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Stability analysis of a large slope overhanging the Vagli Basin (Tuscany, Italy)

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ABSTRACT

The Vagli arc-gravity dam (95.50m in high), in the Northern Apennines (Italy), was built in the early ’50s of the last century. Its basin contains about 34Mm^3 and is one of the largest hydroelectric basins in the peninsular, Italy. Early after the water in-filling, a large landslide developed on a slope of the basin. That resulted in a restriction, with the water level authorized only up 2/3 of the basin capacity. Recently, due to the increase of the petroleum costs and energy demand, a joint research program Universities-ENEL was established to overcome that restriction by verifying the real state of stability of that slope. The first step of the research was a detailed field geological, geostructural and geomechanical survey finalized to define the geological setting and the geomechanical model of the whole slope: the results showing a sub-horizontal setting of thin to thick bedded limestone and limestone with marls, with a thick debris cover. Seismic survey evidenced that near the surface rock-mass appear to be loosened for about a few tens of a meter. Critical analysis of the data from the monitoring performed in the last thirty years outlined movements in the order of about a few mm/y, which is in the range of a natural slope-dynamic. Critical field analysis and document reconstruction of the historical landslide points in favor of a large debris collapse due to the cut of a new road above the full-water-level. A decision was made to perform a full stability analysis of the whole slope according to the most recent geomechanical methods. The slope was analyzed by using a self-developed GIS tool suitable to apply the SMR and the Critical Equilibrium methods to each TIN-grid of the slope: it resulted into a generally stable but raveling slope, thus justifying the thick debris cover. The slope stability was also verified by means of numerical models, namely PHASE2 (© Rocscience Inc.): the slope resulted to be generically stable, but debris cover and loosened rock-mass appear to have a Stability Factor close to 1.3 in the slope segment between 500m and 600m above sea level. Here, some criticalities could grow up in the event of strong rainfall with water saturation of the slope or of a large earthquake.

1 INTRODUCTION

The Vagli arc-gravity dam is 95.50m in height and was built in the early ’50s of the XX century in the Edron creek Valley, Tuscany (Italy). Its basin contains about 34Mm3 and is one of the largest hydroelectric basins in the peninsular Italy. A first dam, 65.50m high, was built during the II World War (1941-1946) and was enlarged in the year 1952-1953 up to the height of 95.50m. The Vagli Basin allowed a yearly electric power production of about 120GWh.

Because the new basin top water level (560m a.s.l) resulted higher than the existing road, a new road was cut in the slope above (180m a.s.l) the top water level.

When the water in-filling reached the level of 550m a.s.l. some gliding events occurred in the slope cut by the new road (Figure 1, Figure 2 – both from Baschieri & Guli, 1956) .

As a consequence the National Dam Board allowed the basin to be used only with the water level below 548m a.s.l.; this restriction became permanent after the severe event of the Vajont basin in 1963.

In the early eighties, the whole slope was equipped with a monitoring control system constituted by: piezometers, inclinometers, distantiometers, estensimeters and topographic high precision survey.

Today, because of the increase of the cost of petroleum and energy demand, ENEL commissioned to the University a research project in order to overcome this restriction by verifying the real state of stability of that slope.

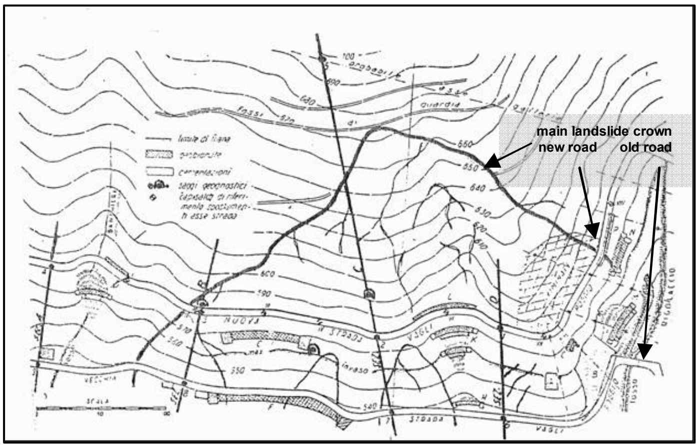


Figure 1: 1953' Landslides, old and new road, geological cross-section

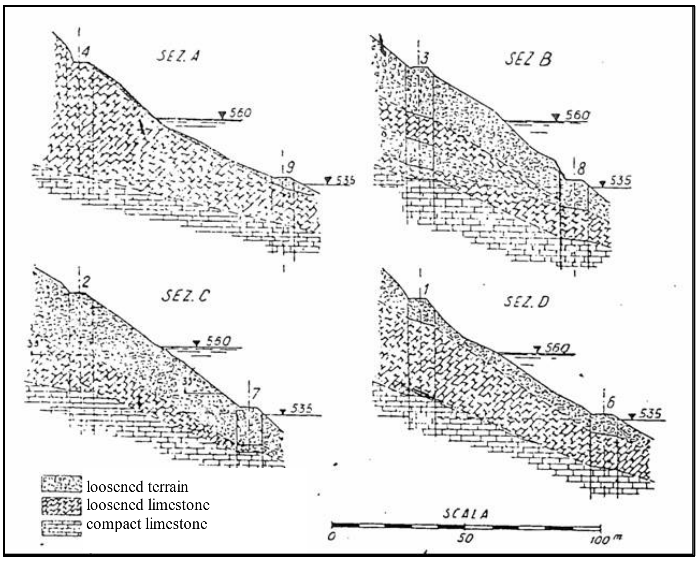


Figure 2: Geological cross-section along the slope

2 MONITORING

The instrumental monitoring that has been executed over 25 years has not displayed any severe shifting. The whole slope displays a systematic down-ward relaxing in the order of a few mm/y.

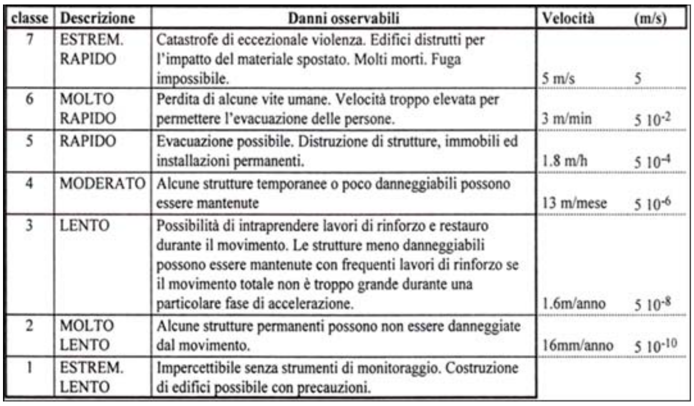
This entity of a movement falls into the range of the natural slope relaxing, according with the Cruden & Varnes (1996) landslide classification (Figure 3).

In this side of Tuscany, Garfagnana, geological survey led to verify that more than 40% of the territory is covered by landslides in different states of activity.

The monitoring data suggest that now the 1953 landslide is in a quiescent-stabilised state of activity.

3 GEOLOGICAL SETTING

The Vagli Basin is located in the Northern Apennines, in an area marked by a tectonic discharge towards the east of the Tuscan Nappe above the Apuan Alps core complex (Coli, 1989).



classe	Descrizione	Danni osservabili	Velocità	(m/s)
7	ESTREM. RAPIDO	Catastrofe di eccezionale violenza. Edifici distrutti per l'impatto del materiale spostato. Molti morti. Fuga impossibile.	5 m/s	5
6	MOLTO RAPIDO	Perdita di alcune vite umane. Velocità troppo elevata per permettere l'evacuazione delle persone.	3 m/min	$5\ 10^{-2}$
5	RAPIDO	Evacuazione possibile. Distruzione di strutture, immobili ed installazioni permanenti.	1.8 m/h	$5\ 10^{-4}$
4	MODERATO	Alcune strutture temporanee o poco danneggiabili possono essere mantenute	13 m/mese	$5\ 10^{-6}$
3	LENTO	Possibilità di intraprendere lavori di rinforzo e restauro durante il movimento. Le strutture meno danneggiabili possono essere mantenute con frequenti lavori di rinforzo se il movimento totale non è troppo grande durante una particolare fase di accelerazione.	1.6m/anno	$5\ 10^{-8}$
2	MOLTO LENTO	Alcune strutture permanenti possono non essere danneggiate dal movimento.	16mm/anno	$5\ 10^{-10}$
1	ESTREM. LENTO	Impercettibile senza strumenti di monitoraggio. Costruzione di edifici possibile con precauzioni.		

Figure 3: Cruden & Varnes (1996) landslide classification.

That resulted in a disharmonic behavior of the stratigraphic sequence of the Tuscan Nappe, expecially in the limestone and marls level of the Ferriera Frm, largely constituting the basin slope.

3.1 Stratigraphy

In the Vagli Basin area, above the Apuan Alps Core Complex metamorphic sequence, the Tuscan Nappe is constituted by dolostone and limestone (Turrite Frm – *Late Raetian-Early Hettangian*), limestone grading up ward to limestone and marls (Ferriera Frm - *Hettangian*) and by pelagic marls and calcareous shales (*Liassic* to *Cretaceous*). The slope of interest in the Ferriera Frm.

3.2 Tectonics

In the area of interest the general tectonic setting (Coli, 1996) is gently dipping towards NE (Figure 4).

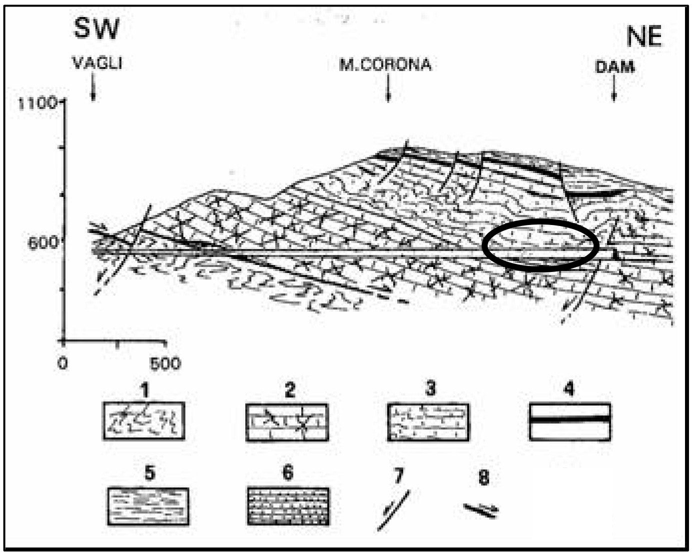


Figure 4: Geological cross-section of the slope of interest. Key: 1) Apuan Alps Core Complex; 2) Turrite and lower Ferriera Frms, with ubiquitary joints; 3) folded Ferriera Frm; 4) 5) pelagic marls and calcareous shales; 6) Oligocene sandstone; 7) normal fault; 8) detachement (modified from Coli, 1996).

The Tuscan Nappe displays an inhomogeneous behavior with strain partitioning according with the competence of the single formations. The basal limestones (Turrite and lower Ferriera Frms, with a ratio pelite/limestone <<1) acted as a rigid deck achieving the deformation with a flattening strain allowed by the development of two sets of ubiquitary sub-vertical joint trending respectively NW-SE and NE-SW (Figure 5).

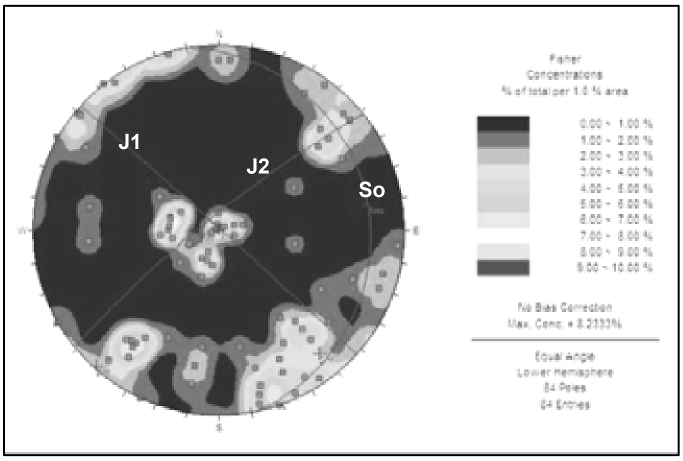


Figure 5: Bedding (So) and Joint setting (J1 and J2).

The mid most marly portion of the Ferriera Frm (p/l > 1) displays a diffuse metric to decametric disharmonic folding which reflects in the above marls and calcareous shales (p/l ≈ 1) into minor faults with at the most a decametric slip.

3 SEISMIC DATA

In order to investigate the underground rock-mass setting, a seismic survey was performed with the focus of defining the Vp values and seismic stratigraphy of the slope (Figure 6).

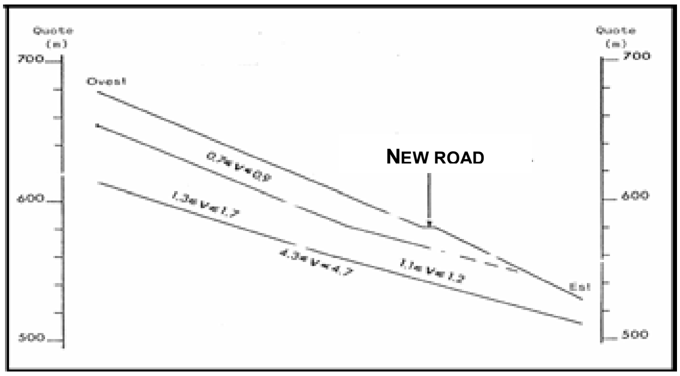


Figure 6: Seismic setting of the slope.

4 GEOMECHANICS

A geomechanic survey was carried out on the Turrite and Ferriera Frms outcropping on the slope of interest, according to the international standard (Bieniawski, 1973; 1979; 1984; 1989; Hoek, 1994; 2002; Hoek & Brown, 1997; Hoek et al., 2002; Marinos & Hoek, 2000; 2001) we defined the RMR and GSI values of the rock-masses constituting the slope.

According to Bieniawski (1979) the seismic Vp field data were matched with the intact rock laboratory Vp values in order to have an indirect estimation of the RMR (Figure 7).

Vp km/s	Vp / Vp intact rock	RMR
0,7	0,14	20
1,7	0,34	40
4,3	0,86	80

Figure 7: Seismic data (Vp) and RMR classification according with Bieniawski (1979).

Geological, geomechanical and seismic data, integrated with log data (Figure 8) led to define, according to the literature (Hoek, 1994; Hoek & Brown, 1997, Marinos & Hoek, 2000; 2001; Hoek, 2002; Hoek et al 2002) a geomechanical model of the slope which shows results divided into four rock-masses, respectively with GSI = 20; GSI = 45; GSI = 55 and GSI = 70 (Figure 9).

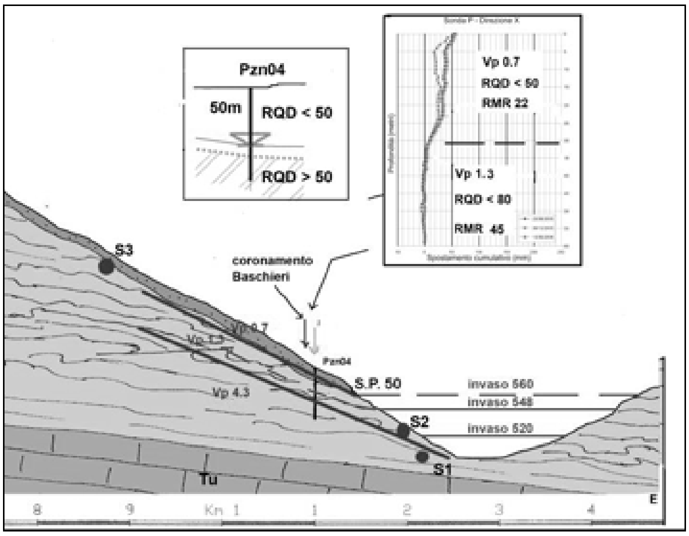


Figure 8: Integration of geological, geomechanical and seismic data.

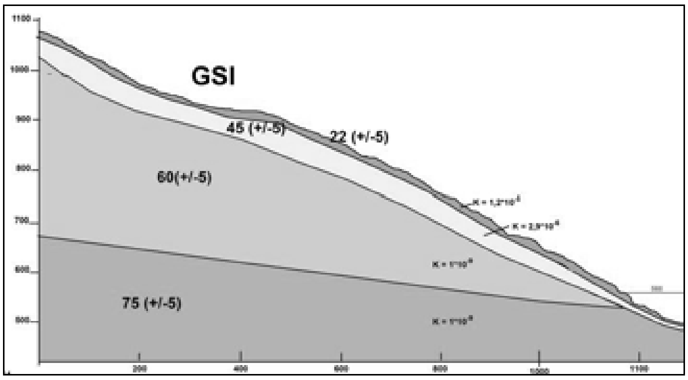


Figure 9: Geomecanical model of the slope.

Rock-mass geomecanical parameters were calculated, following Hoek et al. (2002), by means of RocData (©Rocscience Inc.) (Figure 10).

GSI	mi	mb	s	a	D	σ_c	σ_{cm}	E	To
22	10	0.033	1.62^{-6}	0.544	1		2.5	0.89	-0.5
45	10	0.604	0.0005	0.508	0.6	3	3	14.7	-0.12
60	10	2.000	0.0067	0.504	0	11.8	28.4	13	-0.5
75	10	3.434	0.0357	0.501	0	27	41	31.6	-1.5
						MPa	MPa	GPa	Mpa

Figure 10: Geomecanical values for each rock-mass type.

5 STABILITY ANALYSIS

5.1 Geometric analysis

The Markland (1963) and the Romana (1985) methods of geometric analysis were implemented into a self-developed GIS tool suitable to verify stability applying the SMR and the Critical Equilibrium methods to each TIN-grid of the slope.

On the basis of the relative hazard resulting for each TIN-grid it was possible to integrate Markland and Romana results in order to have a map of the maximum potential hazard of the slope to produce blocks and wedges.

This analysis was performed taking into account a naked slope: without cover and vegetation. It resulted into a generally stable but widespread ravelling slope, thus justifying the thick debris cover (Figure 11).

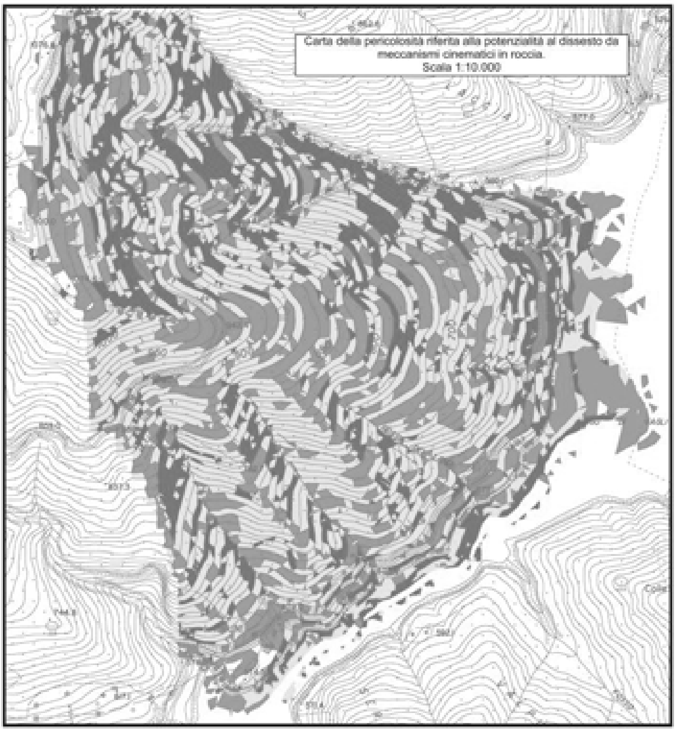


Figure 11: Cumulate wedge and block potential hazard for each TIN-grid of the slope.

5.1 FEM analysis

On the base of the results of the gemecanical analysis the whole slope was discredised in a triangular shaped mesh and a verification of the general stability was run by means of PHASE2 (© Rocscience Inc.) code (Figure 12).

Slope stability was verified for more water level in the basin (empty, 520m, 548m and 560m a.s.l.), for wet and dry conditions of the rock-mass and taking also into account the seismic local input.

The slope resulted to be generically stable, but debris cover (GSI = 22) and loosened rock-mass (GSI = 45) appear to have a Stability Factor close to 1.3 in the slope segment between 500m and 600m a.s.l., here some criticalities can grow up in the event of strong rainfall with water saturation of the slope or of a large earthquake.

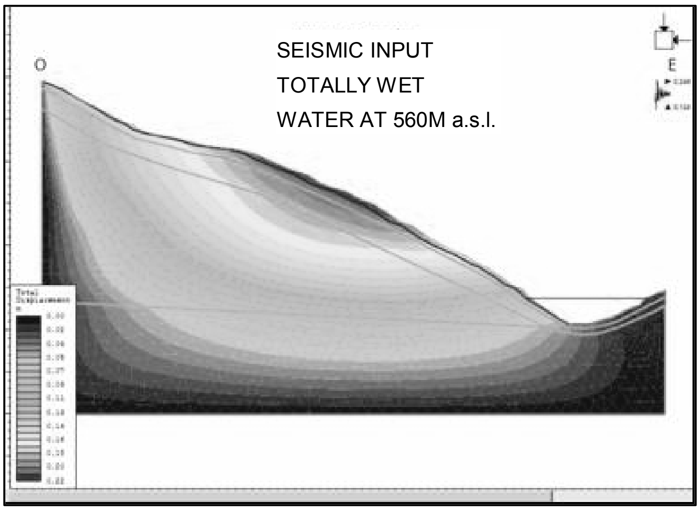


Figure 12: FEM analysis performed by means of PHASE2 (© Rocscience Inc.): result for the worst conditions.

6 CONCLUSIONS

In order to overcome a restriction on the potentiality of use of the Vagli Hydroelectric Basin ENEL commissioned to the Dept a detailed study project in order to verify the stability of a critical slope overhanging the basin.

On the basis of geological, geomechanical and geophysical studies it was verified that the slope had a general natural stable condition, with a natural downward shifting of the cortical debris in the order of a few mm/y.

The metric to decametrici thickness of the cortical debris is justified by the natural aptitude of the slope to ravel.

In the event of concomitant severe boundary conditions (strong rainfall, earthquake, high water level in the basin) the debris cover in the range 500-600m a.s.l. displays localized critical states.

The results of this study led the National Dam Board agreed to agree the basin to be used with the water level at 560m a.s.l.. But the Board link the effectiveness of the permit to a positive result of new stability analysis subsequent to further detailed seismic and geotechnical investigations devoted to exactly define the referencing parameters of the debris rock-mass and of the close loosened rock-mass in the outlined potential critical sites.

These investigations will be specifically devote to verify the importance of the occurrence of the localized less stable portions of the slope and to define the appropriate supports to be put on.

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REFERENCES

Baschieri L. & Gulì F. 1956 Notizie intorno alla frana di Vagli ed al suo consolidamento. *Geotecnica*, 122-130.

Bieniawski Z.T. 1973 Engineering Classification of Jointed Rock Masses. *Trans. S. Afr. Inst. Civ. Eng.*, 15, 335-344.

Bieniawski Z.T. 1979 The Geomechanics Classification in Rock Engineering Applications. *Proc. 4th Int. Congr. Rock Mech., ISRM, Montreux*, vol. 2, 41-48.

Bieniawski Z.T. 1984 *Rock mechanics design in mining and tunnelling. Chap.55*, Balkema, Rotterdam, 55-95.

Bieniawski Z.T. 1989 *Engineering Rock Mass Classification.* Jhon Wiley & Sons, Inc., New York, 251pp.

Coli M. 1989 Times and modes of uplift of the Apuane Alps metamorphic complex - Northern Apennines, Italy. *Atti Tic. Sc. Terra*, 32, 47-56.

Coli M. 1996 La tettonica estensiva nella Falda Toscana nella zona di Vagli, Garfagnana: considerazioni geodinamiche. *Boll. Soc. Geol. It.,* 115, 39-45.

Cruden D.M. &, Varnes D.J. 1996 Chapter 3: Landslides types and processes. In: *Landslides investigation and mitigation*. Turner & Schuster Eds., Special Rep. 247. Transportation Research Board – National Academy Press. U.S.A., , 77 pp.

Hoek E. 1994 Strength of rock and rock masses. *ISRM News Journal,* 2(2), 4-16.

Hoek E. 2002 Practical rock engineering. http://www.rocscience.com

Hoek E. & Brown E.T. 1997 Practical estimates of rock mass strength. *Int. J. Rock Mech. & Mining Sci. & Geomechanics Abstract*. 34(8), 1165-1186.

Hoek E., Carranza Torres C.T & Corkum B. 2002 Hoek-Brown failure criterion – 2002 edition. *Proc. North American Rock Mechanics Society meeting in Toronto in July 2002.*

Marinos P.G. & Hoek E. 2000 GSI: a geological friendly tool for rock mass strength estimation. *Proceedings of the International Conference on Geotechnical & Geological Engineering (GeoEng 2000),* Technomic Publishing Co. Inc., 1422-1440, Melbourne, Australia.

Marinos P.G. & Hoek E. (2001) Estimating the geotechnical properties of heterogeneous rock masses such as flysch. *Bull. Engg. Geol. Env*., 60, 85-92.

Markland J.T. 1963 A useful technique for estimating the stability of rock slopes when the rigid wedge sliding type of failure is expected. *Imperial College Rock Mechanics Research Report,* 19, 10 pp.

Romana M. 1985 New adjustment rating for application of the Bieniawski classification to slopes. *Proc. Int. Symp. Rock Mechanics Mining Civ. Works. ISRM, Zacatecas, Mexico*. pp 59-63.