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Different research techniques and models in rock mass rating and slope stability analysis

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ABSTRACT

Slope stability in Civil Engineering projects is a most important problem. Since 1920's techniques are persistent to stabilize a given slope. The analyses are habitually developed to assess safety of an excavated slope. In the 1950's, many researchers developed different methods like Bishop, Janbu and so on. Tremendous changes took place in the 1960's. Rock Mass Rating and Slope Stability analysis has provided a tremendous amount of information on stability of terrain. Rock or soil slope failure is highly important to prevent one of the important disasters in landslide which has affected many people of the society. This paper highlights different methods to identify slope instability failure and rating. In this paper, the author studies and discusses the available methods – Rock Mass Rating, Rock Mass Classification system and Slope stability analysis in detail. The article discusses the literatures available from 1950 to till date.

Key words: Rock Mass Rating, Slope Mass Rating, Slope stability.

INTRODUCTION

In civil engineering projects, slope stability is one of the most valuable and important problems, mostly present in large and small projects like construction of dams, highways tunneling and urban development in hill stations. This is one of the oldest problems known to civil engineering and its applications throughout history are wide and varied because, slope stability in hilly regions are easily affected and frequent failures are present all over the world. The studies were conducted in different countries and different types of methods were developed. Mountain slope failure, like landslides rock falls are natural activity, often seen in hill slope roads, hill stations, open cast mining areas and underground/tunnel areas. Wherever there is high rain fall, agricultural activities, abnormal erosion and seismic activities along the hill slope gradient it induces instability of hill slopes. Moreover, there is a presence of thick soil cover and highly fissile rock in various scales. Man-made activities like unplanned and improper construction practice of natural slope disturbs natural equilibrium of hill slope and increase the problem of slope instability.

Several factors induce slope instability. These factors can be broadly grouped into three categories: Preparatory factors, Triggering factors, and Controlling factors [76]. Using these factors, to identify landslide hazards, many Landslide Hazard Zonation methodologies are available in literatures [4, 17, 40, 41, 46, 75].

The main objective of this paper is to discuss slope stability analyses which were carried out in different researches in the past five decades. A review of previous works can be found in research articles such as, studies in earth slope by Taylor [83], Janbu [39] studies in embankment dam slope stability, analytical method discussed by Fredlung

[29], Rock slope stability assessed by Lysandros Pantelidis [48], Advanced numerical techniques reviewed by Doug Stead et al.[26], Rock mass rating classification analyzed by Aksoy [2], Current methods evaluated by Amin Pourkhosranai and Behzad Kalantari [3], Text books such as, Slope analysis, Development in Geotechnical Engineering by Chowdhury [19], Biotechnical and Soil Bioengineering Slope Stabilization: A practical guide for Erosion Control by Ray and Sotir [70], The stability of slope by Bromhead[14], Slope Stability and stabilization methods by Abramson et al.[1], Slope stability, Geotechnical Engineering and Geomorphology by Anderson and Richards [6], A Field manual for Landslide investigation by Anbalagan et al.[5], Engineering Rock Mass Classification by Bieniawski [8], Numerical methods for Engineers by Griffiths and Smith [30] and Rock Slope Engineering by Hoek and Bray [35]. In (Brown) 1981, ISRM (International Society of Rock Mechanics) suggested many methods, testing and monitoring the slope [15].

EXPERIMENTAL SECTION

METHODS USED TO PREVENT THE SLOPE INSTABILITY:

Survey of literature betrays that various techniques have been used to present the slope stability. These are classified as follows:

- Rock Mass Classification/Rock Mass Rating and Slope Mass Rating
- Slope Stability Analysis
- Recent Computer Programming Analysis Software.

1.1. Rock Mass Classification:

Rock Mass Classification is mainly used to authenticate the potential failure of rock cut slopes. A century ago, a first rating system was formalised on an empirical approach for tunnel by Ritter [71]. Later tunnel was designed by Terzaghi, and Lauffer proposed rock mass classification [84, 85]. Moreover, from 1972 to till date, many researchers have proposed and updated old and new methodologies, and many national and international level literatures and references are available. The methodologies further unfurl slope stability activities.

In rock mass classification system, most of the methodology is proposed to identify the quantitative condition of road slopes. It is broadly used in underground rock tunneling and road cut slopes. **Table 1** shows different empirical methods developed by different authors worldwide. According to different methodologies and researches four important types of factors have been identified. The first one is, factors mainly used for general condition of rock mass; second one is most commonly used factors like, compressive strength of rock, RQD, factors related to discontinuity, weathering, and groundwater conditions. This fundamental factor was proposed by RMR system [11, 12]. The third factor is mainly involved method of excavation. The last one is less important. The existing factors involving the rock mass classification are listed in **Table 2**.

The failure types of rock slopes have connection with smaller or mega tectonic discontinuities. The presence of discontinuity in rock cut slopes creates unstable conditions or creates abnormality condition [15]. Most of the methods used for slope stability assessment mainly depend upon the following factors.

1. Intact Rock Strength: This is an essential parameter and it is used in most of the methods. Moreover, it is present in all types of rocks and it controls its stability [11]. Intact rock strength is widely used in tunneling and mining areas [15].
2. RQD: This index was proposed by Deere to provide a quantitative estimation from drill core log [21]. The RQD mainly depends upon drilling machine, operator and core handling.
3. Groundwater condition: This is a representative factor in most of the methods used for calculating rating. It is observed by water seepage out of the slope faces.
4. Spacing of Discontinuities: The term covers joints, bedding or foliations, shear zones, minor faults or other surfaces of weakness. The linear distance between two adjacent discontinuities should be measured for all sets of discontinuities.
5. Condition of Discontinuities: This parameter includes roughness of discontinuities surface like its separation, length of continuity, weathering of the wall rock or the planes of weakness and infilling (gauge) materials [53].

Slope Mass Rating (SMR) is a system of classification developed by Romana as an application of Bieniawski - Rock Mass Rating [73, 8]. In order to assess slope instability, risk parameters covering attitude of discontinuities and slope, failure mode (Planar, Wedge and Toppling) and slope excavation methods are introduced. Rock mass quality is evaluated by RMR index. Based on the results, the slopes are classified into different instability classes with risks. ‘Slope Mass Rating’ is obtained from RMR by adding a factorial adjustment factor depending on the method of excavation. The final calculation is of the form

$$\mathbf{SMR = RMR_{basic} + (F1 \times F2 \times F3) + F4}$$

($RMR_{basic)}$ is computed according to Bieniawski proposal by adding rating values [10]. Adjustment rating for joints in rock slopes is a product of three factors:

i) F1 depends on parallelism between joints and slope face strikes. It is in range from 1.00 (when both are near parallel) to 0.15 (when the angle between them is more than 30°).
ii)F2 refers to joint dip angle in the planar mode of failure, in a sense, is a measure of the probability of joint shear strength. This value varies from 1.00 (for joint dipping more than 45°) to 0.15 (for joints dipping less than 20°)
iii) F3 reflects the relationship between slope face and joint dip. Conditions are fair when slope face and joint are parallel. When the slope dips 10° more than joints, very unfavorable condition occur.

The adjustment factor for the method of excavation F4 depends on whether one deals with a natural slope or one excavated by pre-splitting, smooth blasting, mechanical excavation, or poor blasting.

1.2. Slope Stability Analysis – Soil:
In late 1970’s and early 1980’s, slope stability analysis was conducted and some programmes were developed [29]. These previous methods have been improved and the solutions are given to limit upper and lower boundary. The limit is referred as plasticity of the contact or weaker plane. The lower boundary solutions mainly characterized by stresses and upper boundary solutions refer to displacement layer [55]. Worth grouped slope stability methods into i. limit formulation and ii. displacement formulation [88]. A number of slope stability analysis methodologies are available today; researchers must completely understand the strengths and limitations inherent in each methodology.

A few methods are given below:

Important soil slope stability methods:
1. Statistical Prediction model 1988 – Yin and Yan [90]
2. Deterministic Distributed Model 1984 – Brunsden and Prior [16]
3. Thaw Consolidation Theory 1973 – Mc Robets and Morgenstern [54]
4. Limiting Equilibrium Method 1970 – Coates [20]
5. Stability Analysis by Stereographic Projection Method 1981 – Hoek and Bray [35]
6. Stability Analysis of Slopes 1955 – Bishop [13]
7. BIO ENGINEERING approach 1995 – Morgan and Rickson [57]
8. Conventional Slope Stability Analysis 1978 – Chowdhury [19]
9. Reliability Analysis of slope using Fuzzy sets Theory 2000 – Dodagoudar and Venkatachalam [24]
10. Probabilistic and Hybrid Approaches 1976 – Biernatowski K [12]
11. New mark Model for Seismic 1964 – New Mark [60]
12. Stereographic and Kinematic Model 1981 – Hoek and Bray [35]
13. Variational Calculus Method 1965 – Dorfman [25]
14. Slope Stability Probability Classification (SSPC) 1998 – Hack [31]
15. Natural slope methodology (NSM) 1994 – Shuk [79]
16. Ordinary method of slice 1927 – Fellenius [27]
17. Morgenstern and Prices method 1965 – Morgenstern and Price [58]
18. Janbu’s generalized procedure of slices 1957 – Janbu [38]
19. Spencer’s method 1967 – Spencer [82]
20. Log spital method 1969 – Wright [89]
21. The force equilibrium methods 1960 – Lowe and Karafiath [47]

The important finding of slope stability analysis is the Factor of Safety (FOS) for potential failure of slope. FOS is >1, the slope is stable and if it is less than or equal to 1 the slope is unstable.

2. COMPUTER PROGRAMMING ANALYSIS SOFTWARE:

Since 1970's, rock and soil slope stability analysis calculations were done in a small calculator or graphical methods. After the mainframe computer, Fortran and Cobal program were in-house with small programs. In the present scenario, a very vast range of equilibrium methods to sophisticated coats are available to test stability of rock slope, stability of soil slope and mixed with rock and soil slope. Recently every scientist has a personnel computer with very high configuration and does complex analysis of rock and soil slopes. In this section, a few available softwares in the market and research works are discussed.

RocScience (1976) is a pioneer company to develop slope stability software. They developed different models for rock, soil and structural analysis. The software is developed by RocScience Inc, Toronto, Ontario, Canada. A variety of softwares is given below:

DipAnalyst	Slide 6.0
Phase2 8.0	Swedge 5.0
Dips 6.0	RocFall 4.0
RocPlane	RocData
RocTopple 1.0	Examine 3D
RocSupport	Settle 3D
Unwedge	

GEO-SLOPE (1992) is the most adopted slope stability software in the world. The software is developed by GEO-SLOPE International Ltd., Calgary, Alberta, Canada. It is a CAD software programme for soil and rock and calculated factor of safety in different conditions using liquid equilibrium method. The available modules are present below:

Slope/W	Seep/W
Sigma/W	C Tran/W
Temp/W	Quake/W
Vadose/W	Air/W

Itasca (1996) Consultancy Group Inc., Minneapolis, has developed different modules using numerical analysis and it includes finite element method also. The modules are given below:

FLAC 3D	UDEC 3.0
3DEC	PFC 2D/3D

GALENA (1990) software was developed by Australian BAP Engineering Company. This software used Geomechanics algorithm in limit equilibrium method.

ELFEN 2D/3D is mainly used in intense fracture of mine blasting, failure of retaining wall, underground rock structure etc. It is mainly worked in numerical modeling techniques. It is developed by Rock Field Software Ltd., Swangea.

KB Slope and SAFEX software used in limit equilibrium technique follows all assumptions and also includes block theory techniques to assess critical key blocks. This is developed by Western Australian, Rock Technology Software Company, in Leederville.

ANASYS (10) contains two important modules - SAP is a 2 dimensional analysis module mainly used to investigate jointed rock mass slope behaviors and PLAXIS 2D is used to find soil slope stability.

GEO5 is a multipurpose software mainly used in Geotechnical analysis and design with analytical and FEM program. It is developed by Ram Caddsys Pvt. Ltd., Chennai, India.

nhance Engineering Solution, Hyderabad developed **Oasys Engineering multipurpose** software. It contains soil movement, piling, retaining wall analysis and Finite Element Analysis for Geotechnical applications.

RockPack III - Development of the ROCKPACK programs began in the 1980's as a tool for evaluating the safety and stability of rock slopes where stability is controlled by the orientations and characteristics of rock mass ***discontinuities***. Originally written as a series of DOS programs, they have grown in popularity and use throughout the years and evolved into this user-friendly Windows® based program.

Table 1 Existing Rock Mass Classification system Lysandros Pantelidis [48]

Name of the System	Abbreviation	Authors	Application	Comments
--	--	Ritter [71]	Tunnels	The first attempt for the formalization of an empirical approach to tunnel design.
Rock load	--	Terzaghi [84]	Tunnels	The earliest reference to the use of rock mass classification for the design of tunnel support.
Stand-up time	--	Lauffer [45]	Tunnels	Related to the stand-up time of an unsupported tunnel excavation.
Rock Quality Designation	RQD	Du Deer [21]	General	Component factor of many classification systems.
Rock Structure Rating	RSR	Wickham et al. [86]	Small tunnels	First rating system for rock masses.
Rock Tunneling Quality Index	Q	Barton et al. [7]	Tunnels	They are the most commonly used classification systems for tunnels. A raw rating adjustment for discontinuity orientation for application in slopes was added in the1 979 version of the RMR system
Rock Mass Rating	RMR	Bieniawski, [11, 12, 9, 8]	Tunnels and cuttings	
Mining Rock Mass	MRMR	Laubscher [42, 43, 44]	Mines	Based on RMR (1973)
Rating, Rock Mass Strength	RMS	Selby [77, 78] Moon and Selby [56]	Cuttings	Based on natural slope database.
Slope Mass Rating	SMR	Romana [73] Romana et al. [74]	Cuttings	Based on RMR (1979), The most commonly used classification system for slopes.
Slope Rock Mass Rating	SRMR	Robertson [72]	Cuttings	Based on RMR. The classification is provided for of weak altered rock mass materials from drill-hole cores.
Chinese Slope Mass Rating	CSMR	Chen [18]	Cuttings	Adjustment factors have been applied to the SMR system for the discontinuity condition and slope height.
Geological Strength Index, Modified Rock Mass Rating, Geological Strength Index	GSI M-RMR GSI	Hoek et al. [36] Unal [85] Hoek et al. [37] Marinols and Hoek [49, 50] Marinos et al. [51]	General Mines General	Based on RMR (1976) For weak, stratified, anisotropic and clay bearing rock masses. For non-structurally controlled failures.
Rockslope Deterioration Assessment	RDA	Nicholson and Hencher, [61] Nicholson et al. [62] Nicholson [63, 64, 65]	Cuttings	For shallow, weathering-related breakdown of excavated rock slopes.
Slope stability Probability Classification	SSPC	Hack[32] Hack et al. [33]	Cuttings	Probabilistic assessment of independently different failure rock slopes.
Volcanic Rock Face Safety Rating	VRFSR	Singh and Connolly [81]	Cuttings (temporary excavations)	For volcanic rock slopes to determine the excavation safety on construction sites.
Falling Rock Hazard Index	FRHI	Singh [80] Mazzaccola and Hudson [52]	Cuttings (temporary excavations) Natural slopes	Developed for stable excavations to determine the degree of danger to workers. A rock mass characterization method for the indication of natural slope instabilities.

Table – 2 Rock Mass Rating Classification systems Palmstrom[67]

Classification system	Form and type	Main applications	Reference
Terzaghi rock load classification system	Descriptive and behaviouristic form Functional type.	Design of steel support in tunnels	Terzaghi [84]
Lauffer's stand-up time classification	Descriptive form General type	Tunneling design	Lauffer H [45]
New Australian tunneling method (NATM)	Descriptive and behaviouristic form Tunneling concept	Excavation and design in incompetent (overstressed) ground	Rabcewicz [69] Muller and Pacher [59]
Rock classification for rock mechanical purposes	Descriptive form General type	Input in rock mechanics	Patching and Coates [80]
Unified classification of soils and rocks	Descriptive form General type	Based on particles and blocks for communication	Deer et al. [23]
Rock quality designation (RQD)	Numerical form General type	Based on core logging; used in other classification systems	Deer et al. [22]
Size-strength classification	Numerical form Functional type	Based on rock strength and block diameter, used mainly in mining	Franklin [28]
Rock structure rating classification (RSR)	Numerical form Functional type	Design of (steel) support in tunnels	Wickham et al [88]
Rock mass rating classification (RMR)	Numerical form Functional type	Design of tunnels, mines, and foundations	Bieniaws [11]
Q classification system	Numerical form Functional type	Design of support in underground excavation	Barton et al [7]
Unified rock classification system	Descriptive form General type	Use in communication	Williamson [87]
Basic geotechnical classification (BGD)	Descriptive form General type	General applications	Brown [15]
Geological strength index	Numerical form Functional type	Design of support in underground excavation	Hoek [34]
Rock mass index system (RMi)	Numerical form Functional type	General characterization, design of support, TMB progress	Palmstrom [66]

Glossary:
- Descriptive form: input to the system is mainly based on descriptions;
- Numerical form: input parameters are given numerical ratings according to their character;
- Behaviouristic form: input is based on rock mass behavior in a tunnels;
- General type: system is worked out to serve as a general characterization;
- Functional type: system is structured for a special application (for example, for rock support).

CONCLUSION

This paper briefly discusses and explains about rock slope, soil slope and software used in slope stability analysis. Eventually the degree of uncertainty and numerous methods and programs, confused many researches between slope stability factors and ratings. Accurate selection of methods/programs may be based on local conditions/ Terrain conditions, Triggering factors and potential mode of failures, strength and weakness of slope materials/lithology and limitations inbuilt in each methodology and Field knowledge according to the skill of researchers. The preliminary analysis with limited data RMR and SMR is more suitable. The detailed analysis requires more data and a comprehensive study of each layer.

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