ROCKFALL HAZARD AND RISK ASSESSMENT OF ROAD SLOPES

Andrianopoulos A.[1], Saroglou H.[1] and Tsiambaos G.[1]

[1] National Technical University of Athens, School of Civil Engineering, Dept. of Geotechnics, aandrian@tee.gr, saroglou@central.ntua.gr, gktsiamb@ central.ntua.gr

Abstract

This paper presents and compares the main methods of hazard and risk assessment for road slopes. Hazard assessment is achieved by rating several parameters such as the slope's geometry, traffic conditions, the geology and the rockmass properties, weather conditions, historical rockfall data etc. A hazard assessment can also be executed using 2D or 3D trajectory models, by combining the frequency of a rockfall and the kinetic energy of a falling rock. Several methodologies have been developed for risk assessment, varying from simplistic approaches to comprehensive probabilistic or quantitative risk assessment methods. Finally, the most suitable methods were used in order to assess the level of hazard and risk as an example (the data from two sections of the national road at Tempi Gorge, Greece) where many rockfall events occurred in the past few years.
Key words: RHRS, rating, Tempi, Geotechnical conditions.

Περίληψη

Οι καταπτώσεις βράχων σε οδικές αρτηρίες, οδηγούν σε σημαντικές επιπτώσεις και συνεπώς είναι ιδιαίτερα σημαντική η εκτίμηση του επιπέδου της επικινδυνότητας σε πρανή οδοποιίας και η λήψη μέτρων προστασίας.
Στην παρούσα εργασία συγκρίνονται οι σημαντικότερες μέθοδοι εκτίμησης της επικινδυνότητας και της διακινδύνευσης καταπτώσεων βράχων. Όσον αφορά την επικινδυνότητα, λαμβάνονται υπόψη παράμετροι όπως η γεωμετρία του πρανούς, οι κυκλοφοριακές συνθήκες, η γεωλογία και τα χαρακτηριστικά της βραχόμαζας, οι καιρικές συνθήκες, τα ιστορικά δεδομένα, κ.α. Εκτίμηση της επικινδυνότητας μπορεί επίσης να προκύψει μέσω δισδιάστατων ή τρισδιάστατων μοντέλων προσομοίωσης τροχιάς, όπου συνδυάζονται τα δεδομένα της συχνότητας βραχοπτώσεων με την κινητική ενέργεια του καταπίπτοντος τεμάχους βράχου. Όσον αφορά την εκτίμηση της διακινδύνευσης, έχουν αναπτυχθεί διάφορες μέθοδοι, που ποικίλουν από απλοϊκές προσεγγίσεις, έως ολοκληρωμένες πιθανολογικές ή ποσοτικές μέθοδοι. Τέλος, ως παράδειγμα, χρησιμοποιήθηκαν οι καταλληλότερες μέθοδοι εξ αυτών για την εκτίμηση της επικινδυνότητας και διακινδύνευσης από καταπτώσεις βράχων, σε δύο τυπικές διατομές της Εθνικής Οδού Αθηνών – Θεσσαλονίκης, στο τμήμα των Τεμπών, όπου έχουν καταγραφεί αρκετά συμβάντα καταπτώσεων βράχων τα τελευταία χρόνια.
Λέξεις κλειδιά: Καταπτώσεις, διακινδύνευση, γεωτεχνικές συνθήκες, Τέμπη.

1. Introduction

Rockfall phenomena often occur at highway road cuts in mountainous terrain. Until the mid 90's, the common practice for managing an unstable slope was to stabilize it after its failure (WSDOT, 2010). By recognizing the importance and the severity of rock falls and taking into account the difficulties arising from them, several researchers have developed both hazard and risk classification systems of unstable road cut slopes, based on visual observation, simple calculations and by estimating the rock mass properties through rock mass classification systems (Pantelidis, 2009). The purpose of these ratings is to identify the slopes with the highest level of hazard or risk and thus determine priorities for immediate mitigation measures or further detailed investigation. The most efficient and widely applied hazard and risk assessment methods are presented in this paper.

The principal landslide type in Greece is rockfall and usually occurs after heavy rainfalls or earthquake events. Rockfalls are more common in Western Greece, due to a combination of factors related to topography, geological and tectonic conditions, climate and human activities (Koukis et al., 1994). Indicatively, recent rockfall incidents occurred at Monemvasia historical site (Saroglou et al., 2008), at the archaeological site of Delphi (Marinos et al., 2005) and the severe rockfall at Tempi Gorge on the 17th of December 2009, which led to one human life loss and caused major problems on the national road network between Athens and Thessaloniki (Gazetas et al., 2010).

2. Hazard Assessment Methods

In terms of hazard rockfall analysis, one of the most widely used methods is the Rockfall Hazard Rating System, also known as RHRS (Pierson, 1991). RHRS is a standardized methodology, which sets rockfall project priorities.

The following should be executed in order to assess the hazard level (Pierson, 1991):

- Slope Survey. Accurate determination of the number and location of the rockfall sites. According to RHRS, a rockfall section is defined as "any uninterrupted slope along a highway where the level and occurring mode of rockfall are the same"
- Preliminary rating. The rockfall sections are categorized into three broad categories, shown in Table 1.

Table 1 – Preliminary Rating System – RHRS methodology (Pierson, 1991).

Criteria \ Class	A	B	C
Estimated potential for rock on roadway	High	Moderate	Low
Historical rockfall activity	High	Moderate	Low

- Detailed rating. 10 categories are evaluated, scored and summed. Slopes with higher scores present higher risk. These categories are presented in Table 2 and represent their contribution to the overall hazard. Each category is associated to a score of 3, 9, 27 or 81 depending on the severity of each category, which is representative of a continuum of points between 0 to 100. This exponential scoring system aims to a rapid and user-friendly way of distinguishing the hazardous sites.

Table 2 – Rating Categories of RHRS.

Rating Categories			
Slope Height*	Ditch effectiveness	Average Vehicle Risk*	Percent of Decision Sight Distance*
Roadway width including paved shoulders*	Block size / Volume of rockfall-event*	Climate and presence of water on slope	Rockfall History
Geological Characters			
Case 1		Case 2	
Structural condition	Rock friction	Structural condition	Difference in erosion rates

*Scored with values between 0 and 100, according to the NHI-RHRS

Based on the rating, suitable rockfall remedial measures are recommended and preliminary a cost estimate can be determined. It is noted that no recommendations on remedial action, depending on the hazard rating, are included in the RHRS system, since decisions on remedial action for a specific slope depend upon many factors such as the budget allocation for highway work, which cannot be taken into account in the ratings. However, literature data indicate that slopes with a rating of less than 300 can be considered as of very low priority while slopes with a rating greater than 500 are identified for urgent remedial action.

Pierson et al. (1993) proposed a slight modification of the initial RHRS known as the improved RHRS method (in this paper denoted as NHI-RHRS). This system allows scoring of parameters with values between 1 and 100, those marked with an asterisk (*) in Table 2. Using the full range of points instead of the set points, it allows greater flexibility in evaluating the relative impact of conditions that are extremely variable.

The NHI-RHRS was adapted to the requirements of the region of Tennessee and a new system was developed (in this paper denoted as TRHRS). The system focuses mainly on the geological characterization; by considering failure modes based on the standard failure mechanisms of rock slopes (Vanderwater et al., 2005).

Russell et al. (2008) proposed a modified RHRS method for Colorado region (in this paper denoted as CRHRS). This version of RHRS includes the categories shown in Table 3.

Moreover, equations were proposed from which the total hazard scores can be estimated from four of the RHRS parameters, depending on the slope type (Santi et al., 2009). Based on the total score and the geological character of the studied slope, the hazard level can be characterized as Low, Medium or High.

Singh (2004) developed a different approach in order to determine an index, known as Falling Rock Hazard Index (in this paper denoted as FRHI). The parameters taken into account and scored are the following: slope height, slope inclination, slope irregularities, rock condition, spacing of discontinuity, block size, volume of rockfall, excavation method and duration without remedy and rockfall frequency. The hazard level estimation is followed by the proposal of proper mitigation systems.

Saroglou et al. (2012) proposed a rating system, which is slightly based on the RHRS system, but it is not limited on roadway and railway slopes. It refers also to the effect of rockfalls on inhabited areas and estimates the hazard and the risk levels of a potential rockfall. This system involves 20,

appropriately weighted, parameters, grouped in categories according to the geometry of the slope, the geological conditions, the potential triggering mechanisms of the rock fall and the consequences of the hazard. Suggestions for support measures associated with the proposed risk rating assessment are also proposed in this system.

Table 3 – Rating Categories of the CRHRS.

Rating Categories				
Slope				
Slope Height	Rockfall Frequency	Average slope height	Launching features	Ditch Catchment
Climate				
Annual Precipitation	Annual freeze thaw cycles		Seepage/water	Slope aspect
Geology				
Sedimentary Rock: (degree of undercutting, jar slake, degree of interbedding)	Crystalline Rock: (rock character, degree of overhang, weathering grade)	Discontinuities: (block size/volume, persistence/orientation, aperture, weathering condition, friction.		Block in matrix: (block size, block type, vegetation)
Traffic*				
Sight Distance	Average vehicle Risk	Number of accidents		

*For rating the risk level

Abbruzzese et al. (2009) developed a methodology using 2D or 3D trajectory models based on Swiss case studies, in order to assess the hazard level. The hazard analysis is assessed by taking into account rock fall intensity, expressed by the total kinetic energy (translational and rotational) of the falling blocks, which is obtained by rock fall trajectory simulations and the return period, defined as the mean reference time within which a rock fall may occur (inverse of the mean rock fall frequency). According to a matrix diagram combining intensity and return period (shown in Figure 1), the rock fall hazard was classified into three levels: low, moderate, and high.

The methods described above are an indicative selection of the most important and widely applied hazard assessment methods. Depending on the special conditions of the rock slope that is analyzed, the user may find in the literature many different approaches that in some cases may be more appropriate and suitable for a particular case study.

3. Risk Assessment Methods

Many methods have been developed for the assessment of the level of risk of a rockfall.

A risk assessment method has been developed by the Washington State department of Transportation (WSDOT, 2010), (in this paper denoted as WSDOT system) in order to provide a methodology to rationally evaluate known unstable slopes. Following the same scoring principle of RHRS, 11 risk categories are scored with 3, 9, 27 or 81 (Huang et al., 2009). These categories include: the type of the problem that is evaluated (for Soil: cut or fill slope, erosion / settlement or piping / slow-moving landslides / rapid landslides or debris flows and for Rock: minor rockfall, good catchment / moderate rockfall, fair catchment / major rockfall, limited catchment, major

rockfall, no catchment), the average daily traffic, the decision site distance, the impact of failure on roadway, the average vehicle risk, the pavement damage, the failure frequency, the annual maintenance costs, the economic factor (detours distance) and the number of accidents in the last 10 years.

The Swiss Federal Roads Office – FEDRO, 2009, has developed another methodology for risk-based assessment, prevention and response to gravitational natural hazards on national roads. The methodology comprises of three parts:

1. Risk analysis – what could happen? This is made up of the hazard, exposure and consequence analysis.
2. Risk evaluation – what is allowed to happen?
3. Planning of measures – what needs to be done?

The risk analysis is broken down into the following steps:

1. Goals, system boundaries and preparatory work.
2. Hazard analysis: risk identification and impact analysis.
3. Exposure analysis.
4. Consequence analysis.
5. Risk calculation and representation.
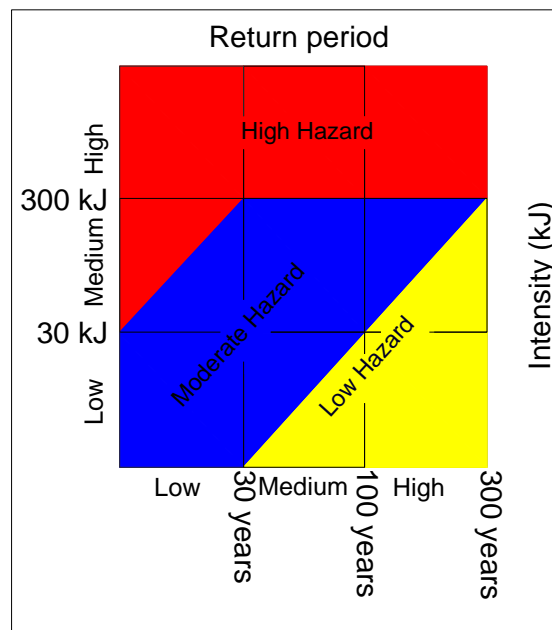
Figure 1 – Hazard level based on intensity – frequency diagram (Abbruzzese et al., 2009).

In FEDRO methodology, several different damage profiles can be assessed. These profiles are divided into direct and indirect damage. Direct damage refers to people that can be killed or injured as a result of a natural event and to endangered objects (e.g. buildings, infrastructure such as roads or railway tracks, power lines, pipes, green areas, etc.) that are buried, damaged or even destroyed by natural events. Indirect damage refers to the consequential damage, the costs resulting from interrupted operations or losses in earnings, damage to nature and the environment and objects to which an economic value cannot easily be assigned can also be affected, such as cultural objects that cannot be replaced either in full or in part when damaged.

Corominas et al. (2008) proposed a quantitative risk assessment method (in this paper denoted as QRA) in which the probability of occurrence of a rockfall is obtained by means of a statistical analysis of past events. While estimating risk in a quantitative manner, integration of the frequency analysis and the consequences is involved. The hazard frequency-magnitude relation has to be determined for the examined type of rockfall. The temporal spatial probability of vehicles and the vulnerability of the persons in the vehicles are calculated in order to estimate the risk. Therefore, the annual probability of the person at risk, which may lose his life by a rockfall event while driving on the road, can be determined.

4. Evaluating Hazard Assessment Methods

The RHRS method is the basis of the most hazard assessment methods. It is an approach that leads to an immediate and relatively user-friendly way of scoring the hazard level of the examined rock slope. In the scoring procedure, several critical parameters concerning the geological and the geometrical features are evaluated. The scoring system divides the influence of each parameter into four scoring areas (3, 9, 27, 81), following an exponential increase in the form of $y=3^x$. This results in an easier discrimination between slopes of low and high hazard level. However, the above separation impairs sensitivity analyzes, because if this analysis is performed over the whole scoring range of a parameter (3 to 81), it will lead to concrete results, the same as for any other parameter examined in the same scoring range. Finally, the scoring result is not interpreted and the hazard level is not categorized e.g. as high, medium or low.

The NHI-RHRS method is a slight variation of the initial RHRS method. A more detailed scoring system (range 1-100) is suggested on five main parameters, thus providing greater flexibility and greater accuracy to the rater, especially when performing sensitivity tests. However, if the level of uncertainty, when estimating a parameter, is high, the sensitivity test results will lead to a broader range between the minimum and the maximum level of hazard. Therefore, it is necessary that the user is trained and experienced enough, to avoid misjudgment.

The TRHRS method is also based on the initial RHRS, but the parameters' influence is differently weighted. The geological character is examined thoroughly by taking into account different kinds of failure modes, thus revealing the effect of the geology on the outbreak of a rockfall. However, in order to accurately rate a slope using this method, a thorough knowledge of the area is needed, which is translated to a sufficient amount of field data and monitoring systems.

The CRHRS method is a reliable and widely accepted method. As mentioned above, it is based on RHRS as well, but it is enriched with more parameters, concerning the slope's geometry, the climatic and the geological conditions. It also includes the four scoring areas (3, 9, 27, 81) with their respective advantages and disadvantages mentioned above. As for the geology, a distinction is made, depending on the rock type (sedimentary, crystalline structure, chaotic), thus enabling more targeted assessment on their characteristics. It requires a very good knowledge of the area to be rated, as it includes 19 scoring parameters. However, statistical analyses of large samples can lead to different weighting of each parameter and eventually some of them can be omitted. A main advantage of this method is that, depending on the geological character the final level of hazard can be divided to low, moderate or high, which helps the user to easily realize the level of hazard. The level of risk is also estimated using this method, however it is not as precise as that calculated from risk assessment methods but it is an indicative and convenient approach.

The Falling Rock Hazard Index (FRHI) was developed to determine the danger to workers and installations in the immediate vicinity of an excavated rock slope as a consequence of rock falls and therefore is not directly related to the hazard assessment of a rockfall at a road cut. Nevertheless, it is easily applicable and therefore can be used for a rapid forecast against rockfalls. The main feature that differentiates this method is that it includes the influence of the excavation method and therefore the disturbance of the rock mass, which leads to fragmentation and activation of rock falls.

The rockfall hazard and risk assessment method proposed by Saroglou et al. (2012) is based on morphological and structural criteria of rock mass and on vulnerability and consequences. It can be applied in any case and is not limited to road cuts. As it is not applicable only for road cuts, it is unable to estimate parameters such as the average daily traffic, the vehicle speed, the number of the passengers, etc. It includes many geological parameters that are to be evaluated, providing a fairly detailed assessment of the geological condition of the examined rock slope. This requires a thorough investigation of the area's geological conditions. The method introduces the influence of seismicity, since an earthquake is a triggering factor for a rockfall and needs to be taken into account when assessing the hazard and risk level in a seismic territory, like the Greek one. The method interprets its results in a qualitative way, providing direct information on the risk level.

The Swiss methodology that is based on 2D or 3D trajectory models is considered as a reliable tool when assessing the rockfall hazard level. It requires detailed topographic data as an input to the trajectory models and historical data in order to determine the return period. The method has set very low limits at the intensity of a rockfall, expressed as kinetic energy of falling rocks. Therefore, it could be concluded that it is not directly applicable, in its original form, for slopes with a significant height.

5. Evaluating Risk Assessment Methods

The WSDOT system is a risk assessment method that is based, as a concept, on the corresponding hazard assessment method of RHRS. The system evaluates four areas of scoring parameters, using the 3^x scoring system, with its respective advantages and disadvantages described earlier. A key element of this method is that it can be applied to both soil and rock slopes, thus providing a broad area of application. On the other hand, the method requires financial input data e.g. annual maintenance cost, which is a value that must be continuously adapted to the constantly changing financial environment, both considering the applied time period and the economic status of each country.

FEDRO methodology is considered in this paper as the most efficient method of probabilistic risk assessment. It is a highly detailed method and examines in detail the traffic conditions of the area, providing great adaptability on the special conditions of area under consideration. It is based on scenarios, such as the direct hit, collision, burial and availability scenario, thus allowing for almost all consequences of a rockfall incident. It enables risk assessment not only for people and vehicles, but for secondary facilities as well. Finally, the method takes into account the existence (or non-existence) of bypass roads and the traffic diversion through them, as it is a crucial parameter when calculating the consequences of a road been closed for remediation or restoration.

6. The Case of Tempi Gorge

The valley of Tempi is formed along a fault zone at a NE – SW direction, along Pinios River. The geological formations in the area are mainly crystalline limestones and locally phyllites. The natural terrain is developed at heights of 10 to 350m, with morphological gradients ranging from 20° to 75°. The national highway that connects Athens and Thessaloniki passes at an altitude of 13 to 50m, at the east steep road slopes, where unstable rock blocks with unfavourable orientation exist (Gazetas et al., 2010). During the period between 1997 and 2009, 31 rockfall incidents have been recorded approximately.

Two road sections have been studied in this area, assessing their level of hazard and risk, as an example: a) Section 1, at chainage 386+200 – 386+300 and b) Section 2, at chainage 387+060 – 387+160. The parameters used for the ratings are shown in Table 4.

For both sections, the hazard has been rated using methods RHRS, NHI-RHRS, CRHRS and the risk level has been assessed using QRA and FEDRO methodologies. In order to compare the hazard assessment methods, all hazard ratings were converted to % values.

It is noted, that, when using the FEDRO methodology, only the scenario of direct hit was calculated. For every method used, suitable sensitivity tests were performed in those parameters that considered as more critical, or of greater uncertainty.

The scoring results for hazard are presented in Figure 2 while the risk rating is presented in Table 5.

Table 4 – Parameters for risk rating in Tempi area.

Geology: thin bedded crystalline limestone, slightly weathered, with discontinuities of unfavorable orientation			
Annual Rainfall: 1800-2000mm			
Average daily traffic: 21500 vehicles, average speed: 70km/h			
Section 1		Section 2	
Slope height	90m	Slope height	55m
Average slope angle	60°	Average slope angle	70°
Road width	8.2m – no trench	Road width	10.4m – no trench
5 rockfall events in the past 13 years (maximum volume: 40m^3)		6 rockfall events in the past 13 years (blocks of 1-3m^3)	
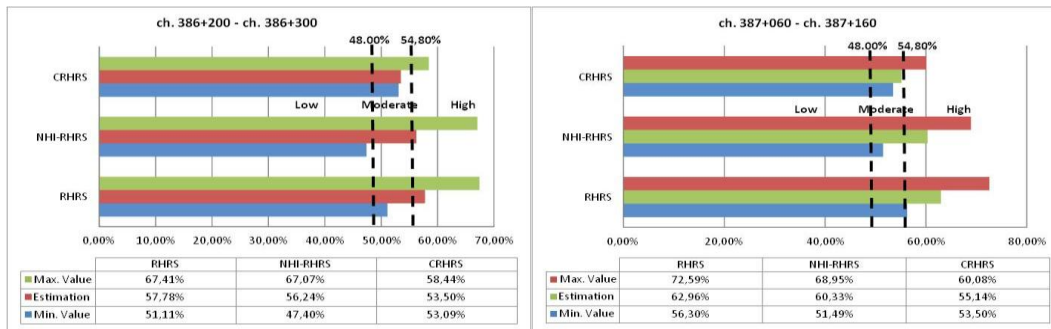
Figure 2 - Hazard rating results. The hazard level limits were set according to CRHRS method for crystalline rock type.

According to the rating results, the hazard level of Section 1 is determined as moderate (to high). Concerning the risk level, it is estimated that the possibility of a car hitting directly to a falling rock is 1.50×10^{-6} for a return period of 300 years and 1.60×10^{-7} for a return period of 10 years.

Respectively, the hazard level of Section 2 is estimated as high (to moderate). The possibility of a car hitting directly to a falling rock is estimated equal to 5.00×10^{-6} for a return period 300 years and 2.5×10^{-6} for a return period of 10 years.

In conclusion, the hazard level of both sections is high and a rock fall is possible to occur. On the other hand, the level of risk, when assuming that only the scenario of direct hit of a car on a falling rock might occur, is lower than the FEDRO's acceptable limits. Nevertheless, if more scenarios (collision, burial, availability) and the possibility of combined incidents are taken into account and calculated, then the level of risk will increase significantly.

Therefore, the appropriate mitigation measures should be applied in order to decrease both the hazard and the risk level of the studied area.

Table 5 – Risk rating results.

Method	Min. Value	Estimation	Max Value	Risk Level
Risk Assessment at Chainage 386+200 – 386+300				
FEDRO (Individual Risk)	Without 500 years scenario			High
	$1,04 \times 10^{-6}$	$1,49 \times 10^{-6}$	$2,09 \times 10^{-6}$	
	For 10 years			-
	$1,15 \times 10^{-7}$	$1,66 \times 10^{-7}$	$2,18 \times 10^{-7}$	
QRA	$4,00 \times 10^{-7}$	$5,71 \times 10^{-7}$	$8,00 \times 10^{-7}$	-
Risk Assessment at Chainage 387+060 – 387+160				
FEDRO (Individual Risk)	Without 500 years scenario			High
	$3,39 \times 10^{-6}$	$4,84 \times 10^{-6}$	$6,78 \times 10^{-6}$	
	For 10 years			-
	$1,68 \times 10^{-6}$	$2,40 \times 10^{-6}$	$3,36 \times 10^{-6}$	
QRA	$1,38 \times 10^{-7}$	$1,99 \times 10^{-7}$	$2,61 \times 10^{-7}$	-

Comparing the aforementioned hazard assessment methods, it is concluded that their results generally converge. According to the CRHRS method, hazard is underestimated in relation to the other two methods, but the difference between the minimum and maximum values is smaller, revealing the lower sensitivity of the method.

Concerning risk calculation, the risk level differentiates between methods at the two studied sections. The QRA method depends on the rockfall history, thus if insufficient rockfall data exist the result could be significantly different. In contrary, FEDRO's analytical risk rating overcomes the lack of precise rockfall records.

7. Conclusions

The significance of preventing rock falls, by taking proactive actions has led many researchers in developing methods to rate the hazard and the risk level of a rock slope.

The hazard assessment methods are mainly based on the RHRS system. Since its publication, many alternative methods have been developed, redefining the rated parameters in order to adjust in the special conditions of the area for which they were developed. The CRHRS method is considered as one of the most efficient methods, as it allows characterization of the hazard level and additionally results in a preliminary risk assessment. The hazard and risk assessment method proposed by Saroglou et. al. (2012), introduces the significance of the earthquake triggering effect on a rockfall, thus this method is more applicable when refering in seismic areas.

The risk assessment method that was developed by FEDRO Swiss authorities is considered as the most efficient when rating risk, due to the range of options available to approach the case study and the flexibility in adapting to the case study's conditions.

The main methods of assessing hazard and risk were used for two cross sections of the Tempi Gorge. The hazard level was determined as moderate and high respectively and the risk between 1.50 and 5.00×10^{-6} for a return period of 300 years and 1.60×10^{-7} and 2.5×10^{-6} for a return period of 10 years. The calculated levels of hazard and risk for the studied Sections denote the need for application of proper mitigation measures.

8. References

Abbruzzese J.M., Sauthier C. and Labiouse V. 2009. Considerations on Swiss methodologies for rock fall hazard mapping based on trajectory modeling, *Natural Hazards and Earth System Sciences (NHESS)*, 9, 1095-1109.

Corominas J. and Moya J. 2008. A review of assessing landslide frequency for hazard zoning purposes, *Engineering Geology*, 102, 193–213.

Federal Road Office (FEDRO) 2009. "Risk concept for natural hazards on national roads. Methodology for risk-based assessment, prevention and response to gravitative natural hazard on national roads", version 2009 V1.30, Confédération Suisse, ASTRA 89 001.

Gazetas G., Kavounidis S., Rozos D. and Tsiambaos G. 2010. Corollary Expert Committee for forfeitures in Tempi, *Technical Chamber of Greece*, (*in greek).*

Huang S., Darrow M. and Calvin P. 2009. Unstable Slope Management Program, Background Research and Program Inception, *Phase I Final Report*, Alaska Department of Transportation and Public Facilities, INE, Alaska.

Koukis G., Tsiambaos G. and Sabatakakis N. 1994. Slope movements in the Greek territory: A statistical approach, *Proc. of the 7th International Congress of the International Association of Engineering Geology*, Lisboa, Portugal, 7, 4621 – 4628.

Marinos P. and Rondoyanni Th. 2005. The archaeological Site of Delphi, Greece: a Site Vulnerable to Earthquakes, Rockfalls and Landslides, *Landslides*, 241-249.

Pantelidis L. 2009. Rock slope stability assessment through rock mass classification systems, *International Journal of Rock Mechanics & Mining Sciences*, 46, 315–325.

Pierson L. 1991. *The rockfall hazard rating system*. Oregon Department of Transportation.

Pierson L. and Vickle R. 1993. The rockfall hazard rating system. Participant's Manual. National Highway Institute, *NHI course No.130220*, FHWA SA-93-057.

Russell C., Santi P. and Higgins J. 2008. Modification and statistical analysis of the Colorado Rockfall hazard rating system, Colorado Department of Transportation, DTD applied research and innovation branch, *Report No. CDOT-2008-7*.

Santi M., Russell C., Higgins J. and Spriet J. 2009. Modification and statistical analysis of the Colorado Rockfall Hazard Rating System, *Engineering Geology,* 104, 55–65.

Saroglou H., Marinos V., Marinos P. and Tsiambaos G. 2012. Rockfall hazard and risk assessment: an example from a high promontory at the historical site of Monemvasia, Greece, *Natural Hazards and Earth System Sciences*, 12, 1823–1836.

Singh A. 2004. FRHI. A system to evaluate and mitigate Rockfall hazard in stable rock excavations, *IE (I) Journal.CV*, vol. 85.

Vanderwater C., Dunne W., Mauldon M., Drumm E. and Bateman V. 2005. Classifying and assessing the geologic contribution to Rockfall hazard, *Environmental & Engineering Geoscience*, XI, (2), 141-154.

Washington State department of Transportation (WSDOT) 2010. WSDOT's unstable slope management program.