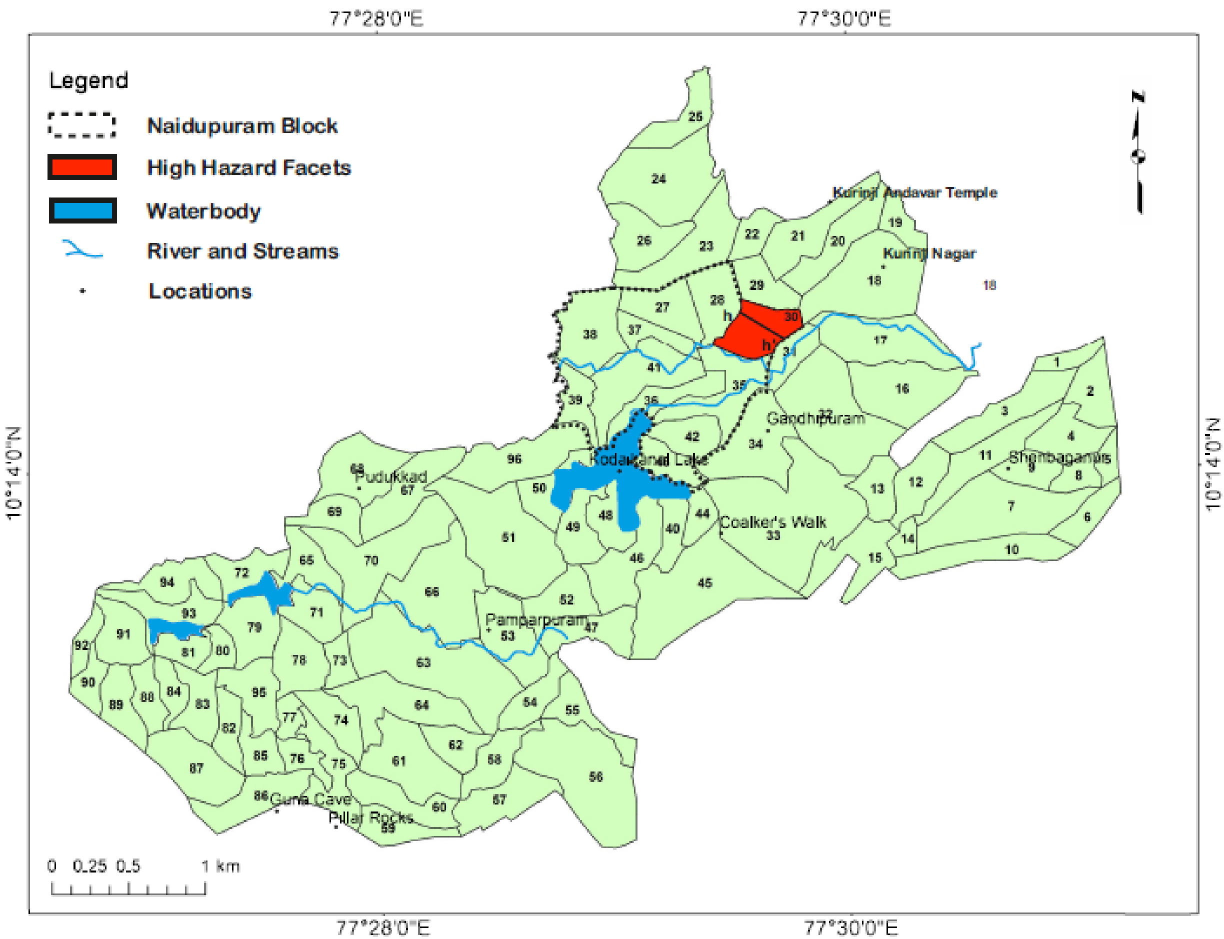


Fig 5.22 Map demarcating the Naidupuram Block and the High Hazard Zone within the block

5.4.1 MM Street Slope:

The M.M. Street slope is located at the western periphery of the Naidupuram Block. The slope has an average angle of 35° towards N133° (Fig 5.24). It is constituted of charnockite rock with thin debris cover. The debris materials of 3-4m thickness are seen deposited on the fairly steep slopes of the upper reaches. Further down, charnockite rocks are well exposed with steep gradients of about 60. The toe of the slope is characterized by mild slopes with fairly thick debris cover.

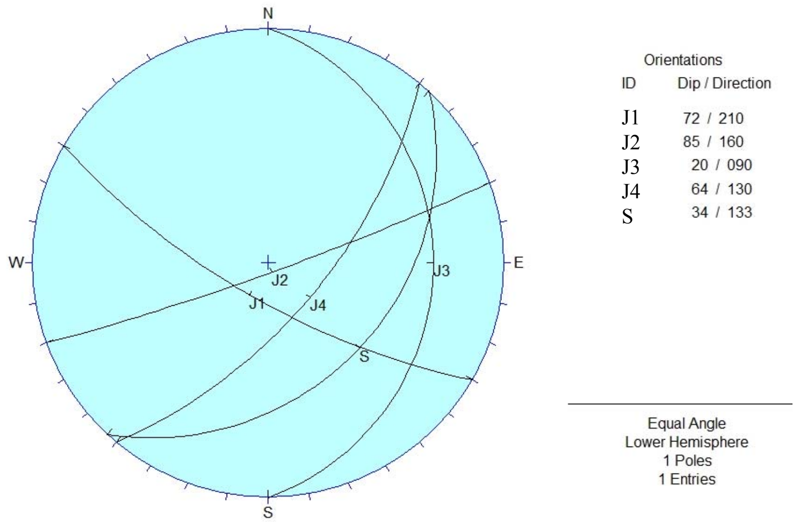


Fig 5.23 Stereoplot of geological discontinuities observed in the M. M Street Slope

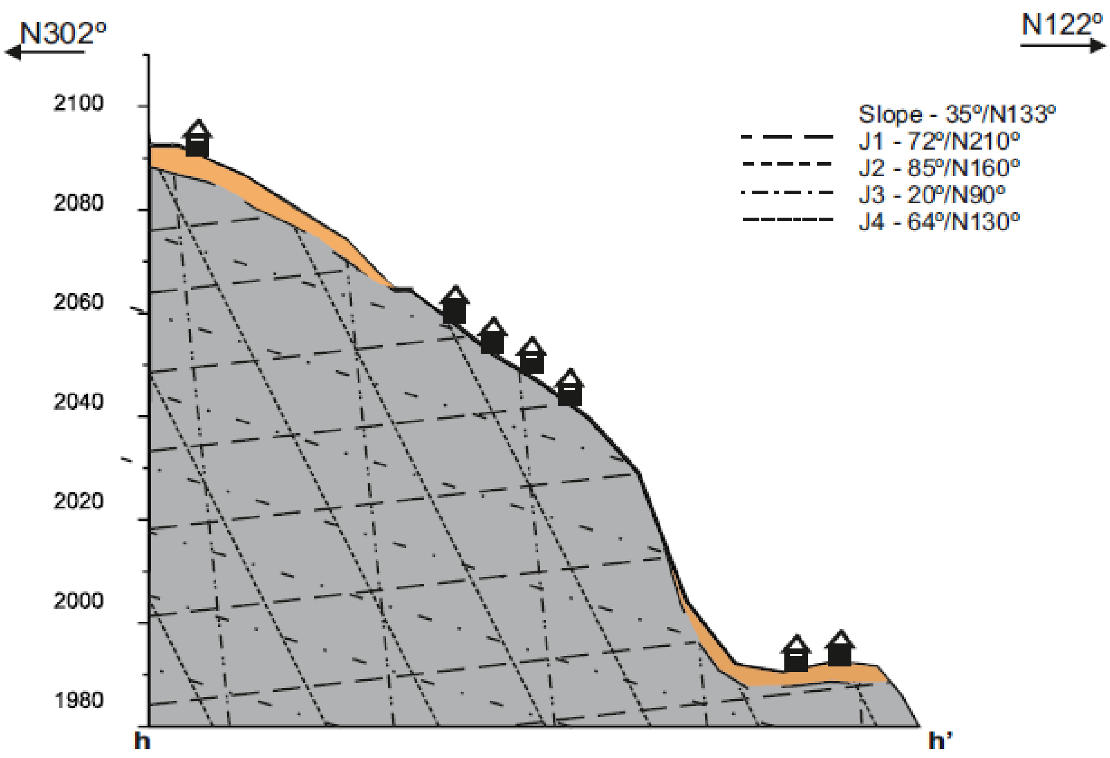


Fig 5.24 Geological cross section along (h-h') the M. M Street Slope

The Bear Shola stream flowing roughly towards the southeast is seen in the middle part of the slope. In the southern boundary of this facet, the Bear Shola stream confluences with the Palar River. Urbanization is spread throughout the slope in the form of residential buildings, hotels, resorts, offices, schools and other civil structures. Large areas of agricultural land are seen on the left bank of Bear Shola stream in addition to portions of moderate vegetation seen at places. Wet patches and dripping conditions are observed on the rock exposure surfaces at places. As seen in other slope facets, no proper system of drainage is followed here as well. The domestic waste water is let out on to the slope directly. Cracks have been observed in the buildings at various locations in the slope.

5.4.1.1 Slope stability of M. M. street slope

a) Stability analysis of rock slope

The inclination of rock slope is about 35° in higher levels and attains an angle of 55° at lower levels, which has been taken up for stability analysis. From the kinematic analysis of the stereoplot (Fig 5.23), it is observed that the joint, J4, dips along the same direction of that of the slope but dips at an angle steeper than the slope inclination. Hence, it does not satisfy the daylighting condition of the joints of the Markland's test condition for plane failure. Similar conditions were obtained for the wedge failure also. Consequently, both the plane failure and wedge failure are eliminated from the possible modes of failure.

b) Stability analysis of talus slope

The overburden debris materials seen over the rocks in the upper reach of the slope have an average thickness of about 3m. The slope has an average inclination of around 35°. Cohesion, c, value of 3.5kPa and friction angle, φ, of 35° was selected judiciously taking into consideration the site conditions.

Table 5.12 Input Parameters and Result of stability analysis for talus slope of M. M Street slope

Location	**Slope Angle (°)**	**Cohesion, c (t/m^2)**	**Friction Angle, φ (°)**	**Height of Talus (m)**	**ϒ (t/m^2)**	**$ϒ_w$ (t/m^2)**	**FOS (Dry)**	**FOS (Wet)**
M. M. Street	35	0.35	35	3	1.8	1	1.13	1.04

The stability analysis (Table 5.12) of the talus slope of the M. M. Street indicates that the slope section is marginally stable under both normal and saturated condition with a FOS of 1.13 and 1.04 respectively. However, during heavy precipitation, the slopes may show conditions of instability.

5.5 Pudukkad block

The Pudukkad or the Observatory block (Fig 5.25) is situated to the north and northwest of the Kodaikanal Lake. This block is characterized by moderate to steep slope inclinated towards southeast with barren rocks exposed on higher levels. Middle slope with fairly steep slope angle of 37°, are occupied by debris. The general thickness of the debris material seen on the slope is of the order of about 4m. The rocks are exposed on the cut faces of the stream as well as in the lower reaches with steep slopes (>45°).

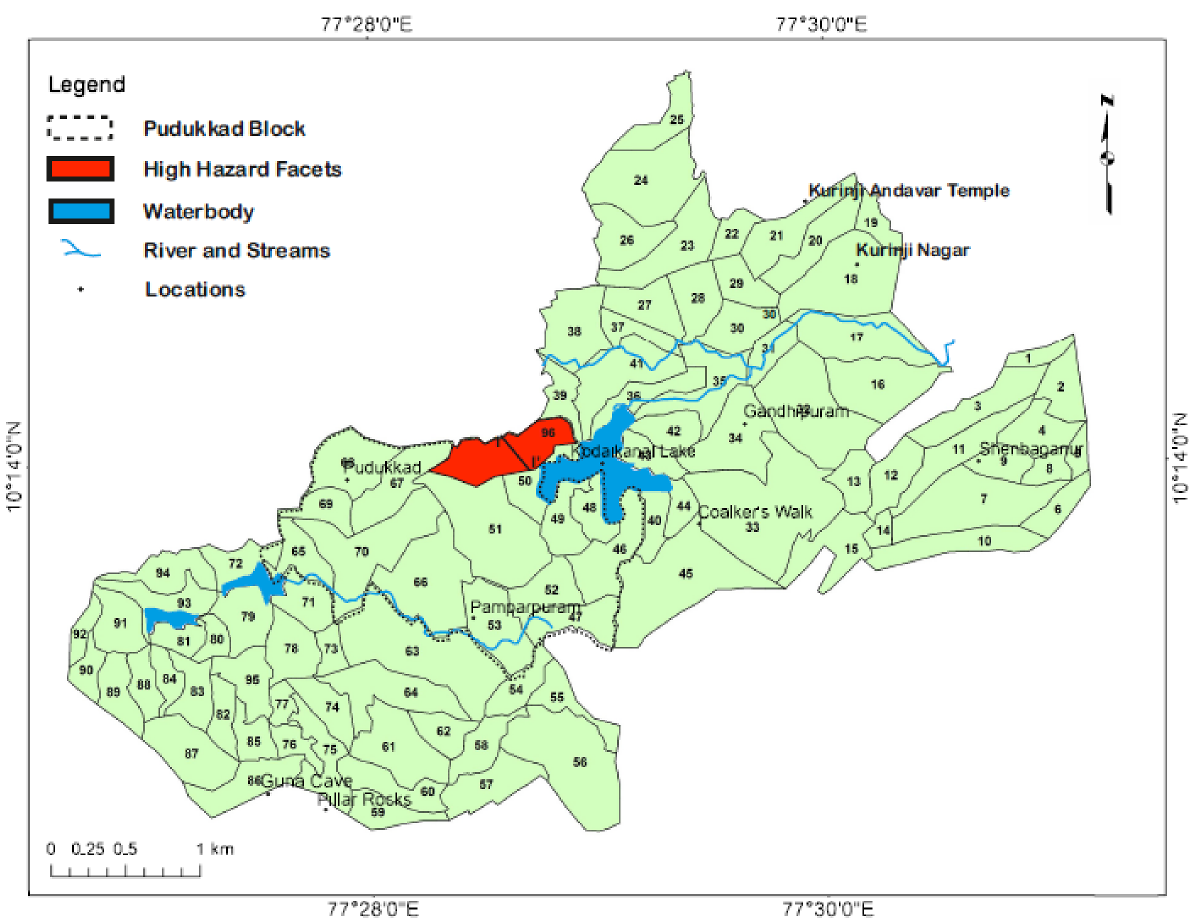


Fig 5.25 Map demarcating the Pudukkad Block and the High Hazard Zone within the block

Moderate to highly weathered charnockite rock exposures are observed in the cut slopes of the roads below the debris cover (3m - 4m). Fresh rock patches could be seen at deeper levels. At places, the rocks are so heavily weathered resembling soil. Moderate urbanization is seen in the area with major portions being covered by agricultural lands with urbanization intermittently. In the south, it is bordered by the Levinge stream originating from the Kodaikanal Reservoir and flowing towards southeast direction. The Fairy Falls is also situated close to western periphery in this block.

Fig 5.26 Water dampening the highly jointed rock exposure in Pudukkad Slope

5.5.1 Pudukkad Slope

The Pudukkad slope facet (Facet No. 96) is located north of the Kodaikanal Lake. It has a fairly steep slope of 35° towards N108° facing the Kodaikanal Lake (Fig 5.29). Charnockite rock exposure is observed in the top reaches of this facet (Fig 5.27). Overburden debris of the order of 2-3m is seen at the lower and middle reach. The rock is heavily jointed with a minimum of 5 sets of joints (Fig 5.28). The frequency of these joints varies from few centimeters to up to 1m (Fig 5.26).

Fig 5.27 Massive charnockite rock exposure along the Observatory Road in Pudukkad Slope

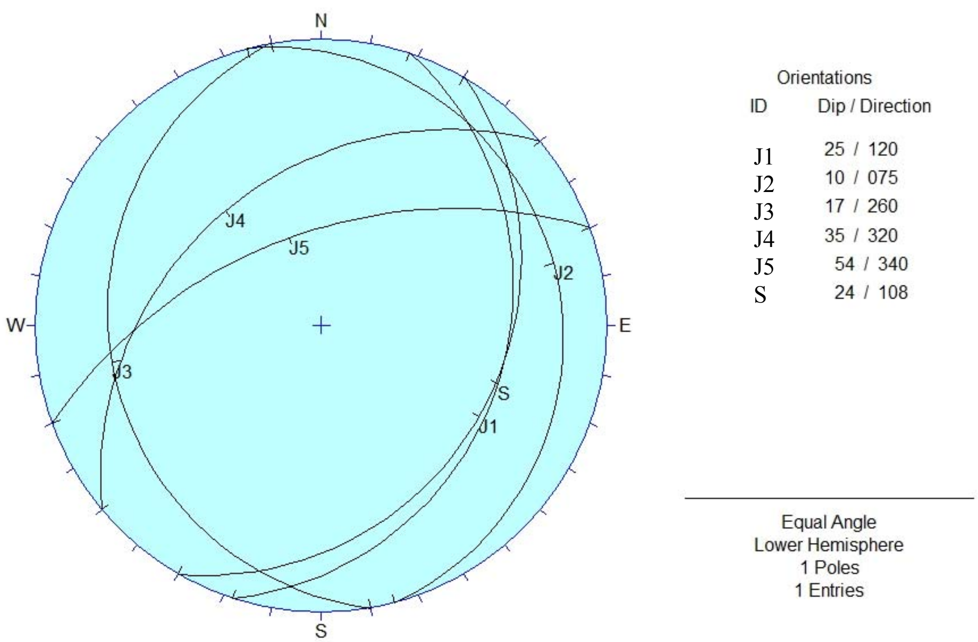


Fig 5.28 Stereoplot of geological discontinuities observed in the Pudukkad Slope

At places, water seepage is also observed along these joints. Moderate urbanization is noticed along the slope. Few cases of instabilities have been reported in this slope in the past. Like the other urbanized areas in the study area, no proper domestic waste water drainage is followed. The waste water from the residential houses is let out directly on to the slope. The slope is generally found to be damp even during the summer (Fig 5.26). Several cases of slope instability has been reported in the past in this area (Fig 5.30 and Fig. 5.31).

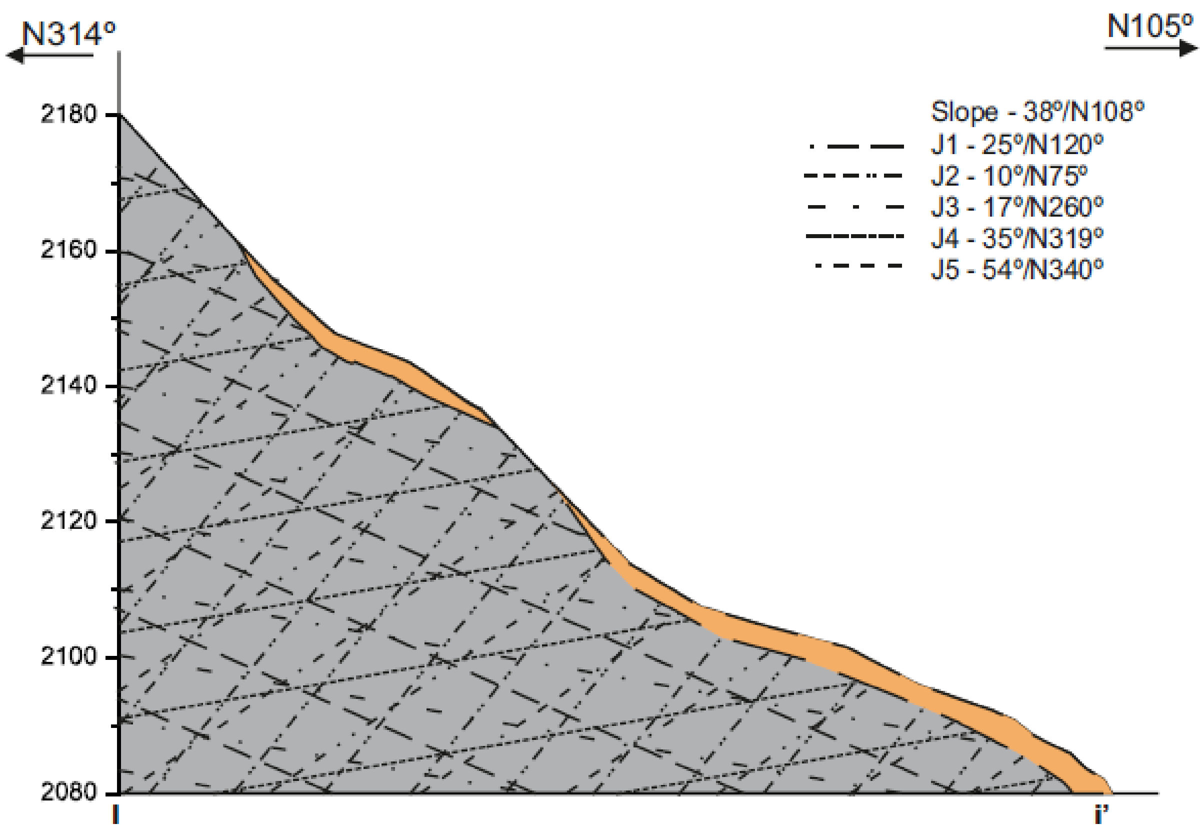


Fig 5.29 Geological cross section along (i-i') the Pudukkad Slope

5.5.1.1 Slope stability of Pudukkad Slope

a) Stability analysis of rock slope

The inclination of rock slope of about 40° in the top reaches and have been taken up for stability analysis. From the kinematic analysis of the stereoplot (Fig 5.28), it is observed that the joint, J1 and J2, dips roughly along the same direction of that of the slope but does not satisfy the daylighting condition. Hence, it does not comply with the Markland's test condition for plane failure. Similar conditions were obtained for the wedge failure also. Consequently, both the plane failure and wedge failure are eliminated from the possible modes of failure.

b) Stability analysis of talus slope

As indicated earlier, the thickness of the debris materials is of the order of 4m. The slope is fairly steep around 35° in the middle portions and decreases substantially at lower levels. Material characteristics. The results of the stability analysis is given in the Table 5.13 along with input parameters.

Fig 5.30 A small slide on the urbanized slope of the Pudukkad slope

Table 5.13 Input Parameters and Result of stability analysis for talus slope of Pudukkad slope

Location	**Slope Angle (°)**	**Cohesion, c**	**Friction Angle, φ (°)**	**Height of Talus (m)**	**Υ (t/m^2)**	**Υ_w (t/m^2)**	**FOS (Dry)**	**FOS (Wet)**
Pudukkad	37	0.52	34	4	1.8	1	1.15	1.02

Fig 5.31 Collapse of retaining wall at Observatory road

CHAPTER 6
FUTURE URBANIZATION

India is on the threshold of facing complex urban planning and development challenges in managing massive urbanization. With more than 1.2 billion population, India is expected to surpass China's population by 2025. A major portion of this increase would be in existing mega cities, posing greatest challenges to India's urban future (Jauhari 2012). At national level, in India, urban planning and development subject is dealt by the ministry of urban development, the ministry housing and urban poverty alleviation, and the planning commission of India. Development plan drives planning of cities in India (Munshi 2013) and it outlines land-use zones in which uses like residential, commercial, institutional, industrial etc., are planned. The urban planning process is more or less same throughout the country following the guidelines stipulated in Urban Development Plan Formulation and Implementation, (UDPFI 1996). Traditionally Town Planning departments are the nodal agency that collects and compiles the relevant information from various departments on their future plans. In addition to the above information, plan formulation takes into consideration of planning theories and principles; planning tools and techniques; and norms and standards, followed by evaluation processes.

Development of hill settlements, especially towns and the surrounding areas is a challenging task, as mountainous regions are largely situated within or near highly sensitive and at times fragile eco-systems. Since most hill areas have abundant scenic capacity, which is a visual resource, development in the hill areas has the potential to affect and be affected by the environment. Moreover, the development issue becomes more complicated when planners take up large urban agglomerations in the hills. If expansions take place in an unplanned manner through indiscriminate cutting of the hills it induces several problems in the drainage. Toe cutting made in the process of unplanned expansion adversely affects the slope stability and the retaining wall constructed as remedial measures may in turn adversely affect the subsurface drainage if sufficient weep holes are not provided or if the permeability aspect of the retaining wall is not addressed properly. This increases the slope instability during rainy season.

The urbanization starts from a relatively flat area available along the ridge line and gradually expands towards the valley. Obstruction to natural drainage may affect the slope stability adversely with varying severity depending on the geology of the formation. Due to their very high population density, these hill settlements are highly vulnerable to irreversible damages caused by overuse, deforestation or rapid changes in the characteristics of land and vegetation resources. Landslides, erosion, flooding, the destruction of scenic capacity and other problems of environmental degradation are caused by the growth in tourism, urban sprawl and intensification of commercial agriculture. Any growth in the hills needs to protect the natural resource base, while giving the hill folk an opportunity to improve their quality of life, without eroding their traditions and values. In other words it should be sustainable.

The different hill regions have varied geo-environmental conditions and resources available for development. To carry out any development work as development in mountainous regions is constrained by difficult terrains, steep gradients, complex geological structure, climatic conditions and rich flora. Hill stations like Shimla, Mussoorie, Nainital, Ooty, Munnar, Kodaikanal, and such places have been experiencing urban expansion for development due to high population growth, large tourist influx and better living conditions for the past few decades, which has changed the environment and visual appearance of hill towns. Hill towns have grown many times more than their design and carrying capacity and are under a lot of pressure for providing residential, educational, health, work and recreational facilities, which is further pronounced due to scarcity of buildable land, as well as high land prices.
Heavy pressure on the housing and existing infrastructural facilities is exerted due to high population increase due to migration from the surrounding regions as well as a high influx of tourists which leads to construction of more multi-storeyed buildings in hill towns for residential, office, and commercial purposes.

Also, degradation of natural topography, vegetation and disturbance of natural drainage pattern due to massive construction has resulted in environmental degradation in the hill towns. (Maitra, 2003).

Construction of houses, offices and commercial premises without any regard for aesthetics or land use has resulted in conflicting land use/constructions and a scenario is created where construction dominates the natural environment of hill towns. Unlike most of the ecological sensitive zones/areas of world, Indian hill towns are peculiar examples of massive urban development in environmentally or ecologically sensitive areas, which are growing exponentially over and above their carrying capacities and are hampering/affecting the ecology at large. (Kumar, 2015)

With this in view, three potential sites have been selected for the future development of the Kodaikanal Town and stability analysis has been carried out in each of them. In order to identify potential locations for future development, extensive field traverses were taken in and around Kodaikanal Township. The core areas of township are urbanized and hence, large areas are not available for future construction purpose. Hence, the fringe areas of Kodaikanal were given due attention to select potential locations. For that purpose, the following criteria were considered:

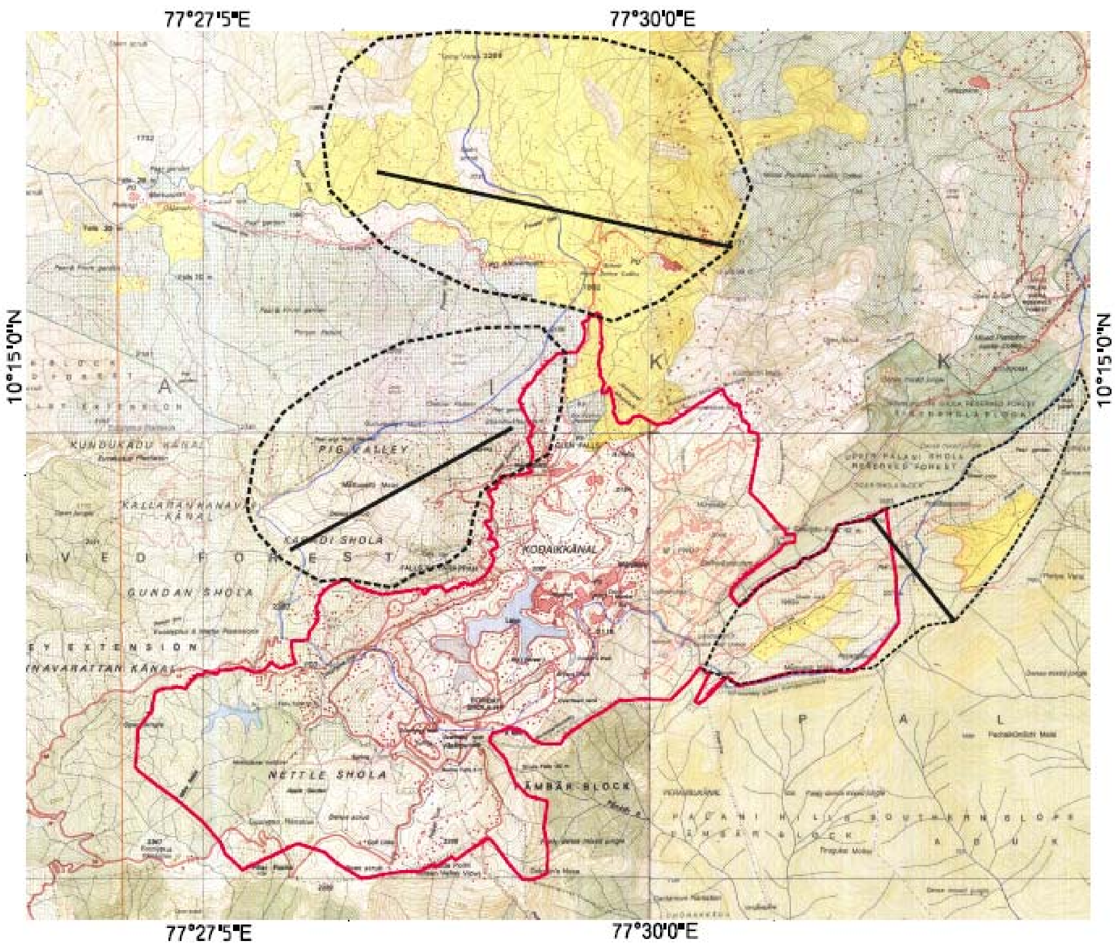


Fig 6.1 Toposheet of Kodaikanal area demarcating the suggested areas for future urbanization

i) Nearly flat ground with gentle to moderate slopes

ii) A fairly large area in order to develop a small satellite township

iii) Considerable thickness of compacted debris material for easy construction purpose

iv) Stable slopes within the terrain and as well as in boundary areas

Technically, the above criteria should be accounted as the minimum requirement during site selection process and they pertain to hill characteristics. The other requirements including transport, electricity, water and other basic amenities shall be arranged by the administration. A walkover survey in different areas indicated three important locations for future urbanization (Fig 6.1). A detailed description in addition to preparing a section across the general slope as well as stability analysis of these locations has been carried out.

6.1 Shenbaganur Area

The almond shaped Shenbaganur area is situated partly within the boundary of the study area at the southeastern margin of the Kodaikanal Township. It is a plateau with rock cliff on the southern periphery of the area and thick debris cover of thickness more than 10m could be seen all along the terrain above the rocks. The area has a general slope of 20° towards N140°. On the other hand, the rock cliff bordering the area on the southern side is steep with cliff face. This stretch of rock exposure provides a stable constructive support for the gentle terrain above. The charnockite rocks exposed on the cliff are dark grey colored, medium to coarse grained, moderately weathered, and well jointed in nature, though at places it is noticed that the rocks are highly weathered.

The observed attitudes of the discontinuities are plotted in a stereonet (Fig 6.2) and obtained three sets of joints. These joints have been projected in the cross section using apparent dip of the discontinuity (Fig 6.3). At present, urbanization in this area is very sparse and could be seen in isolated spots. In this area, cultivation is practiced extensively and throughout the year, leading to dampness of the slope. The southern region where rocks are exposed, the area is dry.

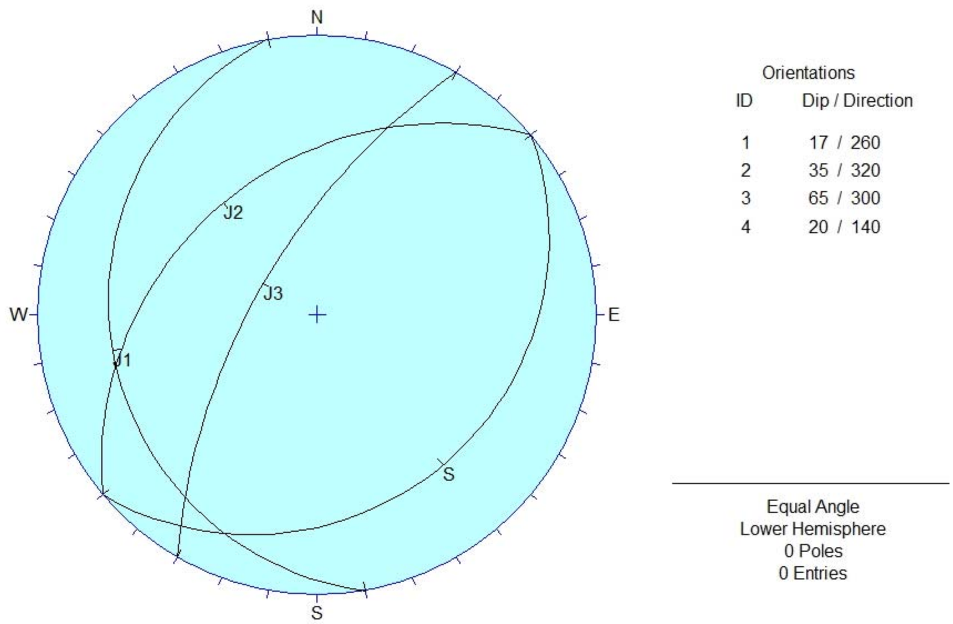


Fig 6.2 Stereoplot of geological discontinuities observed in the Shenbaganur Slope

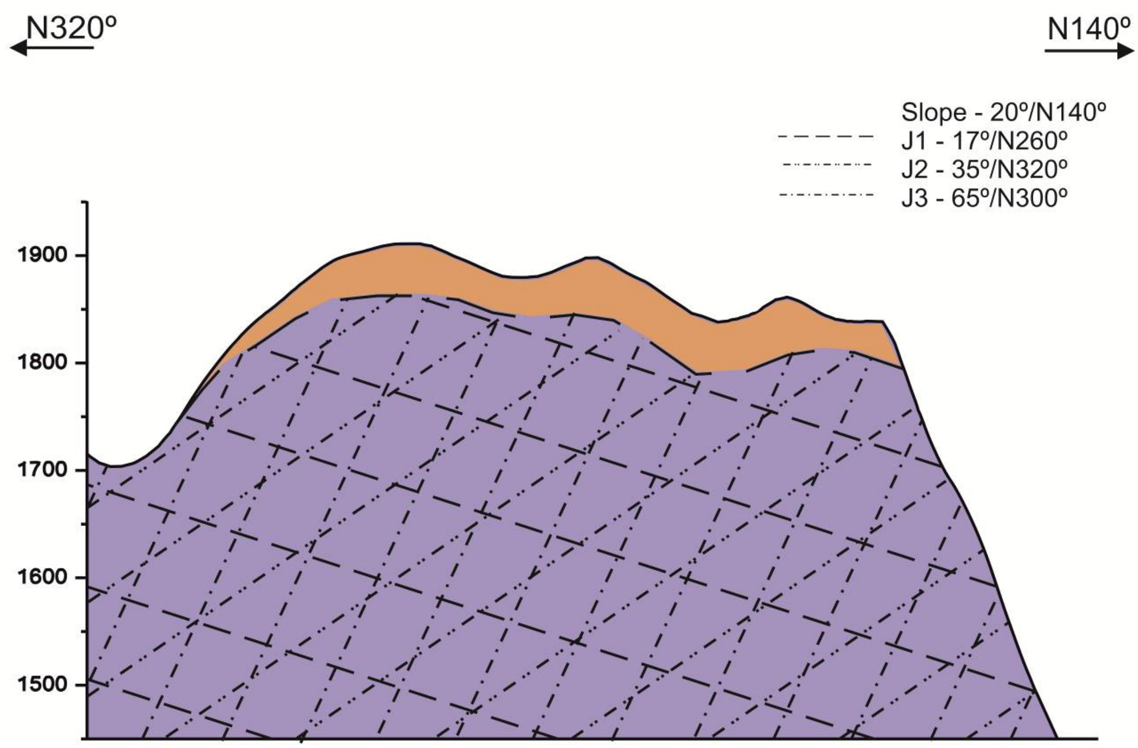


Fig 6.3 Geological cross section along Shenbaganur section

6.1.1 Slope stability analysis of Shenbaganur Area

As the Shenbaganur area is nearly horizontal close to the ridge top, it is characterized by thick debris cover. Steep rock cliff observed in the southern boundary has slope inclination of about 75°. The first step was to deduce the mode of failure in the area. For that purpose, kinematic analysis of the geological discontinuities encountered in this area had been carried out. From the kinematic analysis, it was explicit that the joint planes dip into the hill and do not comply with the Markland’s test conditions for plane failure. It also does not satisfy the conditions necessary for wedge mode of failure too. Hence, both plane and wedge modes of failure are eliminated to be the possible mode of failure.

Since, the slope in the top portion of the ridge is very gentle, the possibility of occurrence of a circular failure and talus failure are really lean. In the boundary areas, the debris have gentle slopes with thickness gradually decreasing close to valley boundaries. It is therefore concluded that the slope is stable and suitable for construction.

6.2 Vilpatti Area

The Vilpatti area is located to the north of the Kurinji Block. Like the Shenbaganur area, the terrain has gentle to very gentle slope close to ridge top with slight undulations. The maximum of the thickness of the debris materials is of the order of 20m close to the ridge top. Charnockite rocks are exposed on the steep slope of the eastern boundary. The charnockite rock exposed in this area is fairly fresh to moderately weathered. The gentle ground to the west of rock cliff is mainly utilized for agricultural purpose with little spots of urbanization seen within intermittently. The urbanization is seen in small clusters within the slope. The dampness of the slope can be accounted to the incessant agricultural practices and also to some extent to the pleasant climatic condition that is present throughout the year. Plotting (Fig 6.4) of the observed joint discontinuities in a stereonet indicates the presence of four sets of well developed joints. The cross section has been prepared taking these discontinuities into consideration (Fig 6.5). The joints are tight with no fillings between them.

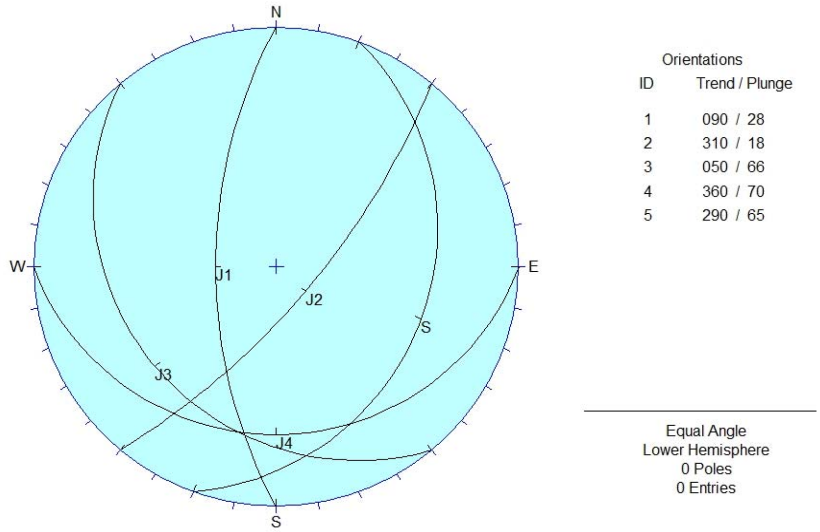


Fig 6.4 Stereoplot of geological discontinuities observed in the Vilpatti Slope

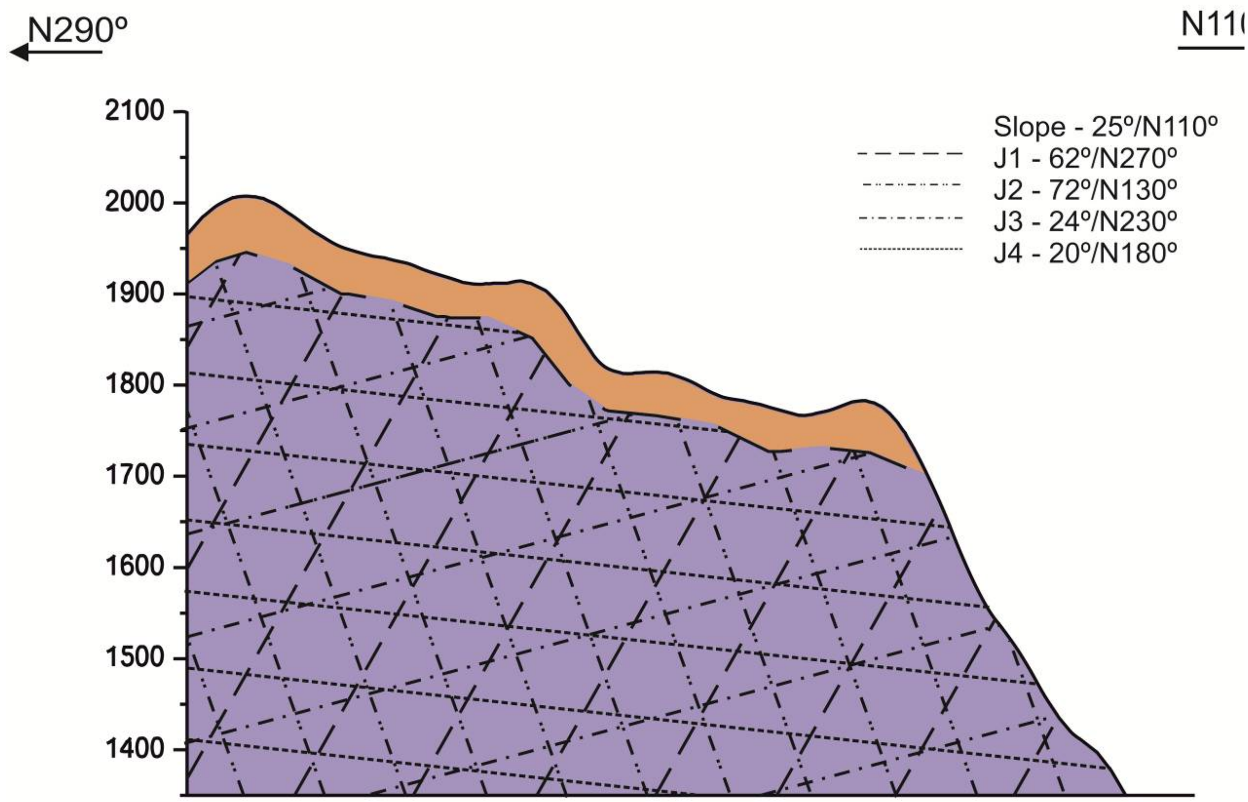


Fig 6.5 Geological cross section along the Vilpatti Slope

6.2.1 Slope stability analysis of Vilpatti Area

The Vilpatti area is nearly horizontal close to ridge top. The whole area is characterized by thick debris cover over the rocks with maximum thickness (20m) close to ridge top. Steep rock exposure observed in the eastern boundary has slope inclination of about 55°. To work out the mode of failure in the area, kinematic analysis of the geological discontinuities encountered in this area had been carried out. From the kinematic analysis, it was evident that the joint planes do not comply with the Markland’s test conditions for plane failure. It also does not satisfy the conditions necessary for wedge mode of failure too. Hence, both plane and wedge mode of failure are eliminated to be the possible mode of failure.

Since, the slope in the top portion of the ridge as well as the entire slope below is gentle to very gentle, the possibility of occurrence of a circular failure and talus failure are ruled out. In the boundary areas, the debris have gentle slopes with thickness gradually decreasing close to valley boundaries. It is therefore concluded that the slope is stable and suitable for construction.

6.3 Perumpallam

The Perumpallam area is located to the west of the Kodaikanal Lake. Similar to the Shenbaganur and Vilpatti area, it also has gentle to very gentle slope close to the ridge top with slight undulations of the terrain. The maximum of the thickness of the debris materials is of the order of 20m close to the ridge top. Fairly fresh charnockite rock exposures are observed on the steep slope of the western boundary. The joints are tight with no fillings between them. The gentle flats are mainly utilized for agricultural purpose. Urbanization is seen in small clusters within the slope. Though the northern portion of this area is explored to some extent, the southern half of this area, is barely touched by any sort of human interaction. Vegetation covers the southern half portion. Plotting (Fig 6.6) of the observed joint discontinuities in a stereonet indicates the presence of three sets of well developed joints. The cross section has been prepared taking these discontinuities into consideration (Fig 6.7).

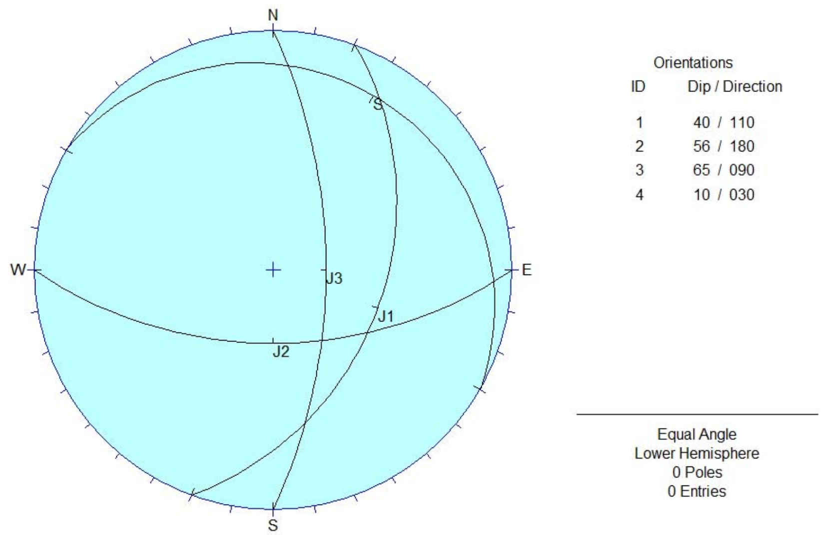


Fig 6.6 Stereoplot of geological discontinuities observed in the Perumpallam Slope

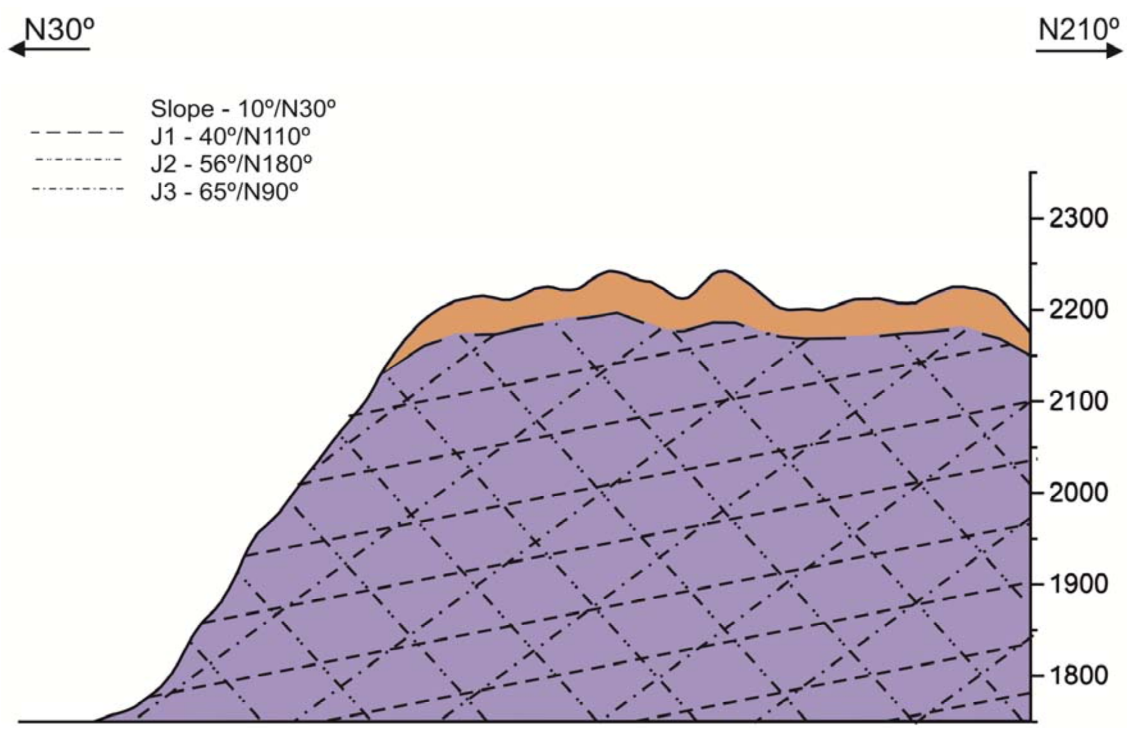


Fig 6.7 Geological cross section along the Perumpallam Slope

6.3.1 Slope stability analysis of Perumpallam Area

The Perumpallam area is nearly horizontal with slight undulations seen close to ridge top. Distinguished by thick debris cover over the rocks similar to the other two areas, the maximum thickness is about 20m close to ridge top. The rock cliff of the western boundary has slope inclination of about 45°. Kinematic analysis of the geological discontinuities encountered in this area was carried out to find out the mode of failure in the area. From the kinematic analysis, it was evident that the joint planes do not satisfy the Markland’s test conditions for plane failure. It also does not satisfy the conditions necessary for wedge mode of failure too. Hence, both plane and wedge mode of failure are eliminated to be the possible mode of failure.

Since, the slope in the top portion of the ridge as well as the entire slope below is gentle to very gentle, the possibility of occurrence of a circular failure and talus failure are ruled out. In the boundary areas, the conditions are similar to that of the Shenbaganur and Vilpatti area. The debris have gentle slopes with thickness gradually decreasing close to valley boundaries. It is therefore concluded that the slope is stable and suitable for construction.

6.4 Discussion

The observations and the analysis of the potential locations for future urbanization indicate that Shenbaganur, Vilpatti and Perumpallam blocks are favorably located with suitable slope gradients, stable and having soft foundation materials such as debris to facilitate easy construction. The administration shall collect further information related to the development of these blocks.

CHAPTER 7
SUMMARY AND CONCLUSION

Hill towns like Kodaikanal are facing fast expansion in the recent times due to growth of tourism and fast pace of urbanization. Most of these development activities do not take into account the existing slope instabilities and as such lead to landslide hazards. Landslides may cause disruption of communication links, damage civil structures and sometime contribute to the loss of properties and casualties in addition of injuries. Planning for civil constructions in hill towns has always been an arduous task as it should consider the nature of slope materials, extent of excavation planned at the site, geotechnical and other factors responsible for slope failures. In the absence of uniform code of practice for construction of civil structures in hilly terrain within India, residential constructions are often taken up on unstable slopes or marginally unstable slopes. These practices cause instabilities resulting in geo-environmental problems of the area.

In fact, proper town planning is need of the hour, based on landslide hazard zonation mapping on meso-scale and other local conditions. The present research focuses mainly on landslide problems of an important Hill town with systematically evaluating various terrain parameters leading to slope instabilities. Kodaikanal, one of the important hill towns of southern India, has been taken as a case study for town planning using LHZ mapping by evaluating terrain characteristics, analysis of individual landslides and also identifying suitable locations for future urbanization. In addition, suitable control measures have also been identified for local areas based on the landslide studies.

The hill town, Kodaikanal is located on a mild sloping hill at an average elevation of 2133m extending from Latitude 10°26’34.6”N to 10°20’59.53”N to Longitude 77°44’59.57”E to 77°52’37.03”E. The study area falls under the Survey of India Toposheets No. 58 F/7, 8, 11 & 12 and it covers an area of about 22 sq. km. The area has been divided into 6 major blocks based on concentration of habitations. The landslide problems each one of these blocks have been evaluated in addition to finding possible control measures. The study concludes by identifying suitable locations for future urbanization.

Geologically, Kodaikanal area falls within Charnockite Group of rocks, which generally comprises pyroxene granulite, pyroxenite and banded magnetite quartzite. However, the Kodaikanal township area is characterised by charnockite with thin (<1m) to thick (>20m) debris overburden above. Thickness of the overburden varies from place to place. Rocks are generally weathered in nature. The outcrops show variable degree of weathering depending on slope gradient and other related factors Fresh rock outcrops are seen on the cut slopes of roads and terraces as well as scarp faces. The rocks show 3 to 4 sets of joints, which are well developed in most places. The foliations is feebly developed at places.

The meso-scale LHZ mapping of the Kodaikanal area on 1:10,000 was carried out with appropriated modification of the Bureau of Indian Standards. From the Landslide Hazard Zonation (LHZ) map, a total of 13 slopes were found to be in VHH and HH zones, which fall in categories of rock slope (7 nos.), talus slope (5 nos.) and thick debris slope (1 no.).The most vulnerable sections of these facets were considered for further detailed study. In case of debris slopes, the shear strength parameters were estimated from laboratory analysis using samples collected from the field. These values were used for rotational failure and talus failure modes. For rock slopes, shear strength parameters were assessed using RMR system as well as using Burton and Brandis (1990). The obtained values were judicially chosen for rock slope stability analysis.

Debris Slope of Kurinji Nagar

Field visits to High Hazard slope facet of the Kurinji block (Facet No. 18) indicated that a part of the slope looks to be unstable. This unstable slope was identified to have a thick debris cover of more than 20m and a steep slope inclination of about 45°. Steep slope, thick overburden cover and the presence of moisture in the slope due to agricultural practices throughout the year were observed to be the cause of instability in this slope. The presence of such thick debris cover (>20m), point out the possibility of circular mode of failure. Hence, stability analysis was carried out for the same using 2 methods namely, i) Circular Failure Chart ii) SARC Computer Program. The result of analysis by both the methods indicated the factor of safety (FOS) values ranging from 1.01 to 1.16 under dry condition indicating the slope to be stable.

Rock Failure Analysis

In the Gandhipuram Block, 5 slope facets (Srinivasapuram, Annanagar, Ananthagiri, Gandhipuram and Coalker's Walk) were found to fall under the high hazard zone category. All the 5 slopes were taken up for the detailed analysis. It was found from the field study that all the slopes in this block constituted of both rock and debris materials. Hence, the slope stability analysis was carried out individually for talus failure and rock failure for each of the slopes. Cohesion and friction angle of the rock was determined from RMR and Barton and Bandis Criterion that were collected during the field visits. From these values, an appropriate value has been chosen for analysis taking into consideration the existing field conditions. As a first step, kinematic analyses of the slopes was carried out from the plotting of the joint discontinuities on a stereoplot. It was found that out of six potential slopes, 4 slopes (Srinivasapuram slope, Annanagar slope and Ananthagiri slopes) did not indicate possibility of either plane mode of failure or wedge mode of failure. The remaining 2 slopes namely, Gandhipuram slope and Coalkers' walk slope, showed potential plane mode of failure and accordingly the analysis was carried out. The result of rock stability analysis of both these slopes indicated a FOS of more than 2 for the rock slopes of Gandhipuram and Coalkers' Walk slopes indicating stable condition.

Similarly M. M. Street slope of Naidupuram Block and Observatory slope of the Pudukkad Block were also analysed for potential rock failure. It was found that from the Kinematic analysis, the slopes did not show plane or wedge modes of failure.

Talus Failure Analysis

The talus slope of the Srinivasapuram slope, Annanagar slope and Ananthagiri slopes of the Gandhipuram block was analysed for talus failure. In particular, two sections were prepared in the Ananthagiri slope as the slope was very wide and highly urbanized. The thickness of the overburden material was found to range between 2m -5m in all these slopes. From the talus failure analysis, even though the slope is stable in dry condition, it is only marginal with FOS ranging from 1.07 to 1.14. When analysed under wet condition (~25% saturation), the slopes are mostly unstable or just have an FOS of 1. Srinivasapuram and Ananthagiri Section 1 and 2 are the slopes that are marginally stable under both dry and saturated condition. The Annanager slopes, though stable under dry condtion are unstable with FOS of 0.95.

Similarly M M Street slope of Naidupuram Block and Pudukkad slope of the Pudukkad Block were also analysed for potential talus failure. It was found that the FOS ranges from 1.13 to 1.15 in case of dry condition and the slope is just stable with FOS of 1.02 to 1.04 in case of saturated condition. Taking into consideration the field conditions, suitable control measures have also been indicated.

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ANNEXURES I

Description of inherent parameters for individual facets for Rock Slopes							
Facet No.	**Orientation**	**Lithology**	**Structure**		**LULC**	**Hydro Condition**	**Relative Relief**
			In-situ rock	**Overburden**			
6	32°/N129°	Charnockite	J_1: 31°/N255°; J_2: 73°/N0°; J_3: 5°/N50°;		Barren	Dry	190
10	42°/N170°	Charnockite	J_1: 17°/N260°; J_2: 35°/N320°; J_3: 85°/N220°;		Barren	Dry	260
16	37°/N125°	Charnockite with thin debris	J_1: 75°/N125°; J_2: 40°/N340°; J_3: 15°/N310°		Top portion is highly urbanised, followed by cultivated land	Damp	280
17	48°/N88°	Charnockite with thin debris	J_1: 60°/N140°; J_2: 40°/N170°; J_3: 5°/N150°		Right half is highly urbanised with moderate vegetation. Left half is cultivated land	Damp	335
30	34°/N133°	Charnockite with thin debris	J_1: 72°/N210°; J_2: 85°/N160°; J_3: 20°/N90°; J_4: 64°/N130°		Highly urbanised at lower reaches with moderate vegetation	Damp	130
31	28°/N317°	Charnockite with thin debris	J_1: 60°/N110°; J_2: 85°/N180°; J_3: 90°/N45°; J_4: 40°/N0°		Highly urbanised	Damp	100
32	26°/N138°	Charnockite with debris	J_1: 70°/N240; J_2: 45°/N320°; J_3: 75°/N130°		Highy urbanised	Damp	255
33	35°/N135°	Charnockite with thin debris	J_1: 62°/N355°; J_2: 25°/N220°; J_3: 70°/N110°; J_4: 25°/N105°		Moderately vegetated along with cultivated land	Damp	430
35	16°/N145°	Charnockite with thin debris	J_1: 10°/N170°; J_2: 45°/N300°; J_3: 80°/N320; J_4: 7°/N125°		Highly urbanised	damp	205

38	14°/N142°	Charnockite Upper reaches rock with debris	J_1: 50°/N100°; J_2: 70°/N170°; J_3: 8°/N300°		Moderately vegetated	damp	80
45	47°/N147°	Charnockite with thin debris	J_1: 65°/N350°; J_2: 70°/N90°; J_3: 80°/N174°; J_4: 20°/N120°		Sparsely vegetsted	damp	510
51	20°/N55°	Charnockite with thin debris	J_1: 75°/N40°; J_2: 72°/N100°; J_3: 14°/N20°; J_4: 25°/N120°; J_5: 70°/N310°		Moderate to sparselyly veg. With cultivated land and sparsely urbanised	damp	160
56	26°/N143°	Charnockite with debris	J_1: 80°/N300°; J_2: 90°/N270°; J_3: 55°/N270°; J_4: 80°/N70°		Upper reaches consists of sparsely urbanised area and lower reaches are cultivated land	damp	495
57	47°/N150°	Charnockite with debris	J_1: 70°/N250°; J_2: 65°/N320°; J_3: 70°/N0°;		Sparsely vegetated	damp	350
59	38°/N190°	Charnockite with debris	J_1: 70°/N50°; J_2: 75°/N135°; J_3: 80°/N230°; J_4: 75°/N140°		Sparsely vegetated	damp	170
66	14°/N240°	Charnockite with thin debris	J_1: 18°/N0°; J_2: 65°/N260°; J_3: 18°/N120°; J_4: 60°/N40°		Sparsely urbanized with cultivated land	damp	85
67	14°/N47°	Charnockite with thin debris	J_1: 60°/N320°; J_2: 5°/N270°; J_3: 15°/N260°; J_4: 35°/N235°; J_5: 70°/N0°		Sparsely urbanized with cultivated land	damp	60
68	31°/N130°	Charnockite with thin debris	J_1: 60°/N40°; J_2: 18°/N140°		Sparsely urbanized with cultivated land	damp	95
69	17°/N144°	Charnockite with thin debris	J_1: 10°/N0°; J_2: 8°/N40°; J_3: 52°/N300°; J_4: 17°/N160°; J_5: 65/°/N40°		Moderately veg	damp	100

70	16°/N132°	Debris with rock exposure	J_1: 31°/N255°; J_2: 73°/N0°; J_3: 5°/N50°; J_4: 90°/N200°		RHS shows rock exposure, sparsely urbanized with cultivated land	damp	155
75	18°/N203°	Debris with rock exposure	J_1: 65°/N300°; J_2: 90°/N270°; J_3: 55°/N0°; J_4: 80°/N70°		Sparsely vegetated	damp	105
86	40°/N158°	Charnockite	J_1: 10°/N270°; J_2: 8°/N40°; J_3: 52°/N300°; J_4: 50°/N160°; J_5: 65°/N40°; J_6: 65°/N300°; J_7: 80°/N130°		Sparsely vegetated	damp	190
96	38°/N108°	Charnockite with thin debris	J_1: 25°/N120°; J_2: 54°/N340°; J_3: 10°/N75°; J_4: 17°/N 260°; J_4: 35°/N320°		Moderately vegetation with cultivated land and sparsely urbanised	damp	170

Description of inherent parameters for individual facets for Soil Slopes							
Facet No.	**Orientation**	**Lithology**	**Structure**		**LULC**	**Hydro Condition**	**Relative Relief**
			In-situ rock	**Overburden**			
1	7°/N240°	Dom. Debris	-	2-3m	Cultivated land	Damp	50
2	22°/N330°	Dom. Debris	-	5-6m	Cultivated land	Damp	225
3	14°/N324°	Dom. Debris	-	8-10m	Cultivated land	Damp	90
4	14°/N280°	Dom. Debris	-	7m	Cultivated land	Damp	195
5	21°/N165°	Dom. Debris	-	5-6m	Cultivated land	Damp	110
7	30°/N318°	Dom. Debris	-	5-6m	Cultivated land	Damp	145
8	13°/N242°	Dom. Debris	-	5-6m	Cultivated land	Damp	95
9	17°/N284°	Dom. Debris	-	5-6m	Cultivated land	Damp	115
11	11°/N164°	Dom. Debris	-	6m	Heaviliy urbanised at upper reaches and cultivated land at lower reaches	damp	80
12	14°/N214°	Dom. Debris	-	~10m	Eastern and lower reaches are heavily urbanised. Dom. Cultivated	damp	110
13	13°/N55°	Dom. Debris	-	~8m	Dom. Cultivated land, sparsely populated	Damp	75
14	11°/N350°	Dom. Debris	-	8m	Cultivated land	damp	60
15	20°/N254°	Dom.	-	6-7m	Moderately vegetated at lower reaches.	damp	135

		Debris			Cultivated land at uper reaches		
16							
17	48°/N88°	Dom. Debris			Cultivated land	damp	310
18	40°/N164°	Dom. debris	-	5-6m	Cultivated land	Damp	60
19	11°/N151°	Dom. debris	-	8m	Upper reaches consists of highly rbanised area and lower reaches are cultivaterd land	Dry	90
20	15°/N154°	Dom. debris	-	10m	Heavily urbanised along with cultivated land	dry	110
21	6°/N113°	Dom. debris	-	8m	Heavily urbanised along with cultivated land	dry	40
22	12°/N152°	Dom. debris	-	5-6m	Rhs is highly urbanised, followed by cultivated land	damp	100
23	32°/N336°	Dom. debris	-	4-5m	Moderately vegetated with urbanization at the western end	damp	210
24	30°/N75°	Dom. debris	-	>5m	Cultivated land with urabanisation	damp	305
25	27°/N106°	Dom. debris	-	>5m	Cultivated land with urabanisation	damp	200
26	14°/N123°	Dom. debris	-	>5m	Highly urbanised	dry	125
27	15°/N190°	Dom. debris	-	5-6m	Heavily urbanised along with cultivated land	damp	75
28	18°/N130°	Dom. debris	-	3-4m	Moderately vegetated with urbanization	dry	85
29	18°/N210°	Dom. debris	-	3-4m	Moderately vegetated	damp	195
34	39°/N114°	Dom. debris	-	3-4m	Highly urbanised	damp	215
36	21°/N136°	Dom. debris	-	5-6m	Moderately vegetated	Damp	70

37	13°/N186°	Dom. debris	-	4-5m	Moderately vegetated	damp	40
39	11°/N110°	Dom. debris	-	4-5m	Moderately vegetated	damp	90
40	11°/N24°	Dom. debris	-	>5m	Densely vegetated	damp	115
41	14°/N311°	Dom. debris	-	4-5m	High to moderately urbanised with cultivated land	Damp	60
42	12°/N37°	Dom. debris	-	5m	Highly urbanised	dry	55
43	12°/N217°	Dom. debris	-	3-4m	Highly urbanised	dry	35
44	15°/N321°	Dom. debris	-	>5m	Moderately vegetated	damp	60
46	23°/N340°	Dom. debris	-	~6m	Densely vegetated	Damp	130
47	27°/N171°	Dom. debris	-	5m	Densely vegetated	Damp	245
48	14°/N190°	Dom. debris	-	4-5m	Moderately vegetated with sp. Urbanization	dry	45
49	12°/N310°	Dom. debris	-	5m	Moderately vegetated with sp. Urbanization	dry	45
50	7°/N46°	Dom. debris	-	4-5m	Moderately veg. With cultivated land and sparsely urbanised	damp	40
52	32°/N15°	Dom. debris		8-10m	Densely vegetated	damp	110
53	11°/N173°	Dom. debris	-	8-10m	Sparsely urbanized with cultivated land	damp	50
54	25°/N310°	Dom. debris	-	5m	Densely vegetated	damp	85
55	16°/N85°	Dom. debris	-	5m	Densely vegetated	damp	145

58	11°/N280°	Dom. debris	-	4-5m	Moderately veg	damp	30
60	15°/N200°	Dom. debris	-	~7-8m	Densely vegetated	damp	50
61	17°/N80°	Dom. debris	-	5m	Densely vegetated	damp	55
62	10°/N68°	Dom. debris	-	5m	Densely vegetated	damp	35
63	19°/N20°	Dom. debris	-	7m	Densely vegetated	damp	115
64	19°/N190°	Dom. debris	-	6m	Densely vegetated	damp	85
65	15°/N210°	Dom. debris	-	6m	Densely vegetated	damp	140
71	23°/N115°	Dom. debris	-	7m	Densely vegetated	damp	110
72	15°/N166°	Dom. debris	-	7m	Densely vegetated	damp	95
73	15°/N300°	Dom. debris	-	7m	Cultivated land in the upper reaches and densely vegetated in the lower reaches	damp	80
74	14°/N230°	Dom. debris	-	7m	Cultivated land in the upper reaches and densely vegetated in the lower reaches	damp	70
76	16°/N30°	Dom. debris	-	7m	Densely vegetated	damp	35
77	12°/N146°	Dom. debris	-	7m	Densely vegetated	damp	75
78	23°/N90	Dom. debris	-	7m	Densely vegetated	damp	105
79	15°/N37°	Dom. debris	-	7m	Densely vegetated	damp	80
80	11°/N55°	Dom. debris	-	6m	Densely vegetated	damp	55

81	14°/N340°	Dom. debris	-	6m	Densely vegetated	damp	85
82	24°/N87°	Dom. debris	-	10	Densely vegetated	damp	80
83	17°/N65°	Dom. debris	-	11	Densely vegetated	damp	95
84	14°/N270°	Dom. debris	-	10	Densely vegetated	damp	50
85	18°/N10°	Dom. debris	-	12	Densely vegetated	damp	65
87	11°/N127°	Dom. debris	-	13	Densely vegetated	damp	70
88	15°/N330°	Dom. debris	-	14	Densely vegetated	damp	65
89	9°/N35°	Dom. debris	-	11	Densely vegetated	damp	30
90	13°/N137°	Dom. debris	-	12	Densely vegetated	damp	40
91	16°/N75°	Dom. debris	-	10	Densely vegetated	damp	105
92	15°/N240°	Dom. debris	-	13	Densely vegetated	damp	50
93	15°/N165°	Dom. debris	-	11	Densely vegetated	damp	60
94	16°/N175°	Dom. debris	-	14	Densely vegetated	damp	90
95	15°/N150°	Dom. debris	-	10	Densely vegetated	damp	95

Facet No.	Orientation	Lithology	Structure		LULC	**Slope Parameter**	Hydro Cond.	Rel. Relief
			In-situ rock	Overburden				
1	7°/N240°	Dom. Debris	-	2-3m	Cultivated Land	Very Favorable	Damp	50
2	22°/N330°	Dom. Debris	-	5-6m	Cultivated Land	Favorable	Damp	225
3	14°/N324°	Dom. Debris	-	8-10m	Cultivated Land	Very Favorable	Damp	90
4	14°/N280°	Dom. Debris	-	7m	Cultivated Land	Very Favorable	Damp	195
5	21°/N165°	Dom. Debris	-	5-6m	Cultivated Land	Favorable	Damp	110
7	30°/N318°	Dom. Debris	-	5-6m	Cultivated Land	Very Favorable	Damp	145
8	13°/N242°	Dom. Debris	-	5-6m	Cultivated Land	Very Favorable	Damp	95
9	17°/N284°	Dom. Debris	-	5-6m	Cultivated Land	Favorable	Damp	115
11	11°/N164°	Dom. Debris	-	6m	Heaviliy urbanised at upper reaches and cultivated land at lower reaches	Very Favorable	damp	80
12	14°/N214°	Dom. Debris	-	~10m	Eastern and lower reaches are heavily urbanised. Dom. Cultivated	Very Favorable	damp	110
13	13°/N55°	Dom. Debris	-	~8m	Dom. Cultivated land, sparsely populated	Very Favorable	Damp	75
14	11°/N350°	Dom. Debris	-	8m	Cultivated Land	Very Favorable	damp	60
15	20°/N254°	Dom. Debris	-	6-7m	moderately vegetated at lower reaches. Cultivated land at uper reaches	Favorable	damp	135
16						Favorable		

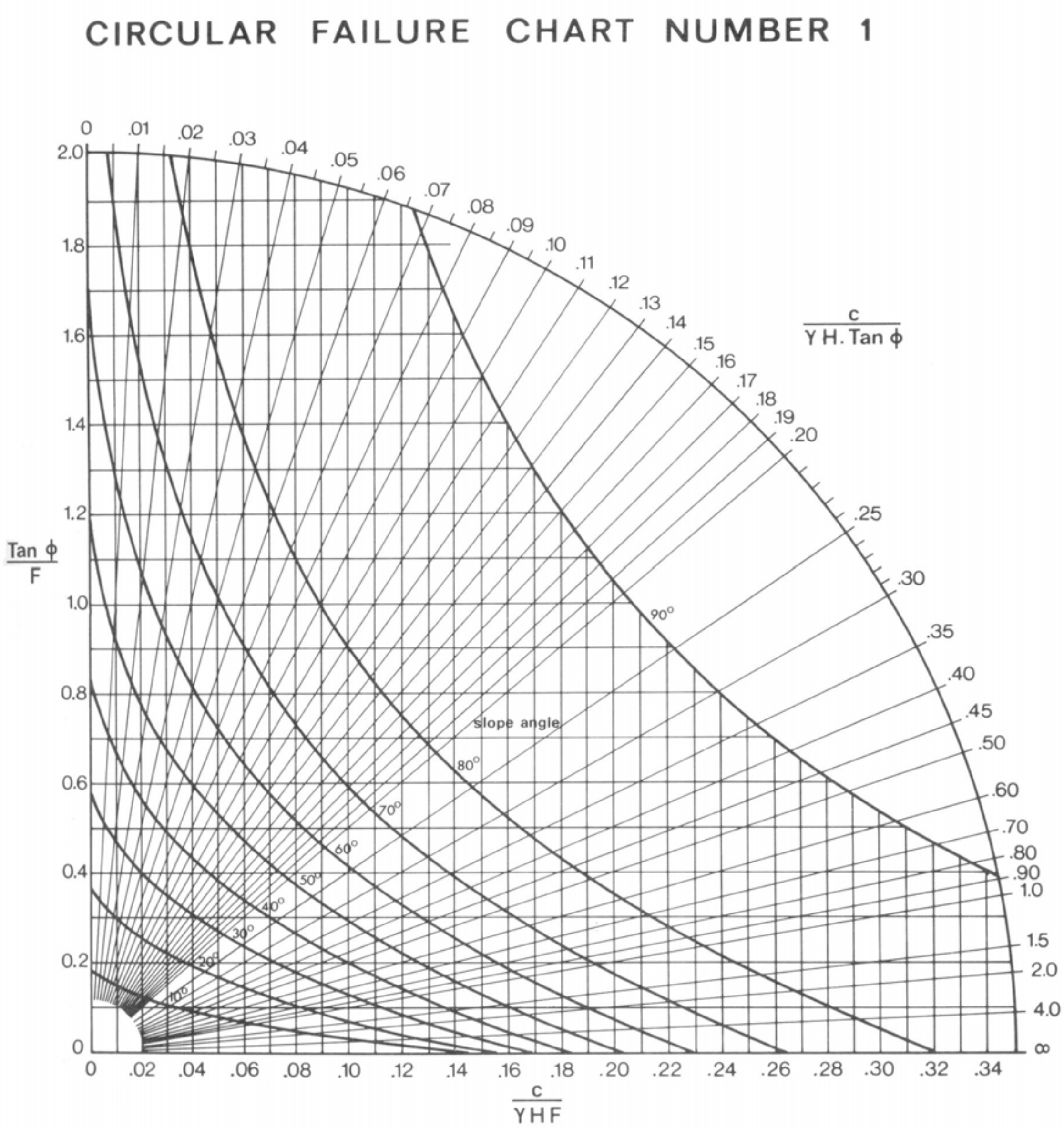
17	48°/N88°	Dom. Debris			Cultivated Land	Very Unfavorable	damp	310
18	40°/N164°	Dom. debris	-	5-6m	Cultivated Land	Moderately Favorable	Damp	60
19	11°/N151°	Dom. debris	-	8m	Upper reaches consists of Highly rbanised area and lower reaches are cultivaterd land	Very Favorable	Dry	90
20	15°/N154°	Dom. debris	-	10m	Heavily urbanised along with cultivated land	Very Favorable	dry	110
21	6°/N113°	Dom. debris	-	8m	Heavily urbanised along with cultivated land	Very Favorable	dry	40
22	12°/N152°	Dom. debris	-	5-6m	RHS is highly urbanised, followed by cultivated land	Very Favorable	damp	100
23	32°/N336°	Dom. debris	-	4-5m	Moderately vegetated with urbanization at the western end	Moderately Favorable	damp	210
24	30°/N75°	Dom. debris	-	>5m	Cultivated Land with urabanisation	Unfavorable	damp	305
25	27°/N106°	Dom. debris	-	>5m	Cultivated Land with urabanisation	Moderately Favorable	damp	200
26	14°/N123°	Dom. debris	-	>5m	highly urbanised	Very Favorable	dry	125
27	15°/N190°	Dom. debris	-	5-6m	Heavily urbanised along with cultivated land	Favorable	damp	75
28	18°/N130°	Dom. debris	-	3-4m	Moderately vegetated with urbanization	Favorable	dry	85
29	18°/N210°	Dom. debris	-	3-4m	moderately vegetated	Favorable	damp	195
33						Unfavorable		
34	39°/N114°	Dom. debris	-	3-4m	highly urbanised	Unfavorable	damp	215
36	21°/N136°	Dom. debris	-	5-6m	moderately vegetated	Favorable	Damp	70
37	13°/N1	Dom.	-	4-5m	moderately vegetated	Very Favorable	damp	40

	86°	debris						
39	11°/N1 10°	Dom. debris	-	4-5m	moderately vegetated	Very Favorable	damp	90
40	11°/N2 4°	Dom. debris	-	>5m	densely vegetated	Very Favorable	damp	115
41	14°/N3 11°	Dom. debris	-	4-5m	high to moderately urbanised with cultivated land	Very Favorable	Damp	60
42	12°/N3 7°	Dom. debris	-	5m	highly urbanised	Very Favorable	dry	55
43	12°/N2 17°	Dom. debris	-	3-4m	highly urbanised	Very Favorable	dry	35
44	15°/N3 21°	Dom. debris	-	>5m	moderately vegetated	Very Favorable	damp	60
46	23°/N3 40°	Dom. debris	-	~6m	densely vegetated	Favorable	Damp	130
47	27°/N1 71°	Dom. debris	-	5m	densely vegetated	Moderately Favorable	Damp	245
48	14°/N1 90°	Dom. debris	-	4-5m	moderately vegetated with sp. Urbanization	Very Favorable	dry	45
49	12°/N3 10°	Dom. debris	-	5m	moderately vegetated with sp. Urbanization	Very Favorable	dry	45
50	7°/N46 °	Dom. debris	-	4-5m	moderately veg. with cultivated land and sparsely urbanised	Very Favorable	damp	40
52	32°/N1 5°	Dom. debris		8-10m	densely vegetated	Moderately Favorable	damp	110
53	11°/N1 73°	Dom. debris	-	8-10m	sparsely urbanized with cultivated land	Very Favorable	damp	50
54	25°/N3 10°	Dom. debris	-	5m	densely vegetated	Favorable	damp	85
55	16°/N8 5°	Dom. debris	-	5m	densely vegetated	Favorable	damp	145
58	11°/N2	Dom.	-	4-5m	moderately veg	Very Favorable	damp	30

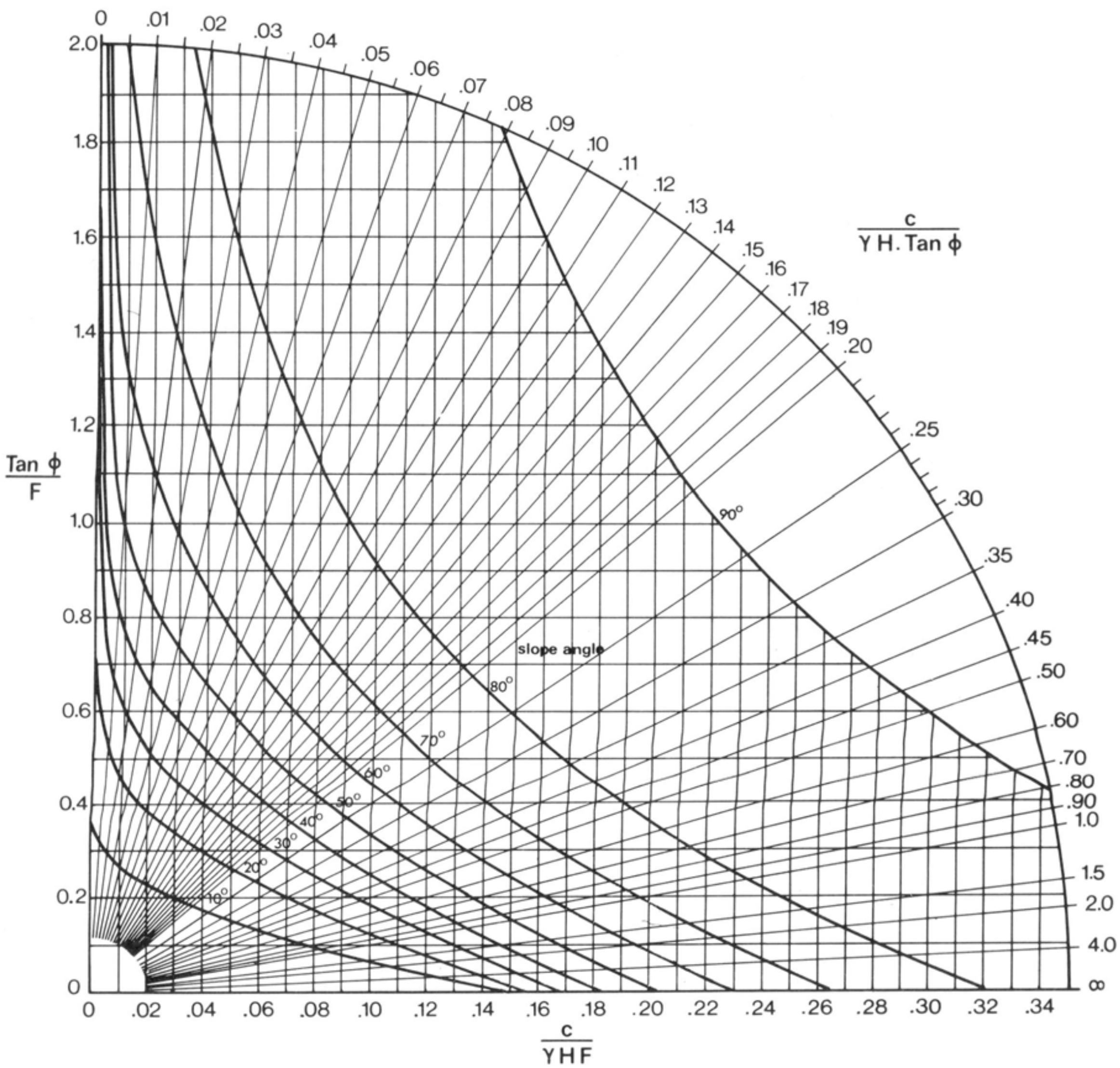
	80°	debris						
60	15°/N200°	Dom. debris	-	~7-8m	densely vegetated	Very Favorable	damp	50
61	17°/N80°	Dom. debris	-	5m	densely vegetated	Favorable	damp	55
62	10°/N68°	Dom. debris	-	5m	densely vegetated	Very Favorable	damp	35
63	19°/N20°	Dom. debris	-	7m	densely vegetated	Favorable	damp	115
64	19°/N190°	Dom. debris	-	6m	densely vegetated	Favorable	damp	85
65	15°/N210°	Dom. debris	-	6m	densely vegetated	Very Favorable	damp	140
71	23°/N115°	Dom. debris	-	7m	densely vegetated	Favorable	damp	110
72	15°/N166°	Dom. debris	-	7m	densely vegetated	Very Favorable	damp	95
73	15°/N300°	Dom. debris	-	7m	cultivated land in the upper reaches and densely vegetated in the lower reaches	Very Favorable	damp	80
74	14°/N230°	Dom. debris	-	7m	cultivated land in the upper reaches and densely vegetated in the lower reaches	Very Favorable	damp	70
76	16°/N30°	Dom. debris	-	7m	densely vegetated	Favorable	damp	35
77	12°/N146°	Dom. debris	-	7m	densely vegetated	Very Favorable	damp	75
78	23°/N90	Dom. debris	-	7m	densely vegetated	Favorable	damp	105
79	15°/N37°	Dom. debris	-	7m	densely vegetated	Favorable	damp	80
80	11°/N55°	Dom. debris	-	6m	densely vegetated	Very Favorable	damp	55
81	14°/N3	Dom.	-	6m	densely vegetated	Very Favorable	damp	85

	40°	debris						
82	24°/N87°	Dom. debris	-	10	densely vegetated	Favorable	damp	80
83	17°/N65°	Dom. debris	-	11	densely vegetated	Favorable	damp	95
84	14°/N270°	Dom. debris	-	10	densely vegetated	Very Favorable	damp	50
85	18°/N10°	Dom. debris	-	12	densely vegetated	Favorable	damp	65
87	11°/N127°	Dom. debris	-	13	densely vegetated	Very Favorable	damp	70
88	15°/N330°	Dom. debris	-	14	densely vegetated	Very Favorable	damp	65
89	9°/N35°	Dom. debris	-	11	densely vegetated	Very Favorable	damp	30
90	13°/N137°	Dom. debris	-	12	densely vegetated	Very Favorable	damp	40
91	16°/N75°	Dom. debris	-	10	densely vegetated	Favorable	damp	105
92	15°/N240°	Dom. debris	-	13	densely vegetated	Very Favorable	damp	50
93	15°/N165°	Dom. debris	-	11	densely vegetated	Very Favorable	damp	60
94	16°/N175°	Dom. debris	-	14	densely vegetated	Favorable	damp	90
95	15°/N150°	Dom. debris	-	10	densely vegetated	Very Favorable	damp	95

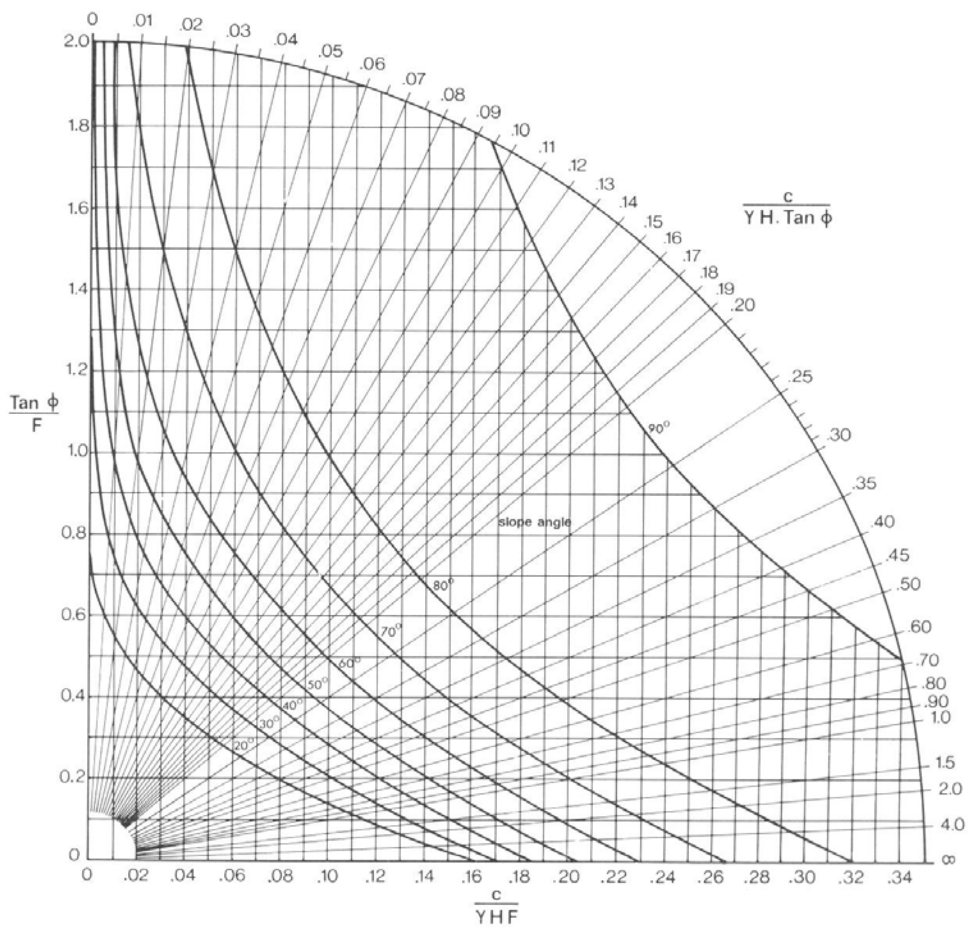
ANNEXURES II



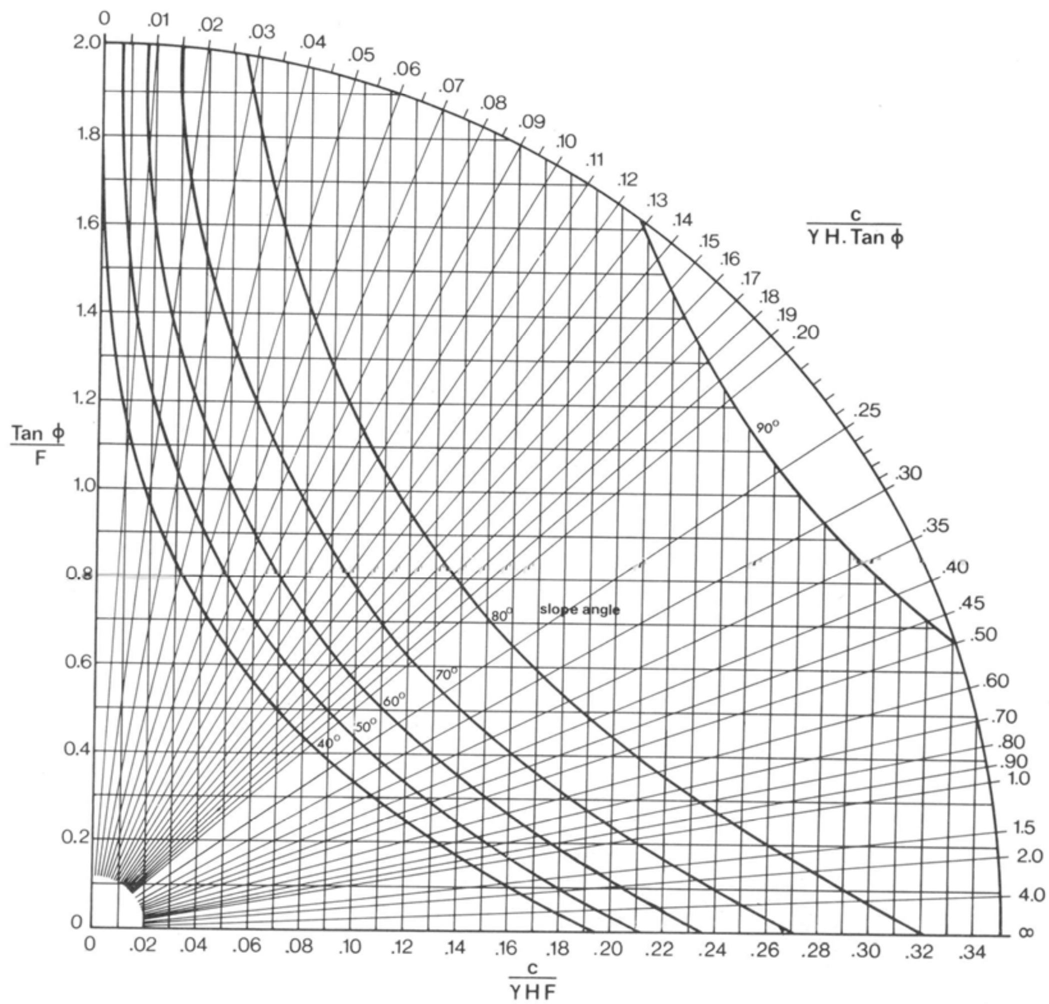
CIRCULAR FAILURE CHART NUMBER 2



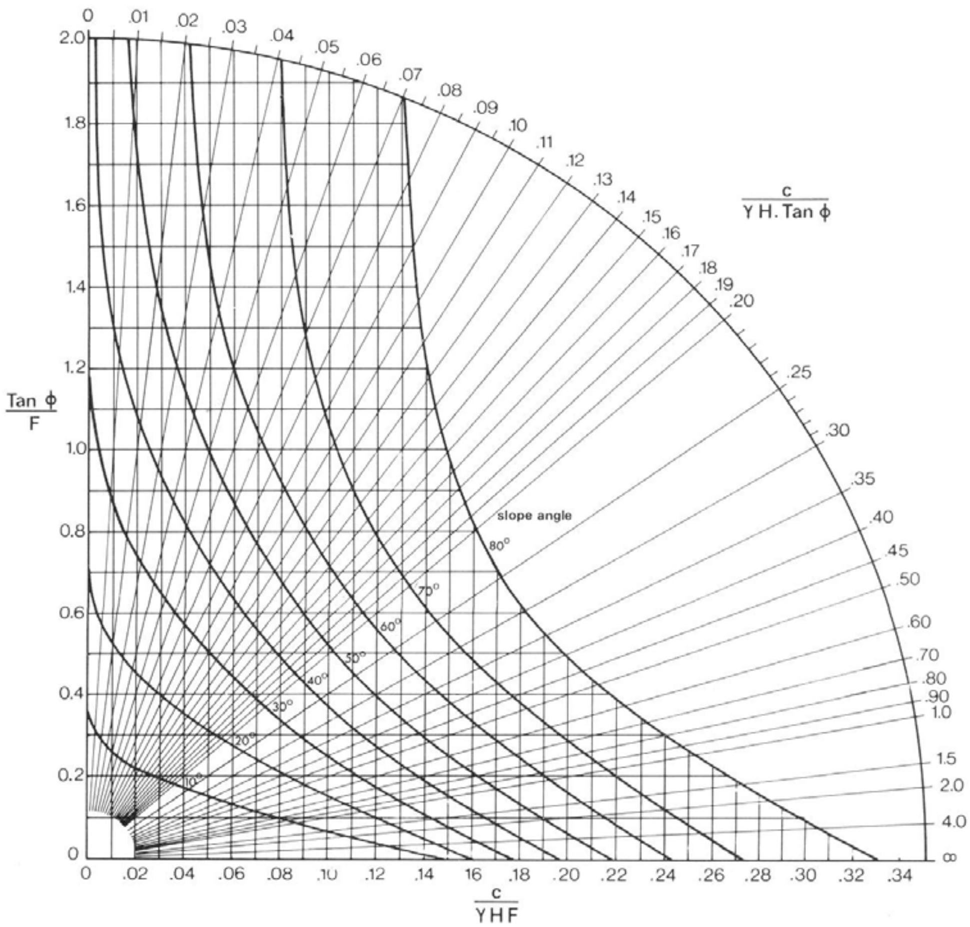
CIRCULAR FAILURE CHART NUMBER 3



CIRCULAR FAILURE CHART NUMBER 4



CIRCULAR FAILURE CHART NUMBER 5



ANNEXURES III

STABILITYANALYSIS OF ROCK SLOPE WITH CIRCULAR SLIP SURFACE IN KURINJI NAGAR

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~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
    UNITS USED          -> TONNE - METER - DEGREE
    INPUT FILE NAME     ->circin.dat
    OUTPUT FILE NAME    ->circout.dat
~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
 COORDINATES OF POINTS ALONG SLOPE ->

    X( 1)=    .00000    Z( 1)=    .00000
    X( 2)=  10.00000    Z( 2)=  15.00000
    X( 3)=  20.00000    Z( 3)=  20.00000
    X( 4)=  30.00000    Z( 4)=  35.00000
    X( 5)=  40.00000    Z( 5)=  45.00000
    X( 6)=  50.00000    Z( 6)=  55.00000
    X( 7)=  60.00000    Z( 7)=  65.00000
    X( 8)=  70.00000    Z( 8)=  75.00000
    X( 9)=  80.00000    Z( 9)=  95.00000
    X(10)=  90.00000    Z(10)= 105.00000
    X(11)= 100.00000    Z(11)= 115.00000
    X(12)= 110.00000    Z(12)= 120.00000
~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
 ROCK =   -25.000    RWL  =      .000    XS   =      .000    WI   =      .000
 ZC   =      .000    ZWR  =      .000
 C    =     3.700    PHI  =    35.000    GAMA =     1.800    GAMAW=     1.000
 BBAR =      .000    AH   =      .000    AVR  =      .000    EQM  =      .000
~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
 ENTX =      .000    ENTY =      .000
 NEP  = 0            NOPT = 0
 XEXITI=    30.000    XEXITL=    60.000    GAP  =    10.000
~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
 F.S   : DYN. :WEIGHT OF:AH CRI : COORDINATES OF   : COORDINATES OF    :RADIUS
*******:DIS(M):WEDGE(T) :TICAL  : CENTER(XC,YC)    : EXIT POINT        :R(M)
~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
 1.1627   .000   .13E+04   .092 (  -31.69,   89.45) (   60.00,   65.00)   94.89
 ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
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ANNEXURES IV

Slope stability of Gandipuram area - talus - wet

```
******************************************************************************
   UNITS USED          -> TONNE - METER - DEGREE
   INPUT FILE NAME     ->talusinn1.dat
   OUTPUT FILE NAME    ->talusout.dat

******************************************************************************

CASE NUMBER =    1
~~~~~~~~~~~~~~~~~~
C    =     .520   PHI  =   34.000   GAMA  =    1.800   GAMAW =    1.000
Z    =    4.000   ZW   =    3.000   SIF   =   34.000   AH    =     .000
AV   =     .000   EQM  =     .000   Q     =     .000   FS    =    1.300
~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
~~~~
FACTOR OF SAFETY WITH DIFFERENT CONDITIONS******     CRITICAL
DYNAMIC
                                        ACCELERATION DISPLACEMENT(M)
FS1(No Surcharge & E.Q.,But Dry)          =1.156
FS2(With Surcharge & W.T.,But No E.Q.)    =1.017
FS3(No Surcharge & E.Q. , But W.T.)       =1.017
FS4(No Surcharge , With E.Q. & Dry)       =1.156       .072            .00
FS5(No Surcharge , With E.Q. & W.T.[WORST]=1.017       .008            .00
~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
~~~~
Measure adopted to get required factor of safety ->

DEPTH OF EXCAVATION REQUIRED =   3.272  FOR FACTOR OF SAFETY(3)= 1.30
******************************************************************************
*
```

Slope stability of M. M. Street area - talus - wet

****
UNITS USED -> TONNE - METER - DEGREE
INPUT FILE NAME ->talusinn1.dat
OUTPUT FILE NAME ->talusout.dat

****

CASE NUMBER = 2
~~~~~~~~~~~~~~~~~~~~
C = .250 PHI = 35.000 GAMA = 1.800 GAMAW = 1.000
Z = 3.000 ZW = 2.500 SIF = 35.000 AH = .000
AV = .000 EQM = .000 Q = .000 FS = 1.300
~~~~~~
~~~~
**FACTOR OF SAFETY WITH DIFFERENT CONDITIONS****** CRITICAL DYNAMIC**
**ACCELERATION DISPLACEMENT(M)**
**FS1(No Surcharge & E.Q.,But Dry) =1.099**
**FS2(With Surcharge & W.T.,But No E.Q.) =1.006**
**FS3(No Surcharge & E.Q. , But W.T.) =1.006**
**FS4(No Surcharge , With E.Q. & Dry) =1.099 .046 .00**
**FS5(No Surcharge , With E.Q. & W.T.[WORST]=1.006 .003 .00**
~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
~~~~
Measure adopted to get required factor of safety ->

DEPTH OF EXCAVATION REQUIRED = 2.654 FOR FACTOR OF SAFETY(3)= 1.30
****
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~~~~

Slope stability of Srinivasapuram area - talus - wet

****
UNITS USED -> TONNE - METER - DEGREE
INPUT FILE NAME ->talusinn1.dat
OUTPUT FILE NAME ->talusout.dat

****

CASE NUMBER = 3
~~~~~~~~~~~~~~~~~~
C = .500 PHI = 35.000 GAMA = 1.800 GAMAW = 1.000
Z = 4.000 ZW = 3.000 SIF = 35.000 AH = .000
AV = .000 EQM = .000 Q = .000 FS = 1.300
~~~~~~
~~~~
**FACTOR OF SAFETY WITH DIFFERENT CONDITIONS****** CRITICAL DYNAMIC**
**ACCELERATION DISPLACEMENT(M)**
**FS1(No Surcharge & E.Q.,But Dry) =1.148**
**FS2(With Surcharge & W.T.,But No E.Q.) =1.009**
**FS3(No Surcharge & E.Q. , But W.T.) =1.009**
**FS4(No Surcharge , With E.Q. & Dry) =1.148 .069 .00**
**FS5(No Surcharge , With E.Q. & W.T.[WORST]=1.009 .004 .00**
~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
~~~~
Measure adopted to get required factor of safety ->

DEPTH OF EXCAVATION REQUIRED = 3.309 FOR FACTOR OF SAFETY(3)= 1.30
****
*
~~~~

Slope stability of Anna Nagar area - talus - wet

****
UNITS USED -> TONNE - METER - DEGREE
INPUT FILE NAME ->talusinn1.dat
OUTPUT FILE NAME ->talusout.dat

****

CASE NUMBER = 4
~~~~~~~~~~~~~~~~~~~~~~
C = .400 PHI = 34.000 GAMA = 1.800 GAMAW = 1.000
Z = 4.000 ZW = 3.000 SIF = 35.000 AH = .000
AV = .000 EQM = .000 Q = .000 FS = 1.300
~~~~~~
~~~~
FACTOR OF SAFETY WITH DIFFERENT CONDITIONS****** CRITICAL DYNAMIC
ACCELERATION DISPLACEMENT(M)
FS1(No Surcharge & E.Q.,But Dry) =1.082
FS2(With Surcharge & W.T.,But No E.Q.) = .948
FS3(No Surcharge & E.Q. , But W.T.) = .948
FS4(No Surcharge , With E.Q. & Dry) =1.082 .038 .00
FS5(No Surcharge , With E.Q. & W.T.[WORST]= .948 -.025 .00
~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
~~~~
Measure adopted to get required factor of safety ->

DEPTH OF EXCAVATION REQUIRED = 3.458 FOR FACTOR OF SAFETY(3)= 1.30
****
*
~~~~

Slope stability of Anandagiri area1- talus - wet
****
UNITS USED -> TONNE - METER - DEGREE
INPUT FILE NAME ->talusinn1.dat
OUTPUT FILE NAME ->talusout.dat

****

CASE NUMBER = 5
~~~~~~~~~~~~~~~~~~
C = .500 PHI = 38.000 GAMA = 1.800 GAMAW = 1.000
Z = 4.000 ZW = 3.500 SIF = 40.000 AH = .000
AV = .000 EQM = .000 Q = .000 FS = 1.300
~~~~~~
~~~~
**FACTOR OF SAFETY WITH DIFFERENT CONDITIONS****** CRITICAL DYNAMIC**
**ACCELERATION DISPLACEMENT(M)**
**FS1(No Surcharge & E.Q.,But Dry) =1.072**
**FS2(With Surcharge & W.T.,But No E.Q.) =1.007**
**FS3(No Surcharge & E.Q. , But W.T.) =1.007**
**FS4(No Surcharge , With E.Q. & Dry) =1.072 .036 .00**
**FS5(No Surcharge , With E.Q. & W.T.[WORST]=1.007 .004 .00**
~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
~~~~
Measure adopted to get required factor of safety ->

DEPTH OF EXCAVATION REQUIRED = 3.172 FOR FACTOR OF SAFETY(3)= 1.30
****
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~~~~

Slope stability of Anandagiri area2 - talus - wet

****
UNITS USED -> TONNE - METER - DEGREE
INPUT FILE NAME ->talusinn1.dat
OUTPUT FILE NAME ->talusout.dat

****

CASE NUMBER = 6
~~~~~~~~~~~~~~~~~~

C = .450 PHI = 38.000 GAMA = 1.800 GAMAW = 1.000
Z = 4.000 ZW = 3.500 SIF = 37.000 AH = .000
AV = .000 EQM = .000 Q = .000 FS = 1.300
~~~~~~
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FACTOR OF SAFETY WITH DIFFERENT CONDITIONS**** CRITICAL DYNAMIC**
ACCELERATION DISPLACEMENT(M)
FS1(No Surcharge & E.Q.,But Dry) =1.167
FS2(With Surcharge & W.T.,But No E.Q.) =1.095
FS3(No Surcharge & E.Q. , But W.T.) =1.095
FS4(No Surcharge , With E.Q. & Dry) =1.167 .080 .00
FS5(No Surcharge , With E.Q. & W.T.[WORST]=1.095 .045 .00
~~~~~~
~~~~

Measure adopted to get required factor of safety ->

DEPTH OF EXCAVATION REQUIRED = 3.118 FOR FACTOR OF SAFETY(3)= 1.30
****
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ANNEXURES V

Slope stability of M. M. Street -Plane failure

```
*****************************************************************
UNITS USED          -> TONNE - METER - DEGREE
INPUT FILE NAME     ->spin.dat
OUTPUT FILE NAME    ->spout7.dat
*****************************************************************
            CASE NO.    2
*****************************************************************

COHESION                              =   34.5000
RESIDUAL ANGLE OF FRICTION            =   38.0000
JOINT ROUGHNESS COEFFICIENT           =   10.0000
JOINT WALL COMP. STRENGTH             =  100.0000

HEIGHT                                =   45.0000
DIP OF JOINT PLANE                    =   17.0000
DEPTH OF WATER IN TENSION CRACK       =     .0000
COEFF. OF HORIZONTAL ACCELERATION     =     .0000
FOR EARTHQUAKE MAGNITUDE(RICHTER SCALE)=    .0000
UNIT WEIGHT OF ROCK                   =    2.6000
UNIT WEIGHT OF WATER                  =    1.0000
DEPTH OF TENSION CRACK                =   15.2650
SLOPE ANGLE                           =   35.0000

*****************************************************************
STATIC FACTOR OF SAFETY               =    6.0958
DYNAMIC FACTOR OF SAFETY              =    6.0958
DYNAMIC SETTLEMENT IN METER           =     .0000
CRITICAL ACCELERATION                 =    1.5580
FACTOR OF SAFETY - DRAINED SLOPE      =    6.0958
DYNAMIC FACTOR OF SAFETY-DRAINED SLOPE =   6.0958
SLIDING ANGLE OF FRICTION             =   42.4014

*****************************************************************
```

Slope stability of Coalker Walk- Plane failure

****
UNITS USED -> TONNE - METER - DEGREE
INPUT FILE NAME ->spin.dat
OUTPUT FILE NAME ->spout7.dat
****
CASE NO. 4
****

COHESION = 35.0000
RESIDUAL ANGLE OF FRICTION = 40.0000
JOINT ROUGHNESS COEFFICIENT = 12.0000
JOINT WALL COMP. STRENGTH = 120.0000

HEIGHT = 850.0000
DIP OF JOINT PLANE = 20.0000
DEPTH OF WATER IN TENSION CRACK = .0000
COEFF. OF HORIZONTAL ACCELERATION = .0000
FOR EARTHQUAKE MAGNITUDE(RICHTER SCALE)= .0000
UNIT WEIGHT OF ROCK = 2.6000
UNIT WEIGHT OF WATER = 1.0000
DEPTH OF TENSION CRACK = 460.3534
SLOPE ANGLE = 60.0000

UNREINFORCED SLOPE MAY FAIL BY OVERTOPPLING IF
CONTINUOUS CROSS JOINT DIPS MORE THAN 59. DEGREES

****
STATIC FACTOR OF SAFETY = 1.5928
DYNAMIC FACTOR OF SAFETY = 1.5928
DYNAMIC SETTLEMENT IN METER = .0000
CRITICAL ACCELERATION = .2158
FACTOR OF SAFETY - DRAINED SLOPE = 1.5928
DYNAMIC FACTOR OF SAFETY-DRAINED SLOPE = 1.5928
SLIDING ANGLE OF FRICTION = 28.6617

****

Slope stability of Observatory Road - Plane failure

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***********************************************************
UNITS USED          -> TONNE - METER - DEGREE
INPUT FILE NAME      ->spin.dat
OUTPUT FILE NAME     ->spout7.dat
***********************************************************
               CASE NO.    5
***********************************************************

COHESION                          =   29.0000
RESIDUAL ANGLE OF FRICTION            =   34.0000
JOINT ROUGHNESS COEFFICIENT           =   10.0000
JOINT WALL COMP. STRENGTH             =   94.0000

HEIGHT                            =   70.0000
DIP OF JOINT PLANE                  =   24.0000
DEPTH OF WATER IN TENSION CRACK       =     .0000
COEFF. OF HORIZONTAL ACCELERATION      =     .0000
FOR EARTHQUAKE MAGNITUDE(RICHTER SCALE)=     .0000
UNIT WEIGHT OF ROCK                  =    2.6000
UNIT WEIGHT OF WATER                  =    1.0000
DEPTH OF TENSION CRACK               =   19.0103
SLOPE ANGLE                        =   40.0000


UNREINFORCED SLOPE MAY FAIL BY OVERTOPPLING IF
CONTINUOUS CROSS JOINT DIPS MORE THAN   88. DEGREES

***********************************************************
STATIC FACTOR OF SAFETY              =    3.3073
DYNAMIC FACTOR OF SAFETY              =    3.3073
DYNAMIC SETTLEMENT IN METER           =     .0000
CRITICAL ACCELERATION                =    1.0273
FACTOR OF SAFETY - DRAINED SLOPE       =    3.3073
DYNAMIC FACTOR OF SAFETY-DRAINED SLOPE =    3.3073
SLIDING ANGLE OF FRICTION             =   37.5771

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Slope stability of Annanagar failure

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************************************************************
UNITS USED          -> TONNE - METER - DEGREE
INPUT FILE NAME     ->spin.dat
OUTPUT FILE NAME    ->spout7.dat
************************************************************
              CASE NO.    6
************************************************************

COHESION                        =   31.0000
RESIDUAL ANGLE OF FRICTION             =   36.0000
JOINT ROUGHNESS COEFFICIENT            =   11.0000
JOINT WALL COMP. STRENGTH              =  110.0000

HEIGHT                          =   70.0000
DIP OF JOINT PLANE                     =   22.0000
DEPTH OF WATER IN TENSION CRACK         =     .0000
COEFF. OF HORIZONTAL ACCELERATION       =     .0000
FOR EARTHQUAKE MAGNITUDE(RICHTER SCALE)=     .0000
UNIT WEIGHT OF ROCK                    =    2.6000
UNIT WEIGHT OF WATER                   =    1.0000
DEPTH OF TENSION CRACK                 =   36.1918
SLOPE ANGLE                     =   60.0000


UNREINFORCED SLOPE MAY FAIL BY OVERTOPPLING IF
CONTINUOUS CROSS JOINT DIPS MORE THAN   67. DEGREES

************************************************************
STATIC FACTOR OF SAFETY                =    2.8455
DYNAMIC FACTOR OF SAFETY               =    2.8455
DYNAMIC SETTLEMENT IN METER            =     .0000
CRITICAL ACCELERATION                  =     .7456
FACTOR OF SAFETY - DRAINED SLOPE       =    2.8455
DYNAMIC FACTOR OF SAFETY-DRAINED SLOPE =    2.8455
SLIDING ANGLE OF FRICTION              =   37.4683

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