

Response to Reviewer 1 (Authors' answers in blue)

Q1. The objective of this manuscript concerns the risk assessment characterizing a roadway network affected by different hazards in Spain. For this, a "hybrid" quali-quantitative method mainly expressed in monetary terms has been proposed (as a multiple of a cost unit amounting to 1,000 EUR). The failure probability is evaluated with reference to four types of geotechnical hazards (rockfalls, anchored wall failures, slow landslides, and sea wall failures), whereas the related risk level is based on an economic criterion expressed as the average annual repair cost, at the considered section. The annual final risk is given by the product of probability/frequency occurrences of events, in assigned magnitude classes, per the monetary value of the elements at risk. Even though the work is interesting, there are some questions which I would like to highlight.

A1. We would like to thank the Reviewer 1 for his/her comments and insights, which helped us a lot to improve the quality of the manuscript. We tried to address all comments and suggestions. Please find below the point-to-point response.

Q2. I don't understand why the Authors put together the rockfalls (natural hazard) with the failures of man-made structures such as anchored walls, road platforms and sea walls. It is clear that these failures can be caused by natural causes linked to the slope movements but, in such a case, I would have expected the analysis of failures of passive retaining structures (barriers, fences, etc.), due to rockfalls.

A2. The hazards that were addressed at this work are the hazards that are mostly encountered in the road network of the study area, and are related to the major intervention costs. The challenge in this case, and the motivation for this work was indeed to analyse all hazards at a common scale, so as to prioritize those road sections that need urgent interventions against other where the risk is lower. Putting together all these hazards and comparing the related risk has been the challenge due to the fact that the hazards generated by these processes follow different temporal patterns and intensities have different type and extend of consequences. To the author's knowledge this is the first time that risk from different hazards is calculated in a quantitative way. This is extensively explained in the introduction.

Q3. Another big concern is for using heuristic methods in order to calculate the annual P/F occurrence for addressing the lack of adequate data. It seems to me that sometimes they are based on not adequately justified or tested expert judgments. This is particularly true for rockfalls and slow landslides types, where these approaches are used in order to overcome the lack of complete rockfall and landslide catalogues. In this respect, the Authors extend the frequency/magnitude relationships, calculated for sites with adequate data, to slopes with similar geostructural characteristics, scars, heights and block sizes (see on page 9, line 14).

A3. The approaches followed, except for the risk related to sea walls, is not heuristic, instead it is based

on analogs and proportionalities for calculating the probability of occurrence of the events of a given magnitude/intensity which is assessed based on quantitative data. This procedure is not heuristic. In any case, quantitative analysis can be based on expert judgment as well. Most of the procedures for risk assessment are based on analogs. As for example, the most well-known approach, which is the Rockfall Hazard Rating System follows the same logic, as it assigns the same level of risk to slopes showing similar geometric and geomechanical features. In our work, for the rockfall hazard, we followed such a logic, starting from the slopes with F-M available and assigning these values to slopes showing similar characteristics. This assumption is not restrictive but justified on the grounds of geomechanical characterization and its relation to the hazard, as for the RHRS mentioned above. A similar approach is followed for the slow-moving landslide, where we try to identify their pattern movements and their relation to the triggering factor (rainfall in this case), the latter with a known recurrence. This procedure is in the same line with the calculation of the occurrence of landslides, based on the recurrence of the triggering rainfalls, which is widely used.

Q4. With reference to rockfalls, the scoring assignment for the frequency index (IF) calculation involves five frequency indicators both qualitatively and quantitatively defined. In my opinion, this is a hybrid approach linking qualitative terms to quantitative data. With reference to the Differential Erosion indicator please, clarify what is the used figure for the score 2 (No, Yes, and...?). Then, the scores are summed up to calculate IF (see eq. 2), and a relationship between IF and the rockfall frequency, for enabling the assessment of thresholds, has been established. For this purpose, a calibration has been performed. I thought it would be interesting if the Authors would speak to us the calibration procedure and results.

A4. The index IF is not a frequency indicator but an indicator corresponding to the geomechanical characterization of the slope (please see also comment R1), thus is used to provide 5 different geomechanical characterizations, which after that, they are assigned with a frequency, considering that slopes in the same geomechanical class have common frequency and equal to the one available in some of the sections. Frequency is obtained quantitatively and not qualitatively. The authors recognize that in the way that the text was written, the term "calibration" is not representative of the procedure explained here, which is the followed procedure. For this we rephrased it in the text. On the contrary of what the reviewer mentions here, we do not link qualitative terms to quantitative data, but vice versa, we link quantitative data (frequency) to already defined qualitative descriptors (geomechanical class).

We reference to the differential erosion, if it is present the score for the I_F is 1 and if there is not it is 0, which means that it does not add to the IF. It is not the scores 0, 1, or 2 which are assigned to the indices, but the indices get qualities that correspond to a score. In this sense the qualities of the index IE are no or yes, which correspond to the scores 0 or 1, and 2 is not relevant here, that is why there is not quality in the relevant. We added "not applicable" to avoid confusion.

A5. Also with reference to the correction factors (Fr) assigned to different protection measures, it seems to me that this was done to ensure too high safety standards (See Table 6). I understand that,

lacking in literature adequate tested values, the Authors adopted precautionary data but (e.g. see the tunnel case) assuming a range of values between 4 and 2, for magnitude classes A-D it seems to me too high!

A5. As also mentioned in our response to question 4, the correction factors were assigned to different protection measures based on the observed frequencies in the study area, and in particular at the sections that this data was available. Volkwein et al. (2011), report capacity for energy absorption about 3000 kJ, without cushion materials, and about 5000 with it. These capacities are sufficient to retain most volumes of the categories A and B, considering the potential energy of the rock, for falling heights of few tens of meters, as the heights of the rocky slopes in the area,. For magnitudes C and D, given the fragmentation of the initial rock mass a percentage of the blocks is expected to be retained.

Reference:

Volkwein, A., Schellenberg, K., Labiouse, V., Agliardi, F., Berger, F., Bourrier, F., ... & Jaboyedoff, M. (2011). Rockfall characterisation and structural protection-a review. *Natural Hazards and Earth System Sciences*, 11, p-2617.

Q6. Similar considerations must be done for the failure of retaining structures, where the HI factor is only based on subjective evaluations and expert judgments. Hybrid data (qualitative and quantitative in nature) is also reported in Table 7. What means sound rock or mixture? For instance, is it adequate the use of the Schmidt hammer or pocket penetrometer for their characterization? As the Authors area well-known team working in the field of the hazard and risk assessment, I think that they must be very wary of suggesting not well-tested approaches because they have big authority in this very poorly explored research field.

A6. For assessing the probability of failure of retaining structures, we adopted the approach proposed by Silva et al. 2008, who argues that the probability of failure of structures can be assessed, considering besides the Safety of Factor, the quality of the construction. Similarly the HI factor is calculated based on an objective indicator model, including data from the load cells, and the specifications of the technical project. The approach is not based on expert judgement, but clear criteria. Sound rock or mixture refers to the ground where the structure is anchored, and is used as a factor to measure effectiveness and uncertainties for the support of the anchors. Schmidt hammer is not used. We are based on the geotechnical reports of the works.

Q7. Concerning the slow movements affecting the roads, might the slight/moderate damage on the road be due to shallow subsidence of the subgrade? (as it appears to me by some photos). Since the inclinometers are very often affected by installation problem, or malfunctioning causing lack of data have you been performing a reliability analysis?

A7. We would like to clarify that in all the cases analysed here, the road traverses well identified landslides, as such movements are associated to landslide activity. This part was added to the text. The

methodology that we propose here for the evaluation of the probability of landslide reactivation based on the indications of the inclinometers can be applied given that the inclinometers function well and are reliable. Indeed, in the study area there are some inclinometers which are inoperative or not reliable. However, the analysis presented here in this paper, refers to those sections with good inclinometer data. Please not, that according to yours and other Reviewers's suggestion, we added up some text in the Discussion section, on the reliability of the inclinometers.

Q8. For the failure of sea walls, I think that in an oversimplified way the procedure for the PIP index calculation is evaluated. As it is well know, the undercutting by waves is very important in causing the sea-cliff retreat or wall failure (mainly for toppling). Waves erode the cliff toe, undercutting and over steepening it. This destabilizes the overlying slope, causing it to collapse. Also with reference to the sea walls, the main failure mechanism is linked to erosion by waves. Consequently, the main factors affecting this failure process are the real dynamic pressure exerted by the water at the wall toe, the mechanical strength of concretes and design characteristics. As these quantities are very difficult to assess, generally the research approach uses aerial or satellite photos, topographic survey comparisons, LIDAR techniques, etc. Also the on-shore wave characteristics and meteorological observations in time and space are needed. With reference to eq. 7, and according to my opinion, the protection mass index (M_p) already should incorporate the correction factor (F_c) for the protection structure. What do you think? I suggest that you remove this hazard from the text.

A8. The reviewer is right, and we also on removing this hazard from the new version of the manuscript.

Q9. In conclusion, the suggested approach must be considered as a first attempt that cannot be extended to areas with different geotechnical and geomechanical characteristics, respect to the studied ones. The study confirms that a reliable quantitative risk analysis involving man-made structures can be performed using reliable and numerous data only. Otherwise and for wide areas, only heuristic approaches based on expert judgments can be used. But the question we have to ask is whether it is worth using complex procedures which incorporate not yet well-tested ratings.

A9. The authors would like to thank again the reviewer for the comments. For the reasons exposed in the introduction we think that quantitative risk analysis for roads, involving manmade structures is of wide interest. To the authors' knowledge, this is the first time that risk from different hazards is calculated in a quantitative way. Of course, several challenges exist which are also exposed in the introduction. It has to be mentioned that in the study area, there is an extensive and systematic collection of data, which has allowed the development of the proposed procedures, not always available in other study areas. Given the existence of this data, we think that the development of the approaches presented here, even if they leave a margin for refinement and validation is the added value if this work, permitting objectivity and reproducibility in the assessment. However, to avoid any misunderstanding we stress again in the conclusions that the procedures were development here given the local characteristics and available data in the area, and that direct transfer of the results to other study areas, without prior study of the local characteristics, is not recommended.

Q10. (see Table 6 – please, check the correct numbering of all tables and figures; the figure 4 is several times duplicated!)

A10. The numbering of Tables and Figures was checked and adapted to the changes in the text. In our version, we do not see Figure 4 duplicated.

Response to Reviewer 2 (Authors' answers in blue)

Q1. The manuscript presents a quantitative / qualitative procedure to assess hazard and vulnerability and their integration into risk calculations for roads by considering four different hazardous processes: rockfalls, retaining walls, slow moving landslides, and coastal erosion induced failures. The work is well written and the subject of the manuscript is of interest for NHESS, however, the manuscript needs some moderate revisions before to be accepted to be published.

A1. We would like to thank the Reviewer 2 for his/her comments and insights, which helped us a lot to improve the quality of the manuscript. We tried to take all the suggestions of the Reviewer into account and prepared a new version integrating them.

Q2. Major comments:

The manuscript is basically focused on the hazard evaluation, using quantitative and mainly heuristic approaches. The cost of direct road and retaining structures are not explored along the work, as they were obtained directly from the regional administration.

A2. The approaches followed, except for the risk related to sea walls is not heuristic, instead it is based on analogs and proportionalities for calculating the probability of occurrence of the events of a given magnitude/intensity which is assessed based on quantitative data. Most of the procedures for risk assessment are based on analogs. As for example, the most well-known approach, which is the Rockfall Hazard Rating System follows the same logic, as it assigns the same level of risk to slopes showing similar geometric and geomechanical features. In our work, for the rockfall hazard, we followed such a logic, starting from the slopes with F-M available and assigning these values to slopes showing similar characteristics. This assumption is not restrictive but justified on the grounds of geomechanical characterization and its relation to the hazard, as for the RHRS mentioned above. What we would like to stress here, is that the criteria established for the quantitative risk assessment proposed here are transparent, reproducible, and they are based on quantitative data.

The cost of repair for roads and retaining structures was obtained by the co-authors engineering companies and regional administration, based on real repair costs, by previous interventions. Its calculation is based on the works that have to be made for each types consequences. These works are explored and detailed in the Table of the Annex. We think that it is no use for the readers to the actual costs in monetary terms here, as these prices fluctuate a lot, according to location and time.

Q3. The few works worldwide dealing with both direct and indirect costs resulting from road damage

by landslides have shown that indirect costs can be orders of magnitude higher than direct costs. Although authors clearly state they do not address indirect costs, this topic should be highlighted in the discussion section of the paper.

A3. We agree with the Reviewer. Indeed indirect costs are very significant when calculating economical loss due to landslide road disruption. We highlighted this section in the discussion section as suggested by the Reviewer.

Q4. The methodological section of the manuscript is well balanced, but section 4 is not very well balanced. Section 4.5 (overall results and discussion) is poorly developed when compared with the description of the 8 studied cases for which the risk was calculated. The discussion can be enlarged and improved namely by incorporating the sensitivity analysis of the heuristic options used to assess the hazard.

The conclusion section also need to be improved. The first six paragraphs are not conclusions but a summary of the work.

A4. We enriched the discussion section, with comments related to the uncertainties which are included in the proposed procedure. A sensitivity analysis, showing in quantitative terms the effect of the uncertainties in the estimation of the risk components and the final risk would require systematic information on the data quality, which we do not have available. For this reason, and according to the Reviewers' most useful comments, we included some comments on the most important uncertainties involved in the analysis.

As for the conclusion section, we tried to eliminate information which is repeated in the text, however we have left the most important results from the application.

Q5. Minor comments

References are missing along the description of the geology of the study area (Page 6. Line 9 – 18).

A5. The references for the geology of the study area are provided in page 5.

Q6. Page 6 – line 6-8 The text is not clear. Explain better the relationship between lithology and landforms in the study area.

A6. It was rephrased.

Q7. In section 2, authors should provide the number of Points of Risk corresponding to each considered hazardous process (rockfalls, retaining walls, slow moving landslides, and coastal erosion induced failures). The relevant information is provided in the manuscript only in section 4.4 (page 29).

A7. Done

Q8. What is the difference between hazards and instability mechanisms that are referred in caption of table 2? Table 2 is not very much informative. Authors can provide the number of PoR considered for each instability mechanism class considered.

A8. The reviewer is right. As part of this information is repeated in the Appendix, we deleted this table.

Q9. In the first part of section 3 - General Methodology for the Risk Assessment, authors should state that different procedures are used to assess magnitude and frequency for the processes that are presented in the next sections.

A9. Done

Q10. Figure 3 is not referred in the text.

A10. We added reference for Figure 3 in the text.

Q11. Table 3 – How relates the events indicated in table 3 with the 95 PoR referred before? Are some of them the same? It is not clear.

A11. Please note, that as we deleted the part referring to the failure of sea walls, we are now referring to 84 PoR instead of 95 in our manuscript. Out of them 20 concern rockfalls. These latter are distributed in the entire network and not only in the sections of the road N-634. The events indicated in Table 3, instead refer only to the 5 PoR of the road N-634. This was clarified in the text too.

Q12. Page 10, line 1-4 The typical size of slope face is uniform? To each extent a scale effect may control the extent of observed discontinuities in the rock mass?

A12. The slopes have in principle an altitude of few tens of meters and large lateral extension, up to tens and hundreds of meters. As a result, there are no persistence limitations due to topography.

Q13. In table 5 The maximum IF should be fixed as 9?

A13. Indeed. This was also indicated in Table 9, in the revised version

Q14. Page11,line1-3,Authors state: "To assess the expected frequency of a given rock[fall] size, the total expected number of events is distributed over the rockfall volume classes, as observed in situ. If this datum is lacking, the proportion of a modal size of blocks multiplied by the total annual frequency is suggested instead. The statement is not enough clear. Please, provide more information regarding this topic.

A14. This part was rephrased to:

During the in situ inspections, data is collected for the relative frequency (%) of potential rockfalls, per volume class and for the most frequently encountered rockfall size on the slope (modal). The annual number of events per volume class is calculated by multiplying the total annual frequency with the relative frequency of each class. If the relative frequency data has not been collected, risk calculations are made, for the modal size, as an average approximation.

Q15. Page 12, line 2 “The six magnitude classes”, instead of “the five magnitude classes”. Apparently, some data is missing in table 7. It is not clear which score applies to ‘yes’ / ‘no’ for the project and construction. Therefore, it is difficult to solve equation (5).

A15. The Reviewer is right. “Five” was replaced by “six”, as it is six classes.

There are three possible scores for PQ. 1 if “available data for anchors” is yes and “Technical assistance during construction” is yes, 3: if “available data for anchors” is no and “Technical assistance during construction” is yes, and 5: if available data for anchors” is no and “Technical assistance during construction” is no.

Q16. Page 17 , line 17-23 Rainfall is not continuous in time neither in space. Please, provide where the rainfall data was registered. Also, authors state that the rainy period of January-February 2013 that was characterized by moderate to low daily intensity but of long duration, with cumulative precipitation measurements that exceeded the maximums of the reference period 1971-2000. How many weeks refer the long duration?

A16. Rainfall data that is mentioned here was collected at the Añarbe Dam (inside the study area). Unfortunately, we do not have available official data for the exact number of rain days in this period, as it also depends on the location inside the study area.

Q17. It is not clear the way authors obtained the intensity classes referred in table 11.

A17. The four intensity classes were established so as to correspond to the four damage classes in Figure 5, which in turn correspond to different repair costs. Damage levels were related with the intensity classes, based on observations of the damage on the road and the inclinometer indications.

Q18. Page 22, line 15 Table 12 instead of Table 16. Concerning the sea wall failures, is there any relation between the annual probability of failures and the magnitude (size) of the failures?

A18. After the suggestions of Reviewer 1, this section was removed. In any case, to provide an answer to Reviewer 2, there is no relation between the annual probability of failure and their size.

Response to Reviewer3

Q1. The paper presents a model of evaluation of multirisk in selected points of the route network of the roadway network of Gipuzkoa, Basque Country. The model tries to quantify risks in four scenarios pertaining to about 100 already detected point of risk. The transformation of the inhomogeneous and scarce data in a quantitative score is made up with criteria driven by the judgement and on the basis of the historical available data about instability on the roadway network. So the model is a heuristic one, currently not yet validate. The paper is well articulated and developed, but generates some perplexity.

A1 The authors would like to thank Reviewer 3 for the comments that helped us to improve the quality of the manuscript. Please check also our comments to Reviewers 1 and 2. As also we responded to the comments of Reviewer 1 and 2, we would like to emphasise that our approach, except for the risk related to sea walls is not heuristic, instead it is based on analogs and proportionalities for calculating the probability of occurrence of the events of a given magnitude/intensity which is assessed based on quantitative data, as most of the procedures for risk assessment are based on analogs.

Q2. First of all, the referee #3 agree with all the specific comments on the submitted paper from referees #1 and 2. One main concern is about the use of the velocity concept in several part of the text and particularly in the section about the slow landslides. Although velocity is widely adopted in many landslide classification systems, it is well known (from Physics) that in a force system the velocity of a rigid body mass is not representative of its equilibrium or disequilibrium state, which is demanded to the first derivative or gradient of the velocity vs time. About the classification and risk management of the “slow landslides”, the main references to this kind of landslide are the monthly slope deformation (periodically measured in inclinometers) and the one year cumulate displacements. So the Authors indirectly and correctly use the terms that contribute to the velocity vs time gradient (the acceleration).

A2. We use two criteria, the maximum monthly horizontal displacement rate and the annual cumulative horizontal displacement. The reason for using the monthly velocity (displacement rate) here is not to indicate the slope equilibrium or disequilibrium state, but to provide a measurement of the stresses and strains induced to the road due to the landslide movement, and to associate this movement with a certain extent of damage. Higher displacement rates (irrespective of the landslide being in a dynamic equilibrium or not) induce larger actions on the road and cause higher damage. The probability of a given landslide intensity, based on displacement rate and the cumulative displacement is based on observations of the inclinometers and not on a geotechnical analysis providing results on the equilibrium/disequilibrium state.

Q3. Some points are not clear or instill some doubts:

We start with the consideration that number and position of the available instruments in each site are well positioned and representative of the deformative field of the whole landslide body; are the deformation readings in the inclinometers constantly and regularly (which is the frequency) performed? Do the deformations of the inclinometer allow durability of the measures? Bigger movements are usually at the head, but do we analyze the correct one phenomenology, i.e. a shallow instead of a most dangerous and deeper incoming failure? Finally: measurements normally refer to a pre-peak failure stage: the post peak behaviour with the typical range of strength reduction (and then the hazard magnitude) is strongly controlled by the dominant lithology, which has been missed throughout the decisional points of the whole proposed model. Lithology and soil plasticity are common factors in many heuristic hazard models. Similar consideration should be extended to short term vs long term groundwater variations.

A3. We would like to thank the reviewer for these comments. The selected inclinometers to measure the data used here are in most cases placed in the vicinity of the road, with a few exceptions. Local accelerations, if any, in areas not monitored by the inclinometers are indeed not captured. However it is not always the case that those local movements affect the roads, and thus of interest.

After 2010, deformation readings are constantly taken, every 3 months. As some inclinometers are functioning about 15 years now, there have been some gaps in measurements, but before 2011 (mostly in 2008-2009). Indeed, some inclinometers become inoperative after suffering large deformations. The proposed procedure takes this into account through the criterion of annual cumulative horizontal displacement.

The slow-moving landslides in the area are well identified and geological and geotechnical studies have been performed, for the identification of the fracture/sliding surface and the back analysis of the stability, at least in most cases. As mentioned in the text, in the area there are clay materials with a viscous behaviour. Inclinometers in principle are deeper than the identified sliding surfaces. There are

exceptional suspicions for deeper sliding surfaces not monitored.

. As mentioned in section 3.3, the relation between the inclinometer indications and the road damage was established for 24 points, out of which 20 yield consistent predictions (coherent results between movement rate and damage), only one presented damage overestimation and 3 presented damage underestimation (out of which one inclinometer was identified to have low reliability). The aforementioned indicate a high rate of consistency of inclinometers with the damage. In exceptional cases, further geotechnical studies would have to be performed to provide us with new data for the risk calculation.

In any case, the authors agree that the inclinometer measurement related uncertainties that the Reviewer mentions might be present, and they point this out in the discussion session. However, despite uncertainties, the focus here has been on the identification of patterns of movements, especially during and after the critical 2011 and 2013 events, trying to see the potential of each landslide for a given intensity (displacement rate), instead of measuring movements with precisión, and this has been possible.

Q4. The model has been applied to a system spatially extended for about 10.000 sq kilo- metres and developing several hundreds of kilometres (see fig.1), whose health and wellness rely on a limited number of instrumentations and on periodical inspections; it is characterized by several geological frames and by a well-developed surface hydrography. The local control apparatus is aged about 16 years and does not allow real time measurements in spite of its expensiveness. In other words, the monitoring system installed and which is the main source of data on which the proposed model works can be considered somewhat obsolete. Today the large areas can be controlled by means of active or passive PS INSAR techniques (measurement return time about 6 days); inclinometers can be flanked by optical or capacitive TDR and other kind of devices able of continuous and real-time response. While the meticulous and complete care in the model deserves great appreciation, some perplexities already expressed, together with the considerations about the repeatability of the scenarios, significantly limit the usefulness of the model in future scenarios.

A4. The methodology was developed according to the available data in the area and an update of the monitoring systems was not part of this work. The Authors are well aware of the technologies and studies involving InSAR and DinSAR measurements for the calculation of the ground terrain movements on roads and certainly consider that these methods could be proved useful for future studies in the area.

Q5. Technical corrections

In fig.6, Patterns of movement for landslides responsive and not responsive to rainfall, nowhere is reported a numerical scale (also indicative) of time

A5. The Figure was replaced and the scale was added.

Integrated risk assessment due to slope instabilities at the roadway network of Gipuzkoa, Basque Country

5 Olga Mavrouli¹, Jordi Corominas², Iñaki Ibarbia³, Nahikari Alonso⁴, Ioseba Jugo³, Jon Ruiz⁴, Susana Luzuriaga⁵ and José Antonio Navarro⁵

¹ Faculty of Geo-Information Science and Earth Observation (ITC), University of Twente, Enschede, Netherlands; previously at Department of Civil and Environmental Engineering, Technical University of Catalonia, BarcelonaTech (UPC)

10 ² Department of Civil and Environmental Engineering, Technical University of Catalonia, BarcelonaTech (UPC)

³ Ikerlur, S.L., Donostia

⁴ LKS Ingeniería, S. Coop., Arrasate/Mondragon

⁵ Diputación Foral de Gipuzkoa-Gipuzkoako Foru Aldundia, Donostia/San Sebastián

Correspondence to: o.c.mavrouli@utwente.nl & jordi.corominas@upc.edu

15

Abstract. Transportation corridors such as roadways are often subjected to both natural instability and cut slope ~~failure~~[failures](#), with substantial physical damage for the road infrastructure and threat to the circulating vehicles and passengers. In the early 2000s, the Gipuzkoa Regional Council of the Basque country in Spain, marked the need for assessing the risk related to the geotechnical hazards at its road network, in order to assess and monitor their safety for the road users. The Quantitative Risk Assessment (QRA) was selected as a tool for comparing the risk for different hazards on an objective basis. Few examples of multi-hazard risk assessment along transportation corridors exist. The methodology presented here consists in the calculation of risk in terms of probability of failure and its respective consequences, and it was applied to [9584](#) selected points of risk (PoR) of the entire road network managed by the Gipuzkoa Regional Council. The types of encountered slope instabilities which are treated are rockfalls, retaining wall failures, [and](#) slow moving landslides, ~~and coastal erosion induced failures~~. The proposed methodology includes the calculation of the probability of failure for each hazard based on an extensive collection of field data and its association with the expected consequences. Instrumentation data from load cells for the anchored walls and inclinometers for the slow moving landslides were used. The expected road damage was assessed for each hazard level in terms of a fixed Unit Cost, UC. The results indicate that the risk can be comparable for the different hazards. [1221](#)% of the PoR in the study area were found to be of very high risk.

30

1. Introduction

Transportation corridors such as roadways are often subjected to both natural instability and cut slope ~~failure~~[failures](#), with substantial physical damage for the road infrastructure and threat to the circulating vehicles

and passengers. The growing societal demand for road safety requires managing this risk, and places in high priority the identification of problematic areas to effectively manage the mitigation works.

Risk is most commonly conceptualized as the product of hazard, exposure, and vulnerability. Qualitative risk analysis for transportation corridors traditionally combines different levels of hazard and vulnerability to provide the risk across the network (e.g. Pellicani et al. 2017). Nevertheless, the interpretation of risk levels which are obtained qualitatively may vary for the different hazards (Eidsvig et al. 2017). The homogenization of the risk for multi-hazards remains a challenge because of the variability in the nature of soil or rock mass movement phenomena and the difference in the type and extent of the consequences. The comparison of different types of geotechnical risks in roadways, such as slope movements and retaining structures failure, requires bringing these phenomena under a common denominator. Quantitative risk descriptors, as being objective expressions of the expected risk extent, may well serve for the homogenization of the risk levels for different hazards and types of exposed elements (persons, vehicles, infrastructure, and indirect economical loss). Common quantitative risk descriptors are the expected annual monetary loss, the probability of a given loss scenario, and the probability of one or more fatalities and others mentioned at Corominas et al. (2014).

One of the major limitations for the quantitative risk assessment in roadways is the great data demand that it implies. The hazard in terms of probability of an event of a given magnitude requires extensive data on the frequency and also magnitude (volume) of the events (Fell et al., 2008; Jaiswal et al. 2010). Most commonly, landslide inventories are required (Dai et al., 2002; Ferlisi et al. 2012), although in most cases they are scarce. Highway and traffic administration authorities are potential data providers (Hung et al., 1999), however complete and reliable maintenance records are rarely kept and made available. Alternative methods to overcome the scarcity of empirical data are provided at Corominas et al. (2014), and they are based on geomechanical or indirect approaches. They associate the occurrence of events with the temporal occurrence of their triggering factors, such as the return period of a rainfall of a given intensity. On the other hand, the calculation of the consequences in terms of realistic expected costs is a challenge for a purely quantitative risk assessment, as the amount of repair or insurance expenses fluctuates greatly depending on the type and extent of the damage, on top of the indirect costs related to traffic interruptions, detours and further loss related to traffic accidents. Due to these limitations, few purely quantitative multi-hazard risk assessments for roadways exist in the literature.

An extensive review of highway slope instability risk assessment systems is provided by Pantelidis (2011), including several qualitative and semi-quantitative methods (here by semi-quantitative we refer to the methodologies that assess the hazard in terms of numerical scores). A well-known example of semi-quantitative methods is the Rockfall Hazard Rating System (Pierson and Van Vickle, 1993) recommended by the FHWA (Federal Highway Administration of the United States), which was later adapted by Budetta (2004), specifically for rockfall risk along roads. The pure quantitative risk assessment (QRA) however consists in the hazard assessment in terms of probability of failure/occurrence of an event of a given magnitude multiplied with its respective consequences (Fell et al. 2008), which is not treated by semi-quantitative methods.

Hung et al. (1999) quantified the rockfall risk along roadways at the British Columbia, after deriving magnitude-cumulative frequency curves. Bunce et al. (1997) were amongst the first to use the roadway damage in order to assess the rock fall frequency. Remondo et al. (2008) proposed a method for the quantification of the damage at the Gipuzkoa road network where losses were calculated on the basis of past damage records and taking into

account budgets for road and railway track repairs. Similarly, Zêzere et al. (2008) assessed the direct risk from translational, rotational and shallow landslides in the north of Lisbon, Portugal, employing road reconstruction costs within a Geographical Information System. Ferlisi et al. (2012) using the fundamental risk equation provided by Fell et al. (2008) calculated the annual probability of one or more fatalities by rockfalls in the Amalfi coastal road, Southern Italy, and Michoud et al. (2012) presented an example from the Swiss Alps. Jaiswal et al. (2010) applied a risk model for debris slides, where the temporal probability was indirectly obtained by the return period of the triggering rainfalls and the road vulnerability was assessed in function of the road location and expected debris magnitude. Ferrero and Migliazza (2013) made a first attempt to incorporate the efficiency of protection measures into the risk assessment (Nicolet et al. 2016). Still, when it comes to the practical application of quantitative risk analysis to linear infrastructures, several challenges exist.

One of the most important is the assessment of the expected magnitude-frequency relations and of the annual probability of occurrence for a hazard of a certain magnitude/intensity, in particular where past event inventories are incomplete or missing. As afore-mentioned, alternative methods have been suggested to this end, however in most cases their application is limited to site specific. There is a scarcity of cost-efficient, quick, simple and easy enough methodologies, to be applied to extensive road networks, using as input the evidences that can be found in the vicinity of the transportation corridors, field inspections or instrumentation. Given those limitations, the determination of landslide magnitude-frequency data requirements and its specifications, within a suitable and feasible framework for transportation corridors, remains an issue.

Assessing the condition of assets such as road pavements and protection infrastructure (in this case retaining walls) allows for monitoring operational efficiency, planning future maintenance and rehabilitation activities and controlling costs, through condition forecasting models (Gharaibeh and Lindholm, 2014). Although models for predicting pavement deterioration under usual stress conditions have been used for more than three decades now, literature is lacking prediction models for disruptive slope instability events. Similarly, simple yet functional and (semi)quantitative-based empirical models for the condition assessment of retaining walls are scarce.

Diverse hazards types require different descriptors for predicting asset condition. In quantitative multi-hazard risk assessment, the use of all descriptors should produce comparable results at a common and meaningful (commonly financial) scale. This requires, in each case, adequate criteria and thresholds for the establishment of hazard classes, to associate with vulnerability levels and costs (Schmidt et al. 2011; Kappes et al. 2012). Very few examples of roadway vulnerability exist in the literature (e.g. Mansour et al. 2011; Eidsvig et al. 2017). Their applicability or adjustment to other case-studies is a topic for further research.

The work that is presented here aims at filling in these gaps for the development of a comprehensive procedure including suitable data collection, hazard and vulnerability assessment and their integration into risk calculations. Up to date and to the authors' knowledge there are scarce integrated approaches for multi-hazard quantitative risk analysis at transportation routes, at site-specific and local scale. The starting point was the need for a risk assessment system for a specific area, and all approaches discussed here for confronting these issues are strongly related to the local characteristics of the study-area and the available documentation and instrumentation.

In particular, in the early 2000s, the Gipuzkoa Regional Council of the Basque Country in Spain, marked the need for assessing the risk related to the geotechnical hazards at its road network, in order to assess and monitor their safety for the road users. The main objective has been the identification of the most problematic areas where

mitigation measures should be prioritized. In that specific road network, a variety of geotechnical hazards coexist, which are relevant to both cut and natural slope instabilities, considering as well coastal erosion, and including the potential failure of retaining walls. A quantitative risk analysis approach was proposed.

5 The methodology presented here was developed with the objective to compare the risk levels, for a variety of elements comprising roads and retaining walls, using a common unique criterion for their evaluation. It consists in the quantitative risk assessment (QRA) in terms of probability of failure and its respective consequences, at about 100 selected points of risk (PoR) of the entire road network managed by the Gipuzkoa Regional Council (Figure 1). The types of encountered slope instabilities which are treated in this manuscript are rockfalls, retaining walls, and slow moving landslides, and coastal erosion induced failures. Further geotechnical risks in the area include debris flows, instability of embankments and brittle slope failures, but their assessment is not included here.

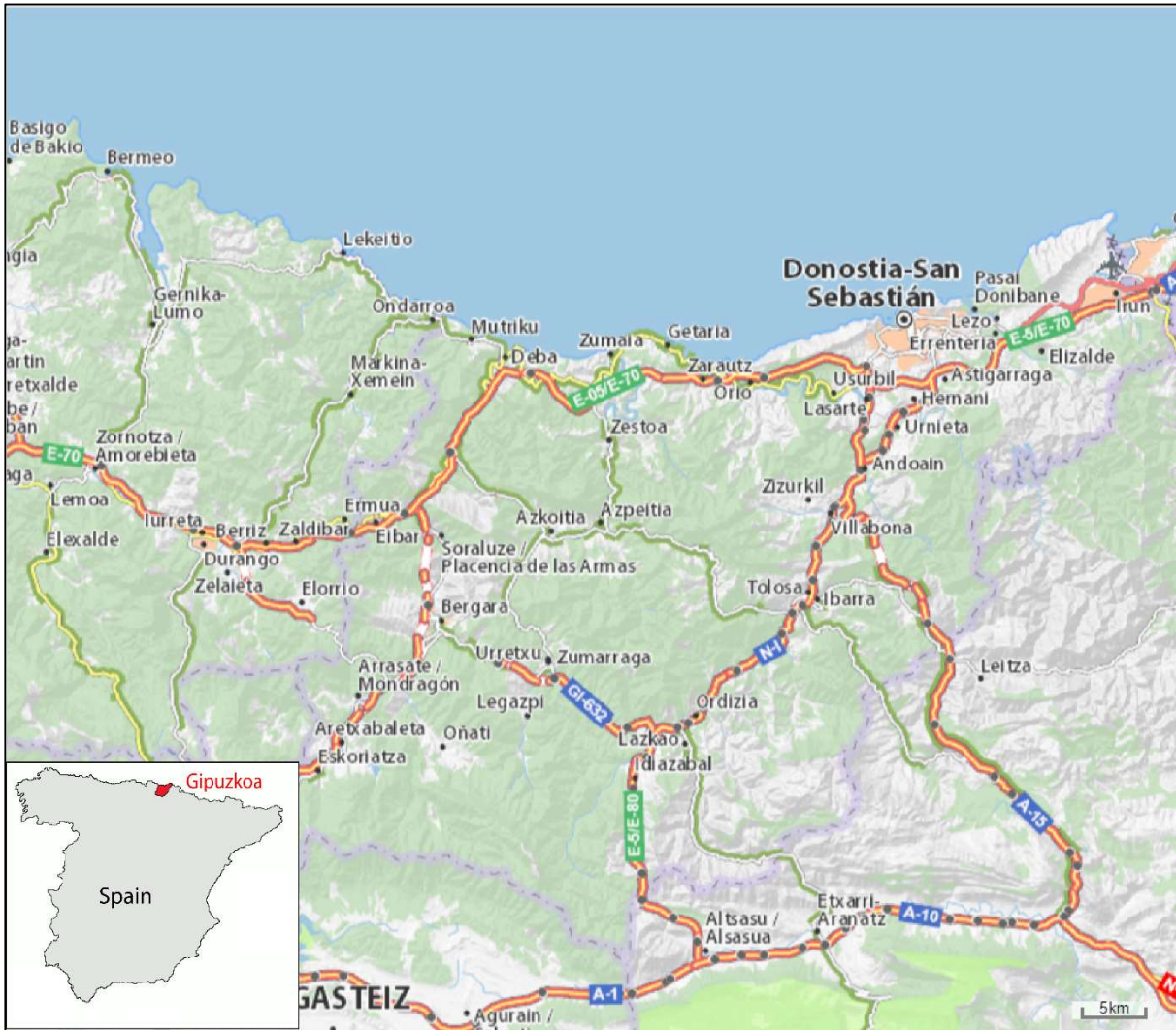


Figure 1: Road network managed by the Gipuzkoa Regional Council (map source ViaMichelin website at <https://www.viamichelin.com/web/Maps>, last accessed in September 2018).

2. Study area and data availability

The study area is the road network managed by the Gipuzkoa Road Authority, in the Basque Country, Spain (Figure 1). It consists of four networks: highways, primary, county, and local roads. Their difference lies in their capacity and function as connecting corridors between major and/or minor urban/rural nuclei. In that region, the layout of the road network has been spatially constrained since its design by its characteristically intense morphological relief. Soil infills or excavations and important constructions such as retaining walls are required to protect the road users and the road infrastructure against soil/rock mass movements and instabilities. An important fraction of the retaining walls is anchored walls.

From a geological point of view, the Gipuzkoa province is part of the Basque-Cantabrian basin (Barnolas and Pujalte, 2004). More specifically, it is the segment connecting the Pyrenees and the Cantabrian mountains to the West (Tugend et al. 2014). It experienced normal faulting and high subsidence rates during the Cretaceous and was inverted during Tertiary compression related to the Alpine orogeny (Gómez et al. 2002). The outcropping rocks cover a wide temporal record, from the Upper Paleozoic to the Quaternary. However, there is no representation of the materials belonging to the period between the Lower-Middle Tertiary (Oligocene) and Early Pleistocene. The geology of the study area is well synthesized by Ábalos (2016) (Figure 2).

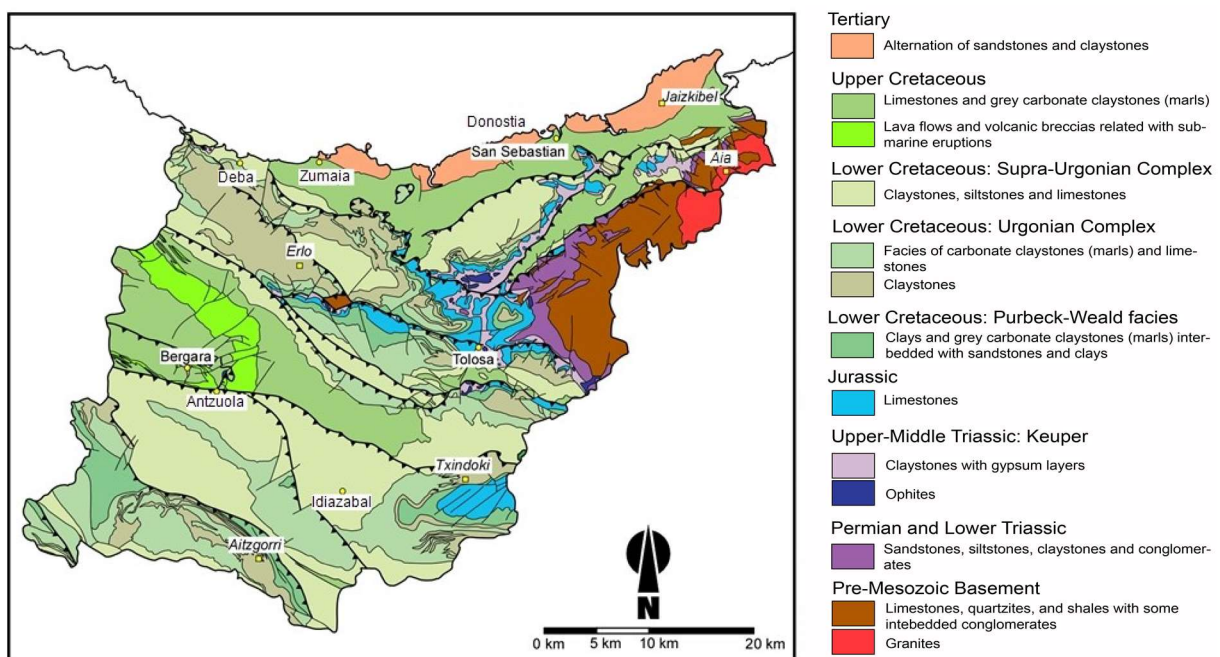


Figure 2: Geological sketch of Gipuzkoa province (modified from Ábalos, 2016).

According to it, two well differentiated geological sectors can be distinguished. The first one extends over the NE corner of Gipuzkoa, in which the Paleozoic rocks (granitoid rocks and limestone layers overlaid by quartzites and shales with some interbedded conglomerate layers) and Triassic rocks (sandstones, siltstones, claystones and conglomerates) are predominant. The rest of the Gipuzkoa province is composed of thick sedimentary assemblages, mainly Cretaceous and Tertiary (Figure 2). The outcropping lithological units are diverse. Jurassic rocks are usually composed of carbonate rocks of marine platform facies. Several stratigraphic units are found in the Lower Cretaceous formations. The Weald complex is composed of continental and freshwater sedimentary

rocks. The Urgonian complex is formed by reefal limestones; the Supra-Urgonian Complex exhibits a considerable internal complexity, mostly clayey limestones, siltstones, and argillites. The Upper Cretaceous is characterized by Flysch alternations and Tertiary flyschoid sandstones. In general, the sedimentary rocks were formed in a great diversity of depositional environments, although they mostly correspond to marine environments, with intercalations of continental or transitional facies.

~~As the resistance to erosion depends on the lithology, strong~~ Materials such as limestones, conglomerates, and sandstones stand out, ~~constituting and form~~ the topographic ~~reliefs, versus the relief, as being~~ more ~~easily erodible areas of soft materials, such as clays and siltstones resistant to erosion than clay and siltstone zones, which are also present in the area.~~

Concerning tectonics, all the aforementioned materials appear folded and fractured as a result of the actions during the two orogenic phases. The oldest one, corresponding to the Hercynian orogeny, affected the Paleozoic rocks while the more recent alpine orogeny has been the responsible for the general uplift of the Pyrenean Mountain Range. During the uplift, the Mesozoic sedimentary cover detached from the Paleozoic basement, in favour of the most deformable lithological units (e.g. Keuper), and created a complex structure of folds, faults and diapirs. Both the folds and the main fractures have alignments oriented in the direction NE-SE and NW-SE, which in the eastern part of the Gipuzkoa province form an arch that bounds the Paleozoic reliefs.

The Quaternary rock deposits pertain to residual soils, originating from the disintegration, weathering or dissolution of the underlying rock mass, without having undergone transport (colluvium, scree deposits on the foot of steep slopes), and alluvial soils.

Since 2002, the Department of Mobility and Road Infrastructure of Gipuzkoa ~~has~~ developed and installed an extensive system for the surveillance and monitoring of the anchored retaining walls with hydraulic or vibrating wire load cells, placed over the most representative and critical retaining structures and slopes. The monitoring system is completed with further instrumentation of the slopes and embankments, comprising piezometers, inclinometers measuring quarterly to semi-annual displacement and extensometers, controlling, on a continuous basis, 100 Points of Risk (PoR). ~~9584~~ of them involve rockfalls, ~~(20 PoR)~~, potentially unstable ~~anchored~~ retaining walls, ~~(37 PoR)~~, and slow moving landslides ~~and potentially unstable sea walls with overlaying roads.~~ ~~(27 PoR)~~. In spite of the instrumentation data available in the area, the comparison of the risk levels at the different PoR and the establishment of a methodology for the homogenous multi-hazard quantitative risk assessment have remained unresolved until the proposal of the methodology that is presented here.

Five road types based on the Average Daily Traffic (ADT) can be distinguished (Table 1), for which the geotechnical hazard situations vary. For the sake of brevity, only the ~~four~~ ~~three~~ aforementioned types of instability are treated here. Typical examples of them in the study area are shown in the Application section. In particular, the different hazard situations can be summarized as follows:

- Rockfalls with or without mitigation measures; ~~(RF)~~;
- Anchored walls partially or totally instrumented with inclinometers and/or load cells inspected on a continuous or annual basis; ~~(RS)~~;
- Instrumented slow moving landslides with available geotechnical study; ~~(SL)~~.

- sea walls for road construction or protection of roads against sea erosion, with available geotechnical study and documented periodical revisions.

Table 1: Occurrence of geotechnical hazard types at different road types (data source: Department of Mobility and Road Infrastructure of Gipuzkoa).

Road Type	ADT	Networks	Anchored walls	Rockfalls	Slow moving landslides
1	>25,000	Highway / Primary	x		x
2	15,000-25,000	Highway / Primary	x	x	x
3	5,000-15,000	Highway/Primary / County	x	x	x
4	1,000-5,000	Primary / County / Local	x	x	x
5	<1,000	County / Local		x	x

ADT: Average Daily Traffic

Rainfall data has been available for the study site by the Meteorological Agency of the Basque country. Further data has been collected after periodical field inspections and from the monitoring network, the type of which differs according to the hazard. This is detailed in the following section. Periodic inspections have been on-going up to date.

3. General Methodology for the Risk Assessment

The objective of the general methodology that is presented here is to compare, on a common basis, the risk at the different PoR. The risk components that are used are the hazard and the consequences. For the calculation of the risk, the methodology takes into account the repair of damage in order to restore normal traffic. This expresses the direct risk for the road. ~~Indirect loss such the economic impact of the road blockage and detours are not described here.~~ The risk quantification in terms of monetary loss requires calculating repair costs for different damages for each hazard, as described in ~~Table 13 (Annex). Indirect loss such the economic impact of the road blockage and detours, although it might be substantial, is not described here.~~

The hazard is expressed in terms of annual probability of failure of a natural/cut slope or retaining wall, of a given magnitude j . ~~For dormant landslides, it is the probability of a sudden reactivation.~~ Magnitude (volume) or intensity (velocity) descriptors were defined for each hazard. ~~Different procedures were used to assess the annual probability of an event of a given magnitude or intensity for the processes that are presented in the next sections. For dormant landslides, the probability of a sudden reactivation was assessed.~~ The consequences include costs related to removal of rubble, repair/replacement of the pavement, scaling of the slopes (the removal of loose non detached rock or debris), and slope stabilization. The cost is evaluated in multiples of a Unit Cost, UC, set at 1,000 €.

~~Table 2: Hazards, instability mechanisms, and principal consequences~~

If more than one types of hazards are present on a given PoR, the total risk is the sum of risks.

The overall methodology for the quantification of the risk consists in the general application of Eq. 1.

$$R_T = \sum_j^k P_{rk} * C_k, \quad (1)$$

Where:

- 5 R_T : Average annual risk in terms of UC per year
- j: Magnitude (volume) or intensity (velocity) class
- k: Hazardous event type (rockfall; failure of an anchored retaining wall; slow moving landslide; failure of a sea wall)
- 10 P_r : Annual probability/frequency of occurrence of a failure/rupture of magnitude j. For slow moving landslides, it refers to the probability of acceleration of a landslide with a given level of intensity (velocity).
- C_k : Consequences of the failure/rupture caused by a hazardous k-type event, of magnitude j in terms of (as multiples of) the UC (set at 1,000 €).
- The magnitude classes of the adverse events are established empirically based on the observed consequences (road damage) and the average cost of the remedial measures typically undertaken (see appendix).
- 15 For each hazard further assumptions are made and steps are followed for the evaluation of the components of Eq. (1), which are described in the following sections.

3.1 Rockfalls (RF)

- 20 Rockfalls are a major threat at the roads of Gipuzkoa. The rockfall hazard magnitude is classified according to the volume of the detached mass. [Figure 3 shows representative examples of different rockfall magnitudes.](#) A frequency or probability of occurrence is attributed to each volume class and the extent of disruption of the transportation corridor is determined.

- 25 For the frequency-magnitude relation, a catalogue of events is available only for limited sections of the road network. An inventory of rockfalls was compiled for the road N-634 connecting Zarautz and Getaria, based on highway administration data and press sources. According to the recorded historical events, six (from A to F) volume ranges were considered (Table [32](#)). For the sections of the road N-634 ([5 out of 20](#)), the frequency was then be assessed as the number of events divided by the number of observation years.



Figure 3: Examples of rockfall magnitudes (C, D, E, and F) in the study area, in relation to the classes of Table 32 (source: photo D, E: Javi Colmenero; F: Servicio Geológico de Obras Públicas)

5 Table 32: Magnitude classes and respective annual frequency for the road N-634 connecting Zarautz and Getaria.

Class	Volume (m ³)	# events	Period	Time span (years)	events/yr
A	<1	104	1994-2009	15	6.933
B	1-5	91	1994-2009	15	6.067
C	5-50	24	1994-2009	15	1.600
D	50-500	5	1960-2009	49	0.102
E	500-5,000	1	1884-2009	125	0.008
F	>5,000	1		>330	<0.003

10 Although the same amount of information is not available for all the PoR, numerous in situ inspections at the PoR have provided extensive topographical and geological data, which can be used for estimating the frequency at the rest of the sections. To this aim, a [relation geomorphological description](#) was [established between the frequency of events and certain geological parameters of the slopes, made](#) for 18 representative [example sections-examples with known frequency of events](#), on the road N-634. [Then, for the rest of the sections with no frequency data, the same relation was then applied to the PoR without rockfall inventories. frequency values were established, for the](#)

15 [sections within the same geomorphological class.](#) The main assumption is the equivalence of the frequency-[magnitude relation](#) at slopes with similar [geostructural-geo-structural](#) characteristics, number of recent scars, slope height and block size. The suggested [frequency indicators to characterize geomorphologically the slope](#) are the joint persistence (I_p), the scar density (I_{DC}), differential erosion (I_E), the number of potentially unstable rock masses (I_{FP}), and the Slope Mass Rating Index (I_{SMR}). These indicators are calculated as follows:

- The persistence of discontinuities in the rock mass, I_P , is assumed high when planes of several tens of meters can be observed on the slope face; moderate when of some meters; and low when it is sub-metric. The stratification is taken into consideration as well. Higher persistence of discontinuities results in the existence of more planes permitting the block detachment from the slope face.
- 5 - The scar density, I_{DC} , is calculated as the ratio of the number of recent scars to the slope height. Scars can be noticed as areas with a different colour (often reddish) from the rest of the slope face. Greater number of recent scars indicates higher and more frequent activity.
- Differential erosion, I_E , can be present or absent and can be observed at rock masses constituted by materials of distinctive strength. Differential erosion leads to loss of support for the overlying rock mass.
- 10 - The number of potential rockfalls, I_{FP} , refers to the number of potentially unstable rock masses as observed by in situ inspections. This number is collected distinguishing between magnitude classes.
- The Index Slope Mass Rating I_{SMR} is the value of SMR, as proposed by Romana (1991).

Table 43: Scoring of the geomorphological indicators used for the rockfall frequency assessment.

Indicators	Scores	0	1	2
I_P (Joint persistence)*		Low	Moderate	High
I_{DC} (Density scars)**		<0.1	0.1-0.3	>0.3
I_E (Differential Erosion)***		No	Yes	(Not applicable)
I_{FP} (Number of points with potential rockfalls)****		<2	3-10	>11
I_{SMR} (SMR)*****		>80	40-80	0-40

15

Each indicator, depending on its value, scores 0, 1 or 2 points, applying the criteria of Table 4.3, with the exception of I_E , which scores up to 1. The indicator scores are summed up to provide the frequency index I_F according to Eq. 2. We established the thresholds to relate the geomorphologically-based index I_F was first calculated at the cut slopes with an available inventory of rockfall events in order to establish a relationship between the I_F and with the frequency of events of all magnitudes. After calibration, the thresholds of this relationship were established the events, after application to the sections with known frequency, as shown in Table 54.

20

$$I_F = I_P + I_{DC} + I_E + I_{FP} + I_{SMR} , \quad (2)$$

25

Table 54: Annual frequency f_a for different I_F values.

I_F	Annual frequency f_a (events/yr)
8-9	≥ 3
6-8	$1 \leq f_a \leq 2$
5-6	$0.2 \leq f_a \leq 1$
3-5	$0.1 < f_a \leq 0.2$
0-3	≤ 0.1

To assess

5 During the expected in-situ inspections data is collected for the relative frequency F_r (%) of a given rock potential rockfalls per volume class, and for the most frequently encountered rockfall size, on the total expected slope (modal). The annual number of events is distributed over the rockfall volume classes, as observed in situ. If this data per volume class is lacking, the proportion of a modal size of blocks multiplied calculated by multiplying the total annual frequency is suggested instead with the relative frequency of each class. If the relative frequency data has not been collected, risk calculations are made, for the modal size, as an average approximation.

10 The implementation of measures of stabilization measures (bolts, anchors), retention (nets and/or gunitite), or protection (barriers, galleries), partially or entirely, reduces the annual frequency of rock blocks reaching the roadway. To account for this, a corrected reduced frequency F_{rc} is proposed to be used, upon a correction factor n (Table 65), according to Eq. 3:

$$F_{rc} = \frac{F_r}{10^n}, \quad (3)$$

15

where,

F_{rc} : annual corrected frequency

F_r : annual frequency before correction

N: correction factor given by Table .

20

Table 65: Correction factor for different protection measures, to be applied on the annual frequency according to Eq. 3, for each magnitude.

Magnitude (m ³)	A	B	C	D	E	F
Volume (m ³)	<1	1-5	5-50	50-500	500-5,000	>5,000
Gunitite, bolts (effective and extense)	0.5	0.25	0	0	0	0
Gunitite, bolts (partial)	0.25	0.1	0	0	0	0
Shotcrete with bolts	1	0.5	0	0	0	0
Cable nets	0.25	0	0	0	0	0
Triple torsion nets	0.5	0	0	0	0	0
Low rigid foot barrier	0.25	0	0	0	0	0
High rigid foot barrier	1	0.5	0	0	0	0
High rigid foot barrier (partial)	1	0.5	0	0	0	0
Ditch width <5 m	0.2	0	0	0	0	0
Ditch width <5 m with vegetation	0.5	0.1	0	0	0	0
Ditch width >10 m	0.5	0.25	0	0	0	0
Ditch width > 15 m	1.5	1	0	0	0	0
Flexible Barriers <2000KJ	3	1	0	0	0	0
Flexible Barriers >2000KJ	3	2	1	0	0	0
Gallery	4	3.5	3	2	1	0

The thresholds of Table 43 for the scoring of indicator, the I_F values and the annual frequency as indicated in Table 54, were obtained after a trial and error iterative-calibration procedure, so as to optimize the matching of the results with the observed frequency from real events at natural slopes (the latter marked as 1-2 events per year, or 1 event every 1-5 years, or 1 event every 5-10 years). The calibration-yields results which are from this iterative procedure yield an overestimation at of maximum 2 events per year, in 5 sections, while at the rest of the sections the results are compatible. At a second stage, further calibration was performed considering the protection measures, which yields the correction factors of Table 65.

The risk at each point is then calculated for each PoR by the general Eq. (1). For this, the consequences are assessed per rockfall magnitude classes as indicated in the Appendix. The five six magnitude classes also shown in Table 32 were defined judgmentally, based on the principal consequences and disruption of the road, as observed from previous rockfalls and road maintenance interventions. In Table 413 (Appendix) the principal consequences and disruptions are shown for each magnitude class, as the respective actions which are used as a guide for the establishment of the costs in terms of UC.

3.2 Failure of retaining structures (RS)

One of the objectives of this work was the analysis of the risk related to the failure of anchored reinforced concrete walls. The uncertainties characterizing the structural design parameters and the terrain resistance are substantial, thus the safety level of these structures cannot be precisely assessed. The probability of failure is considered instead.

The hazard level associated to the anchored retaining walls is evaluated on the basis of a heuristic-hazard index, HI. The evaluation consists in a modification of the Methodology for the Revision of Anchors, developed by the company Euroestudios in 2004. According to it, the HI for the retaining structures is equal to the average of the scores assigned to three components (Eq. 5). These components and their scores are presented in Table 76 and they are: the safety factor of the wall, the anchorage design (DA), and the project and construction quality (PQ).

The scoring for each component range between 1 and 5. Moreover, to calculate the scoring of the index DA, the average value from 3 parameters is considered according to Eq. 4: % working load/ultimate load ratio (UL), grout length per ten tons load (GL), and the anchoring ground (AG). The term sound rock or mixture refers to the ground where the structure is anchored. For the parameter PQ there are three possible scores: 1, if "Available data for anchors" is yes and "Technical assistance during construction" is yes; 3, if "Available data for anchors" is no and "Technical assistance during construction" is yes; and 5, if available data for anchors" is no and "Technical assistance during construction" is no.

5 **Table 76: Scores the hazard index HI components, for the failure of retaining walls.**

Parameter		Value				
		1	2	3	4	5
Safety Factor (SF)		>2	1.55-2.0	1.45-1.55	1.30-1.45	<1.30
Anchor Design (DA)	Working load (% Ultimate load) UL	<55		55-65		>65
	Grout Length GL	>1.2m/10t		0.8-1.2m/10t		<0.8m/10t
	Anchoring ground AG	Sound Rock		Mixture		Weathered soil/rock
Project and construction (PQ)	Available data for anchors	yes		no		no
	Technical assistance during construction	yes		yes		no

The hazard index (HI) is obtained using the following Eq. (4) and (5):

$$DA = \frac{UL+GL+AG}{3}, \quad (4)$$

$$10 \quad HI = \frac{SF+DA+PQ}{3}, \quad (5)$$

The thresholds and the scoring of the parameters was made based on expert judgement, increasing the hazard index when the function of the anchors is critical or uncertain, and decreasing it when loading conditions and supports, as well as when good practices in construction can guarantee a good function of it. In Equations (4) and (5), for simplicity all factors are equally weighted.

Silva et al. (2008) have associated the safety of factor of engineered slopes for a given project category with the probability of failure. For this, the structures are classified according to the level of engineering design. Category I comprises engineered slope which were designed, constructed and managed using the most advanced state of the art knowledge. Category II includes constructions with normal standards. Category III are constructions without specific design that do not follow standards, and Category IV those ones with a poor or completely missing engineering knowledge basis. As the HI is an adaptation of the SF that takes into consideration additional criteria for the level of functioning of the structure, a similar relation between annual probability of

failure of the anchored retaining walls can be established as well. The relation is presented in

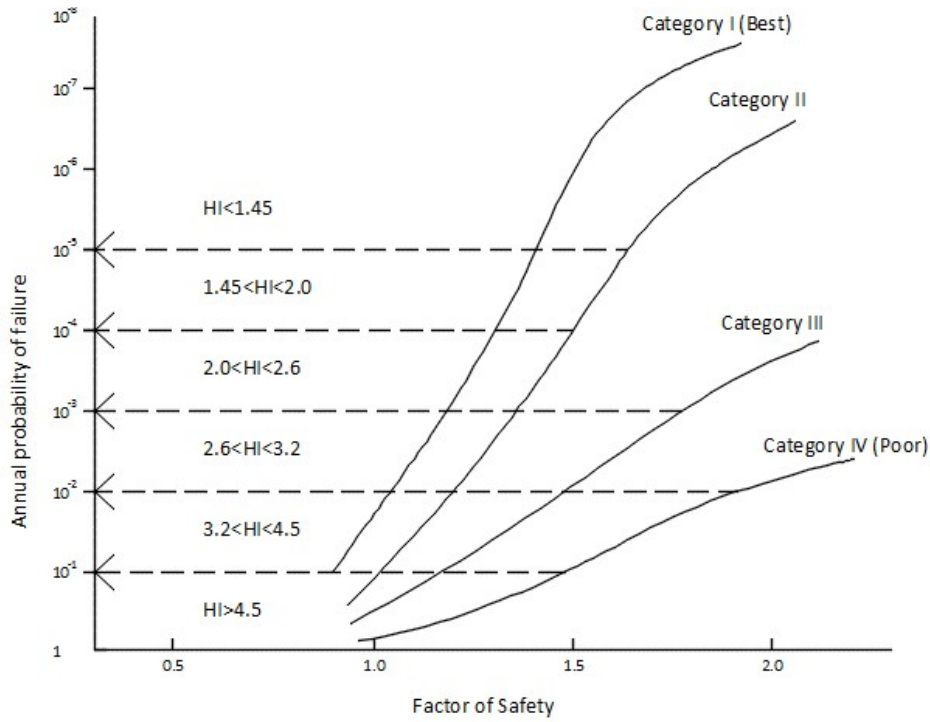


Figure 4 and Table 87.

5

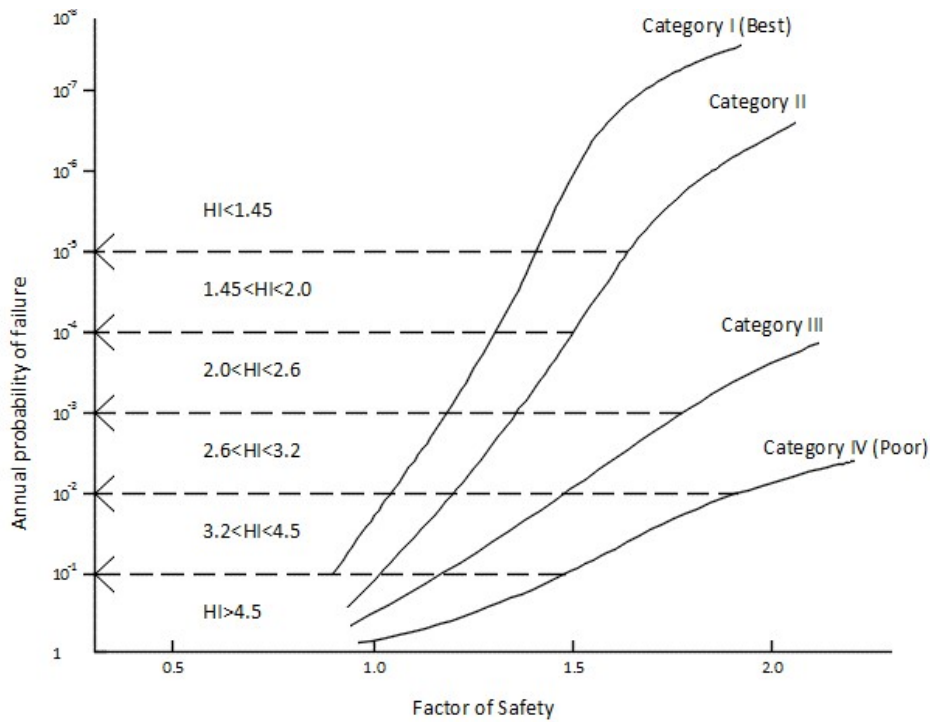
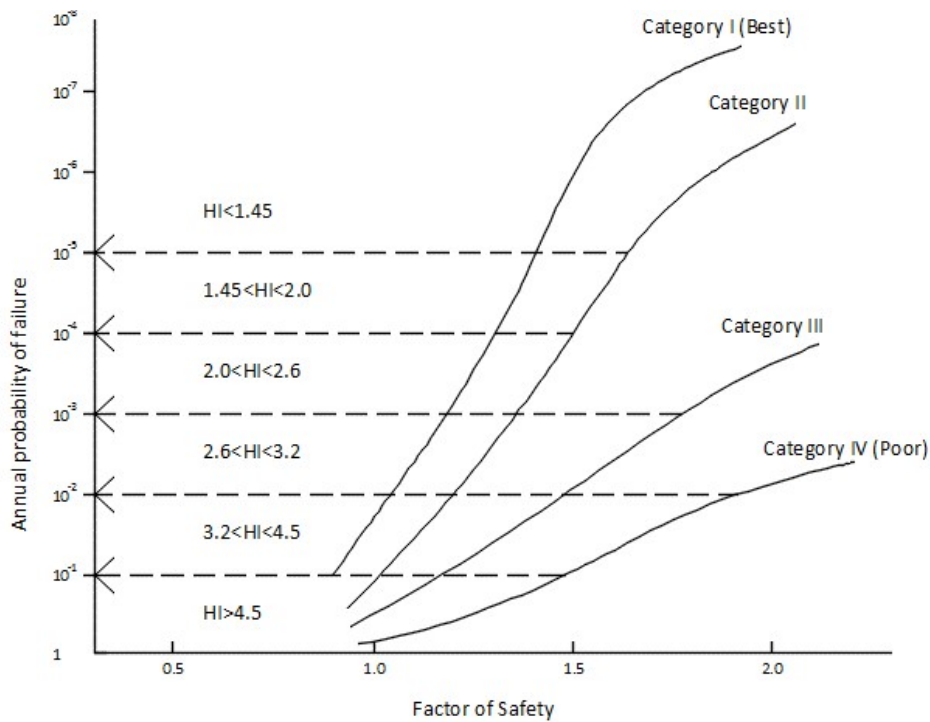


Figure 4: Classification of the engineered slopes and relation to the annual probability of failure (modified from Silva et al. 2008).

Table 87: Annual probability of failure for HI values, according to



5 Figure 4.

Annual probability of failure (P_r)	Hazard Index (HI)
$0.1 < P$	$HI > 4.5$
$0.01 < P \leq 0.1$	$3.2 < HI \leq 4.5$
$0.001 \leq P \leq 0.01$	$2.6 < HI \leq 3.2$
$0.0001 \leq P \leq 0.001$	$2.0 < HI \leq 2.6$
$0.00001 \leq P \leq 0.0001$	$1.45 < HI \leq 2.0$
$P \leq 0.00001$	$HI \leq 1.45$

The proper design and construction of the anchored retaining walls should be reflected in the absence of deformations and anchor overloading. Increased pressure at the load cells, deformations, cracks and wall tilting are interpreted as instability indicators. In that case the annual probability of failure P_r should be increased. Thus, factors of increase are added to the initial value of the HI, as shown in Table 98. The availability of this information implies that periodic and detailed wall inspections are carried out.

Table 98: Increase factor of the HI according to instability indicators at the retaining walls.

HI Increase	Increase of the service load	Deformation of the retaining wall and or/terrain
1	Pressure increase of <65% of ultimate load	Deformation <3mm/a

	External factors (groundwater table changes, erosion,...)	Cumulative deformation >30% of the maximum allowable deformation of the concrete
2	Pressure increase of >65% of ultimate load	Deformation >3mm/a
		Cumulative deformation >60% of the maximum allowable deformation of the concrete
		Presence of cracks, tilting, etc
		Non instrumented retaining wall

For measuring the consequences, we distinguished between the failure of small retaining walls, retaining walls shorter than 6m, and higher than 6m (Table 4413-Appendix). The length of the affected road section, considering the spreading of the debris, was empirically fixed as the triple of the wall height at the section.

5

3.3 Slow moving landslides (SL)

The involved landslides at the PoR have a persistent creeping movement, which in a worst-case scenario can lead to a sudden acceleration. The clay materials in the study area have a viscous behaviour, characterized by resistance increase as the movement rate increases. High rainfall precipitations often result in landslide reactivation, with centimetre displacements. As this analysis involves active landslides or landslides with episodic reactivations, the challenge here was to assess the probability of a given damage level, in function of the landslide movement rate. [All the road sections analysed here, lay on previously and well identified landslides, and as such movements are associated to landslide activity.](#)

10

Mansour et al. (2011) indicated that a relation may be established between the damage expected from slow-moving slides to roads, versus the displacement rate. They proposed ranges for the annual displacement rate leading to different extents of damage, which are 0-10, 10-100, 100-160, 160-1,600, and >1,600 mm/year corresponding, respectively, to limited, minor, moderate, severe damage or total road destruction. They also provided a description for each damage extent with respect to the type and frequency of the actions to be taken for its repair. The aforementioned ranges do not distinguish between horizontal and vertical deformations, on one hand, and on the other, they are based on the assumption that continuous, almost constant, movement takes place.

15

Instead, our experience in Gipuzkoa shows that landslide reactivation is episodic and can be sudden, producing deformations even in short periods, such as few days or weeks. Although those deformations are usually of centrimetric order, they can cause cracks, bumps and puddles on the pavement, and jeopardize road traffic safety. For this reason, more restrictive criteria than those proposed by Mansour et al. (2011) were applied. They relate the maximum observed horizontal landslide velocity and the annual horizontal displacement rate to the annual probability of exceeding a damage level. The following paragraphs describe how they were established.

25

In the case study, horizontal velocity data is available from the inclinometer measurements. [After 2010, deformation readings are constantly taken, every 3 months. In that sense, although the monthly velocity measurements have a limited precision, they can provide certain information on the landslide movement patterns.](#)

30

We inspected the in-situ damage, in order to establish the relation between the velocity and the road damage. Four levels were identified, as shown in Figure 5 and described qualitatively in the following:

- Damage level A (landslides of low intensity): There are rarely cracks and deformations. No speed reduction is required while driving. Crack sealing and resurfacing is periodically performed for periods longer than 1 year.
- Damage level B (landslides of moderate intensity): Damage includes pavement deformation and cracks and/or roadside destruction, without affecting the functioning of the road. If proper signalling is present, the chance of an accident is very low. Traffic conditions can be normally maintained if regular sealing and resurfacing is performed, until a more permanent solution.
- Damage level C (landslides of high intensity): Pavement deformation is substantial, including the presence of steps and puddles, and partial rupture of the platform affecting partly or entirely traffic lanes and/or the roadside. The normal functioning of the road is disturbed. Traffic is not interrupted, although restrictions such as alternative pass and traffic lights regulation are required. Accidents might occur if the vehicles enter the affected zone, without previous signalization. The normalization of the traffic conditions requires slope stabilization and road repair.
- Damage level D (landslides of very high intensity): Displacements are of the same order of magnitude as for level C, however with the vertical component prevailing giving place to complete destruction and loss of the pavement continuity. This situation is typical for roads situated on the crest or on the boundaries of landslides. The operation of the road is seriously affected. There is a high likelihood of an accident due to vehicles falling into the generated depressions. Important stabilization works and reconstruction of the road are required.



20 **Figure 5: The four damage levels identified at the roads of Gipuzkoa: (top-left) No/Slight damage, (top-right) Moderate damage, (down-left) Severe damage, and (down-right) Partial/total destruction.**

To establish damage proxies for the calculation of the expected consequences we correlated the observed road damage with the indications of the inclinometers at 24 reference PoR. The correlation was found to be positive, as, in most cases, increasing displacements were associated with more severe damage. In particular, the maximum horizontal monthly velocity and the cumulative displacement were used as the two proxies for the damage. For the establishment of the thresholds that relate the damage level with the terrain displacements, we tried to maximize the right predictions (when the observed damage level is the same with the calculated damage level), and at the same time to achieve a balance between damage underestimation and overestimation. The proposed thresholds are summarized in Table 409. Out of the 24 PoR, 20 yield right predictions, 1 presents damage overestimation and 3 damage underestimation (out of which one inclinometer measures has low reliability). Partial/total destruction occurs when the criteria for severe damage are fulfilled plus either one of two further criteria: the road is located inside the landslide scarp or a shear crack has being formed (the scarp manifests itself as a semi-circular form on the pavement).

Table 409: Damage criteria in function of landslide velocity (MHDR: maximum monthly horizontal displacement rate; ACDR: annual cumulative horizontal displacement).

Damage levels	MHDR (mm/month)	ACDR (mm/a)	Landslide intensity	Further criteria
A: No / slight damage	<3	<30	low	
B: Moderate damage	3-10	30-100	moderate	
C: Severe damage	>10	>100	high	
D: Partial/total destruction	>10	>100	very high	Road inside landslide scarp and/or shear crack

For the slow moving landslides, the hazard was expressed in terms of temporal probability of reactivation with an intensity exceeding a given level of damage. To assess the temporal probability we first distinguished between the landslides that are responsive to intense rainfall precipitations, from those for which a clear relation between rainfall and reactivation cannot be established. For each case, typical movement patterns, were observed by the inclinometer measurements. Four patterns were identified depending on the maximum monthly velocities. For each type (responsive and not responsive) and each pattern O, X, Y or Z as described in the following, the probability of reactivation with an intensity leading to low (A), moderate (B) and high (C) or very high (D) damage is determined.

As most landslides in the study area are creeping undergoing continuous small deformations, the probability of low damage is always high ($P \sim 1$). For some of them, acceleration takes place for intense or long rainfall periods. Moderate, high or very high damage might then occur with an annual probability equal or lower than 1. Its assessment of which is herein based on the return period of two major extreme rainfall events in the area.

The two extreme events were recorded during the observation period covered by the monitoring network of the Gipuzkoa Road Authority and they are: (1) the rainfall events of 4 to 7 November 2011 that were of high intensity and short duration. The rain recorded [at the Añarbe Dam](#) on the 6th of November 2011 was 185 mm, which according to the Water Management Agency of the Basque Country, corresponds to a return period of the order of 100 years; (2) the rainy period of January-February 2013 that was characterized by moderate to low daily intensity but of long duration, with cumulative precipitation measurements that exceeded the maximums of the reference period 1971-2000, and a return period of over 100 years according the Euskalmet (Basque Meteorological Agency).

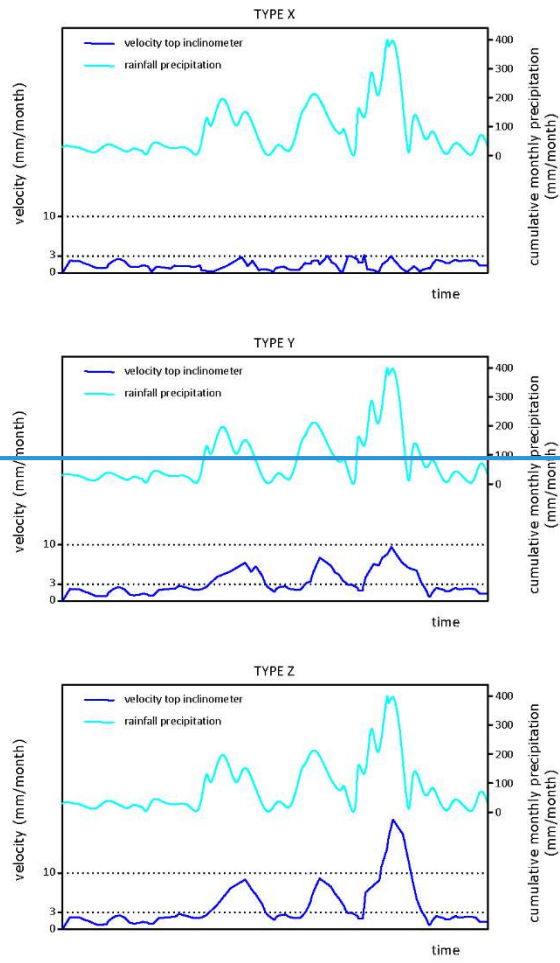
Accordingly, it can be assumed that the annual probability of reactivation or sudden acceleration of the instrumented landslides that have not experienced deformations during the two afore-mentioned events is lower than $P = 0.01$ ($\sim \frac{1}{100}$). Using this probability as a reference, the reactivation probability for the different patterns and types is defined empirically, according to the observed number of peak month velocities on the inclinometer measurements.

For slow moving landslides which are responsive to rainfall events, we distinguish between four movement patterns (Figure 6).

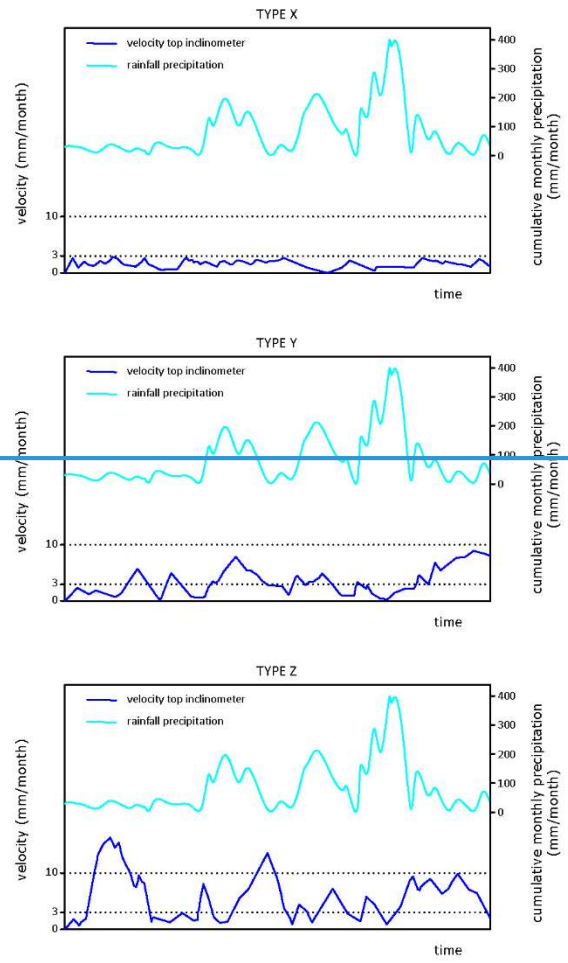
- Pattern O: Landslides which are inactive or extremely slow, which have not experienced deformations neither in extreme nor in common precipitation conditions. The annual probability of a reactivation is $P=0.01$.
- Pattern X : Landslides with a high probability of reactivation and low intensity, characterized by displacement rates lower than 2-3 mm/month and cumulative displacements lower than 30 mm (Figure 6, upper-left). They have not experienced significant accelerations for the two afore-mentioned extreme events. Low damage A is mostly expected.
- Pattern Y: Landslides with a high probability of reactivation and low/moderate intensity, characterized by displacement rates mostly lower than 5 mm/month and cumulative displacements 30-100 mm (Figure 6, middle-left). They have experienced some accelerations for the two extreme events, with a displacement rate under 10 mm/month. Low or moderate damage (A or B) is mostly expected.
- Pattern Z: Landslides with a high probability of reactivation and moderate/high intensity, characterized by rates higher than 2-3 mm/month and cumulative displacements greater than 100 mm (Figure 6, lower-left). They have experienced accelerations for the two extreme events, exceeding the displacement rate of 10 mm/month. For the PoR where the road is situated on the crest, we consider that they follow the pattern Z, irrespectively of the inclinometer measurements. High or very damage (C or D) is mostly expected.

Using the intensity-damage correlations of Table [409](#), the annual probabilities of exceedance of a given damage level were established, as shown in Table [410](#). Similar patterns were detected too for landslides which are hardly or not all responsive to rainfall events (Figure 6, right), even for the two afore-mentioned extreme events. In that case, higher probability values are set in order to reflect the increased uncertainty for the causes leading to the terrain acceleration (Table [410](#)).

LANDSLIDES RESPONSIVE TO RAINFALL



LANDSLIDES NOT RESPONSIVE TO RAINFALL



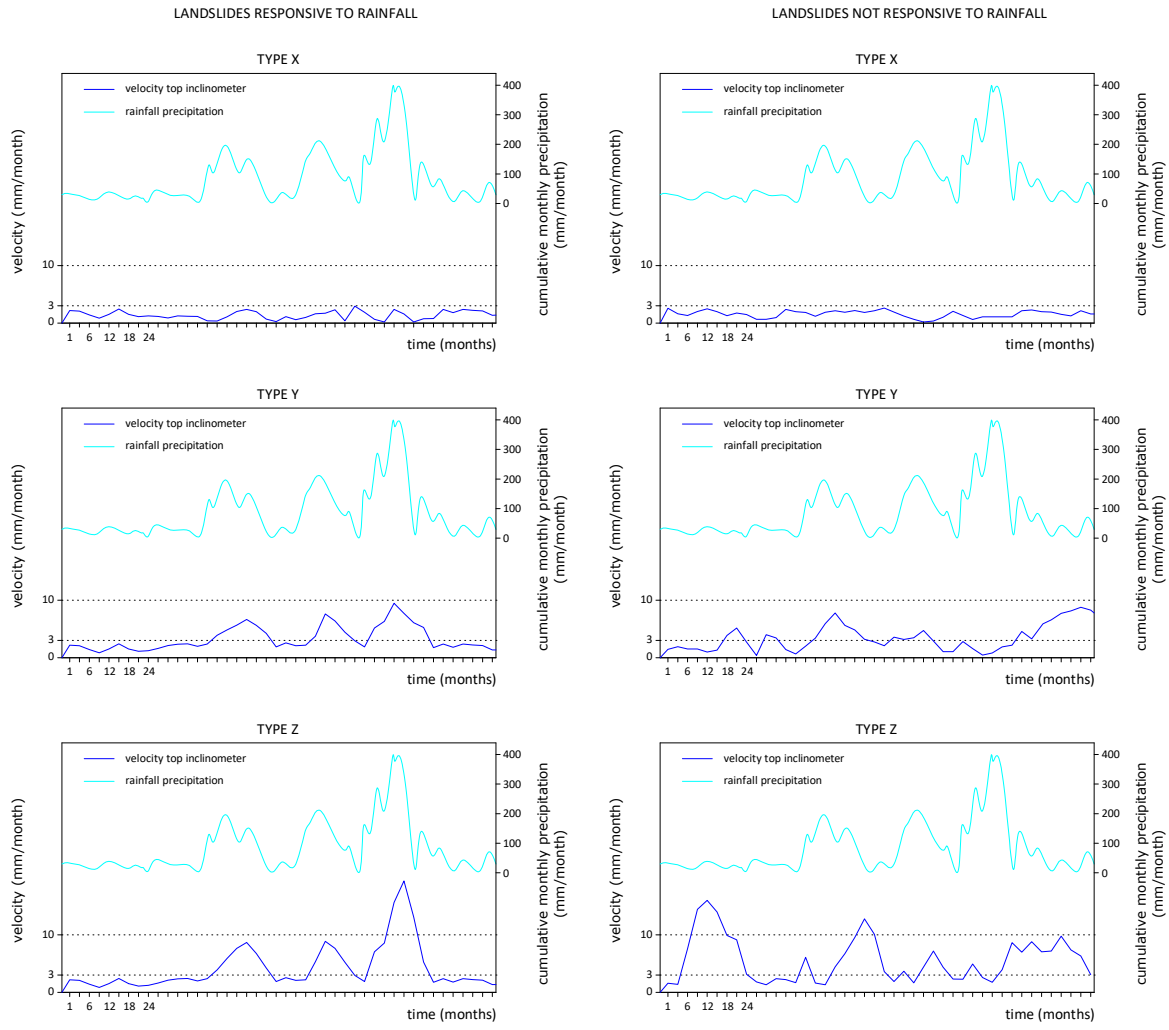


Figure 6: Patterns of movement for landslides responsive (left) and not responsive (right) to rainfall.

Table 4410: Annual probability of exceedance of a damage level and (in parenthesis) return period in years.

	Intensity	Type O	Type X	Type Y	Type Z
Responsive to rainfall	Low (P_l)	0.01 (100)	1 (1)	1 (1)	1 (1)
	Moderate (P_m)	0.01 (100)	0.02 (50)	0.5 (2)	1 (1)
	High (P_h)	0.01 (100)	0.002 (500)	0.01 (100)	0.02 (50)
	Very high (P_{vh})	0.01 (100)	0.002 (500)	0.01 (100)	0.02 (50)
Not responsive to rainfall	Low (P_l)	0.01 (100)	1 (1)	1 (1)	1 (1)
	Moderate (P_m)	0.01 (100)	0.05 (20)	1 (1)	1 (1)
	High (P_h)	0.01 (100)	0.005 (200)	0.02 (50)	0.05 (20)
	Very high (P_{vh})	0.01 (100)	0.005 (200)	0.02 (50)	0.05 (20)

5

The consequences, actions and costs related to slow-moving landslide damage repair that were used for the risk assessment and for the characteristics of the case-study are also reported Table 4413 (Appendix). The risk calculation for slow moving landslide is also based on the general Eq. 1. Nevertheless, in this case, for the realistic application of that equation three further points should be taken into consideration:

1) The probabilities of high or very high damage alternate when applying Eq. 1, depending on the location of the road section on the body (high damage) or on the scarp of the landslide (very high damage), and/or the absence (high damage) of presence (very high damage) of a shear crack on the road platform.

2) To calculate the total expected cost, the UC of Table 4413 has to be multiplied with the affected road section length (multiples of 10 m), for all damage levels. The affected section length is expected to vary for each damage level, in different percentages of the (total) road length that is marked between the landslide boundaries. For no/slight damage the percentage 10% of the total road length is taken, for moderate damage 20%, for severe damage 50%, and for partial/total destruction 100% (worst case scenario).

The reasons for reducing the affected road section to a percentage of the total road section in the landslide are the following:

i) Some of the landslides in the study area demonstrate composite and complex movements, incorporating multiple smaller sliding bodies, with very local displacements. In that case, instabilities and reactivations take place only locally, affecting only smaller fractions of the road;

ii) The landslide velocity is expected to present variations within the landslide body. More severe damage often demonstrates only at limited sections of the road, corresponding to the local highest movement rates. This might occur mostly for lower velocities, while higher velocities are more probably related with a generalized instability and damage.

iii) Minor displacements can be accommodated by the pavement (especially for flexible pavements), thus they do not result in damage of the entire road section. Major displacements, instead, result in greater stresses and strains for the pavement and more extensive damage, especially for rigid pavements that cannot accommodate them.

3) In the case of slow-moving landslides, the annual probabilities for the different damage levels should be mutually excluding, for the risk calculation. The values of Table 4410 provide the annual probability of exceeding a given damage level. Thus the annual probability of damage A, P_A , (none/slight) is the annual probability of exceeding damage A minus the probability of exceeding damage B (moderate). Accordingly, the annual probability of damage B, P_B , is the annual probability of exceeding damage B minus the probability of exceeding damage C or D (partial/total destruction or severe damage). The annual probability of damage C or D, P_C or P_D , is equal to the annual probability of exceeding damage C or D. All probabilities should be in the range [0,1], thus if the result from the above calculations is negative, P_A , P_B , P_C and P_D are taken as 0.

After incorporating these modifications, Eq. (1) is modified to Eq. (6) for slow moving landslides.

$$R_{SL} = P_l * 0.1 * L * C_l + P_m * 0.5 * L * C_m + P_{h(or\ vh)} * 1.0 * L * C_{h(or\ vh)} \quad (6)$$

Where:

R_{SL} : Risk for slow moving landslide

P_j : Annual probability of a given damage level (j takes values of l:low, m:moderate, h: high, and vh: very high)

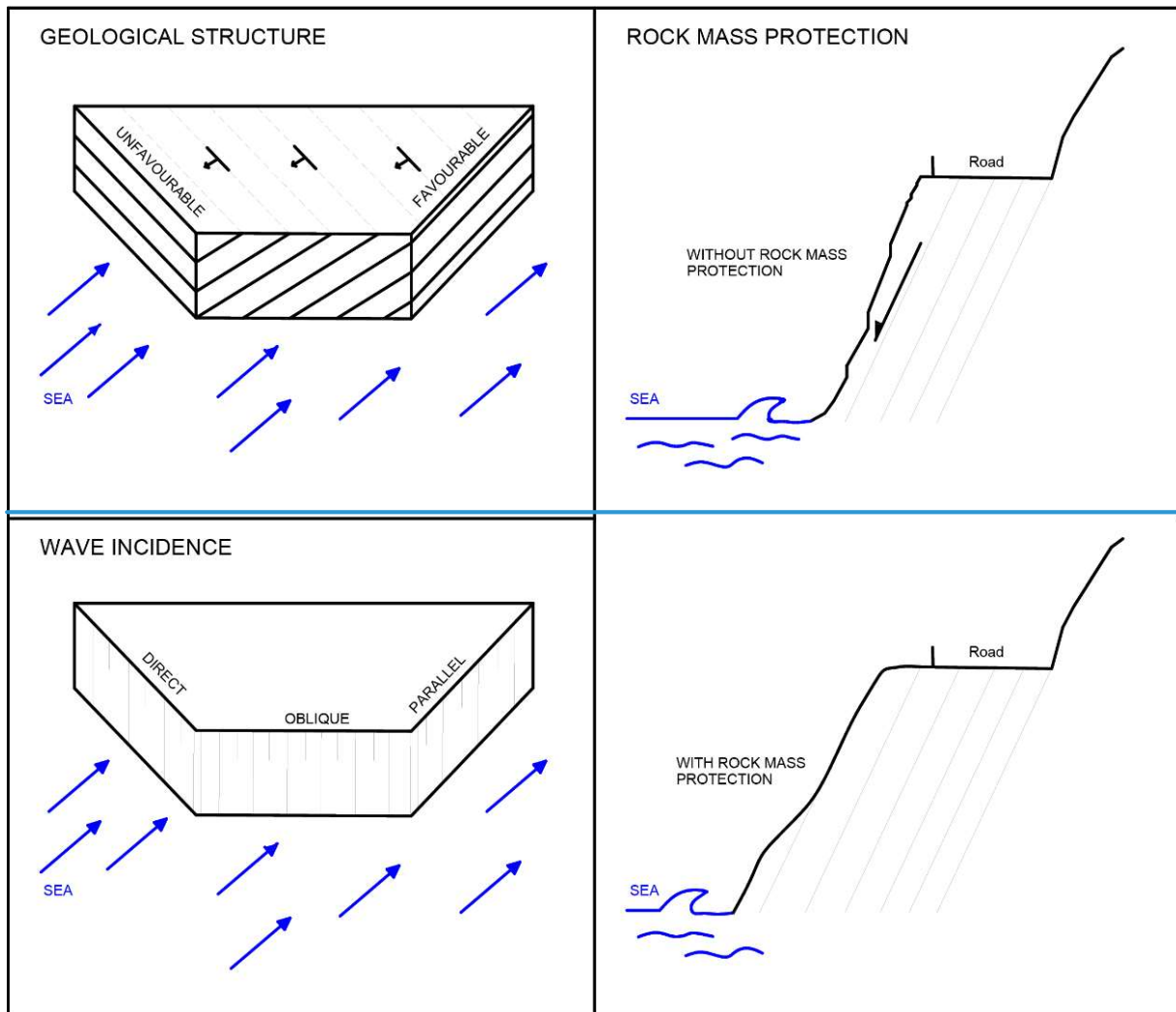
C_j : Consequences corresponding to the velocity associated with the given damage level, in terms of UC

L: total length the affected road section (multiples of 10 m).

3.4 Failure of sea walls (SW)

The pavement stability is determined by its capacity to resist the maritime storms that act on the coastal front, eroding the rock mass and impacting on protection elements like coastal walls. Four fundamental factors were identified for the stability of the road platform, which are used to define an index called Potential Instability of the Platform, PIP. These are:

- (i) — The geological structure that affects the slope stability. If the road is built on layers that dip towards the sea cliffs, the erosive action of the wave at the slope toe affects the slope stability and the platform itself. Figure 7 (top left) presents favourable and unfavourable geological structures, with respect to the orientation of the coastal front. This factor is used to evaluate the existence or absence of a potential failure mechanism, and relates to the cinematic probability of instability.
- (ii) — The existence or not of a terrain buttress that protects the slope toe from erosion (Figure 7, right). This factor is used to evaluate the effect of resisting forces to instability. The higher it is, the lower the probability of failure is.
- (iii) — The incidence angle of the waves. The erosive action is expected to be faster when the sea waves are perpendicular to the coast. At the coastline of Gipuzkoa, the common wave directions are W, NW and N (Figure 7, bottom left). This factor is related to the driving forces inducing instability.
- (iv) — A correction factor to consider the effect of protection structures against coastal erosion. This factor refers to the increase of resisting forces to instability (Table 12).



5 **Figure :** (top-left) Unfavourable and favourable disposition of the geological structure layers of the slope (direction and orientation), in relation to the orientation of the slope face. Arrows indicate the predominant waves; (bottom-left) Direct, parallel and oblique incidence angle of the waves on the coastal front; (right) Rock mass protection effect without and with a protection mass. In the former case the toe erosion destabilises the coastal slope leading to damage of the road platform.

The index PIP is first calculated by Eq. (7), with values that range between 0 and 9.

$$10 \quad PIP = G_s + M_p + I_o + F_c, \quad (7)$$

Where

Geological structure (G_s): score from 1 (favourable) to 3 (unfavourable)

Protection mass (M_p): score from 1 (sufficient) to 4 (without mass)

Wave incidence (I_o): score from 1 (oblique/parallel) to 2 (direct)

15 Correction factor (F_c): values from Table 16.

Table 12: Correction factor of the PIP.

The scoring for the factors of Eq. (7) was selected empirically and equal weights were attributed to all factors.

The index PIP was associated with the annual probability of failure sea walls (Table 13) based on expert judgment. Although there is a lack of empirical data to validate this approach, there is certain equivalence between the annual probability of failure for sea walls and retaining walls, which makes its use practical for the comparison of the two hazards. Sea walls with PIP in the range of 0-2 have the same probability of failure as retaining walls with HI lower than 2.6. For constructions of Category III (without specific design that do not follow standards) and IV (poor or completely missing engineering knowledge basis) this corresponds to a safety of factor greater than 1.7. Respectively, for PIP indices 3-6 (corresponding to HI 2.6-3.2), the safety of factor is higher than 1.5, for PIP 7, it is higher than 1.2, and for PIP in the range of 8-9 the safety of factor can be lower than 1.

Table 13: Annual probability of failure corresponding to the different classes of the PIP.

In the proposed approach, the maintenance state of the walls and of the good functioning of the anchorage is not taken into consideration. Still the sea wall failure is often the result of eroded anchorage and bad support. To overcome this limitation a conservative application of the correction scores of Table 12 is recommended.

The consequences of the failure depend on the mobilized volume, which relates to the extent of the affected platform. Table 14 summarizes the actions that are expected for 4 reference volumes. Interpolation and extrapolation is suggested for other volumes. In lack of further data, and as a simplification the length of the affected height can be taken as three times the wall height.

4. Application examples and results

The methodology is being applied on a periodic basis to the road network of Gipuzkoa. The calculation of the risk for the different hazards was organised using automatized Excel data sheets, where the user introduced the required data from a closed list of options. Some application examples for selected PoR are presented here. The overall results for all analysed PoR during the 2015 inspection are shown in section 4.5. Due to space limitations, only the most important data needed for the application of the proposed methodology are provided here. An extended archive with further details on the location and type of instabilities, accompanied by images and maps and detailed descriptions is at the disposal of the authors. For the same reason only a limited number of figures presenting the current state of the road has been included too.

4.1 Rockfalls

We indicatively present the risk for two different cases of rockfall affected sections: the PoR L1C, situated at the local road GI-3324 (from km 0.700 to 1.450) and the PoR P4C of the highway N-1 (km 407.395 to 407.680). The two PoR are shown in Figure 87.

Rock instabilities at the PoR L1C are due to the unfavourable structural conditions of the rock mass, leading to planar and wedge failures, with a safety factor of the blocks on the slope seemingly smaller than 1. In some few areas toppling mechanisms are also observed. Although rockfalls occur with a frequency higher than 2 events per

year, there is no historical record of the events. The road platform is in a good state without major impact signs, indicating that no high magnitude events have been occurring. Thus, the magnitude-frequency relation of events here is evaluated considering the slope properties from Table 43, and applying Eq. 2 for the calculation of the I_F . For I_P (joint persistence): Low, I_{DC} (density scars) >0.3 , I_E (differential erosion): Yes, I_{FP} (number of points with potential rockfalls) >11 , and I_{SMR} (SMR index): 40-80, I_F results to be 6, which corresponds to an annual frequency of events equal to 1 (from Table 54). This frequency is proportionally distributed amongst the magnitude classes A, B and C, according to the in situ observed relative frequency of potential unstable volumes (45% for $<A: 0.5\text{m}^3$, 40% for B: $0.5\text{-}5\text{ m}^3$, 15% for C: $5\text{-}50\text{ m}^3$). This results in annualized expected frequency of events equal to 0.45, 0.40 and 0.15, respectively for each magnitude class. No protection measures exist, thus no correction is made on that frequency. The risk is then calculated for each magnitude size A, B and C and summed up after Eq. (1), considering the UC, of Table 44. The total annual risk for L1C is 1.55.

For the PoR P4C, a similar procedure was followed. For I_P : Moderate, $I_{DC} >0.16$, I_E : No, I_{FP} : 4, and I_{SMR} : 0-40, I_F results equal to 5, which corresponds to an annual frequency of events equal to 0.2. This frequency is distributed to the magnitude classes: 0.08 for A, 0.09 for B, 0.01 for C, 0.01 for D and 0.01 for E. In this case, a correction is applied on the annual frequency. Considering that the slope is partially protected by gunite and bolts in a bad state of maintenance, and that a ditch with width smaller than 5 m exists, the summative frequency correction factors for the two types of measures from Table 6 are 0.45 and 0.2 for magnitudes A and B. For higher magnitudes, the existing protection measures are not considered to be efficient. The annual frequencies per size after correction are 0.03, 0.07, 0.01, 0.01, 0.01 for A, B, C, D and E, respectively, which after multiplication with the correspondent UC and summing, they result in a higher total annual risk than the previous one, and equal to 3.05. The higher risk is ought to the existence of bigger rock blocks which cannot be retained by the actual protection measures.



Figure 7: (left) PoR L1C of the road GI-3324 (from km 0.700 to 1.450), without protection measures; (right) PoR P4C of the road N-1 (km 407.395 to 407.680) with protection measures.

4.2 Anchored retaining structures

Two further examples, for the risk related to the failure of anchored retaining structures are presented (Figure 98).

The first one is the highway section P2A, where two anchored walls sustain a weathered flysch rock mass. The two walls cover the upper and middle part of the slope. The upper wall has a length of 60 m, with 24 anchors and the lower is 42 m long with 42 anchors. The slope has an inclination of 35 degrees in the first 20 m and of 20 degrees in the rest of its length. At the bottom of the slope there is a concrete wall. During the construction works of the N-121-A, water seepage was detected on the middle and upper parts of the slope, which have been related to the mobilization of soil. The slope is monitored with inclinometers, piezometers and the walls with hydraulic load cells, given the existence of an urbanized area on the top of it. In the upper part of the slope there a weathered zone, with an estimated thickness of 20 to 22 m, which determined the type and length of the anchors.

Following the procedure described in section 3.2, for a Safety Factor >2 (1 point from Table 76), working load $<55\%$ (1 point), grout length >1.2 m/10 t (1 point), anchoring ground is a mixture of sound and weathered rock (3 points), available data for anchors and technical assistance during construction (1 point), the calculated hazard index from Eq. (5) before correction is 1.222. Given the presence of cracks in the lower wall, a correction factor of 2 is applied to the HI, which becomes 3.222 and the corrected annual probability of failure is then 0.0072 (from Table 87). The upper and lower walls together have a total height of 8 m. When applying the general risk equation the respective costs from Table 4413 are considered and adjusted to the total length of the affected road section (24 m or 2.4×10 m), and they are found to be 290.4 UC. The total risk for this section, as the product of failure probability with that cost is equal to 2.09.

The second section, the PoR C8A corresponds to a rocky slope of 240 m and height 37m, of an average inclination of 45 degrees. It is treated with gunite with a protection net and a reinforcement of 646 bolts of 16 m length. The works for the reinforcement of this slope were performed between 1992 and 1993, with 8 strips of gunite, 5 m tall each one. Every strip includes 4 rows of bolts, except the lowest one which has 5 rows and the crest which does not have any. The load cells indicate that presently several bolts are overloaded. The rock mass is slightly to moderately weathered over the entire slope. The maximum volume that has been estimated to be unstable is 21,800 m³.

The parameters that have been used for C8A are (Figure 97, right): Safety Factor <1.30 (it is not known for this case) (5 points), working load $>65\%$ of the ultimate load (5 points), grout length >1.2 m/10 t (1 point) and anchorage on a slight to moderate weathered rock (3 points). Although data exist for some anchors, it is not available for all of them, which is penalized assuming the respective value of “no” in Table 76. Construction was performed with technical assistance. The initially calculated HI is 3.67. As the bolt pressure increase is greater than 65% of the ultimate load (up to 80%), the HI is increased by 2 and it is 5.667 which corresponds to an estimated failure probability of 0.82. This value was calculated according to Table 87, after fitting a power law curve to the HI and the probability threshold values mentioned therein. As the wall height is $H > 6$ m and the affected road length is 111 m the total cost is 1343.1 UC and the risk is 1,101.34, which is substantially higher than the previous one, as a consequence of the higher hazard in this section.



Figure 8: (left) PoR P2A of the road AP-8-1-1 (from km 77.140 to 77.210) where the crest of the slope and the retaining wall with anchors is seen; (right) C8A of the road G-2634 (32.980 to 33.150) with gunite, rock bolts, and anchors.

5

4.3 Slow moving landslides

Two examples of PoR, subjected to damage for being situated within slow moving landslide areas are presented here: the C3C and the C9G (Figure 109).

10 The PoR C3C involves a rotational landslide, occurring in the interface between clay colluvial soil and rock. It affects a road section of almost 200 m, with a retaining wall of 1 m height, along 41 m. There is not a historical record of the damage evolution. The road platform is found to be cracked and vertically deformed, as well as the ditch. For about 20 m the cracks are 2-3 cm open and mostly affect one direction of the road. The most probable reason for the instability is the presence of water and the deficient drainage causing humidity and water flows.

15 Slope movements occur during high rainfall episodes, which was also confirmed by the indications of the inclinometers as explained in the following.

There are two inclinometers starting measuring since November 2013, initially with monthly frequency, which are 14.5 and 15.5 m deep each. Movements were found to be concentrated at a depth of 0.5-2.0 m (corresponding to the thickness of the colluvium soil layer). The inclinometer measurements indicate that the soil movements directly

20 respond to the total monthly precipitation intensity, expressed in mm/month, with records of up to 8 mm/month and cumulative displacement higher than 100 mm. These movement rates correspond to Pattern Z (Figure 6, left). According to Table 110, the annual probability of exceeding low damage is 1, of moderate damage is 1 too, and of high damage is 0.02. As field inspections showed no presence of scarp or shear crack, the potential of very high damage was eliminated. Consequently, the probability of occurrence of only high damage is $P_h=0.02$, of only

25 moderate damage is $P_m=1-0.02=0.98$, and of only low damage is 0 (moderate damage constantly overlaps with low damage). Applying Eq. (2) and the costs of Table 113 for a total length of affected road of 200 m, the risk result here is 66.18.

The soil instability affecting the C9G is ought as well to colluvial soil accumulations of 3-4 meters depth, over the bedrock. There are visible settlements and the ditches are deformed. The landslide is instrumented with two

30 inclinometers that indicate that it is active.

The inclinometer measurements indicate vertical displacements lower than 2-3 mm and cumulative displacement lower than 30 mm, which points to a movement pattern of type X. There is not any scarp or developed shear displacements. Accordingly the probability of exceeding low damage is 1, moderate damage is 0.05 and high damage is 0.005. As previously, the probability is calculated for high damage: 0.005, for moderate damage: 0.045, and for low damage: 0.5, which for total a length of 300 m, and the same as previously costs, gives a total risk of 10.84.



10 **Figure 9:** Road sections situated within slow moving landslides, with damage: (left) PoR C3C of the road GI-2133 (from km 8.280) with observed deformations and cracks on the road pavement; (right) PoR C9G of the road GI2637 (from km 17.891 to 18.220) showing minor cracks already sealed.

15 4.4 Failure of sea walls

The failure of sea walls and the consequent slope instability has direct effects on the stability of the overlaying road platform at the coastal roads of Gipuzkoa, which is transited by a high number of tourists, especially during the summer months. Here, the PoR B9A and P7L are brought as an example. Figure 11 shows part of those slopes and of the sea walls.

20



Figure : (left) PoR B9A of the road GI 638 (from km 1.400), of high risk, with a view of the coastal wall from the road, with oxidised and bent bolt. The sea wave action has left the rock exposed and the bolt unsupported; (right) PoR P7L of the road N 634 (from km 24.650 to 24.750), which was stabilized in May 2014.

5

The section B9A is a 15 m high rocky slope with a 45-degree inclination towards the sea. Sea waves cause foot erosion and loss of support for the overlaying strata. The upper part of the wall is supported by bolts in a very bad maintenance state. The potential failure mechanism is planar failure initiated by the loss of support by erosion of the stratification. The calculation of the index PIP is done considering the following values for the reference parameters: Geological structure (Gs): 3 (unfavourable), Protection mass (Mp): 4 (without mass), Wave incidence (Io): 2 (direct incidence), and Correction factor (Fc): 0 (Table 12), as in practice the bolts are out of order and there is no protection of the coastal front from the waves. Equation (7) provides a value of 9 for the PIP, which from Table 13 and by extrapolation corresponds to very high potential of instability and annual probability of failure $P=0.1$. The cost of the consequences is calculated according to Table 14. An unstable volume of 600 m^3 is roughly assumed from topographical measurements, which sets the cost at 159.6 UC per 10 m of affected road length. The potentially affected road is roughly assumed to be 3 times the wall height and equal to 45 m. Thus the expected cost is 718.2, and the risk is 71.82.

10

15

At the section P7L and for a specific part of the road, there is a masonry sea wall, 6 to 9 m high for the whole length of the section (for the calculation we considered 8 m). The exposed slopes have a fair disposition of the joint sets, which dip orthogonal to the sea. As previously an annual probability of failure $P=0.01$ was calculated for a PIP equal to 6. This PIP is evaluated considering Geological structure (Gs): 2 (fair), lack of protection rock mass (Mp): 4 (without mass), Wave incidence (Io): 2 (direct incidence), and Correction factor (Fc): 2, as the coastal front remains protected by the masonry wall, which is locally reinforced. For the 90 m^3 of mobilized mass corresponding to 34.5 UC per 10 m repair cost, and an affected road length 24 m, the risk for this road is 0.82. The effect of the protection wall in reducing the risk, is reflected by its lower value, when compared to the B9A.

20

25

4.5 Overall results and discussion

As aforementioned in section 2, out of the totally 9584 PoR, 20 concern rockfalls, 37 anchored walls, and 27 slow moving landslides and 11 sea walls. The classification of the risk here, was based on economic criteria, considering that it expresses the average annual repair cost at a section. Five risk levels were used: low (<1 UC), moderate (1-10 UC), high (10-100 UC), and very high (>100 UC).

5

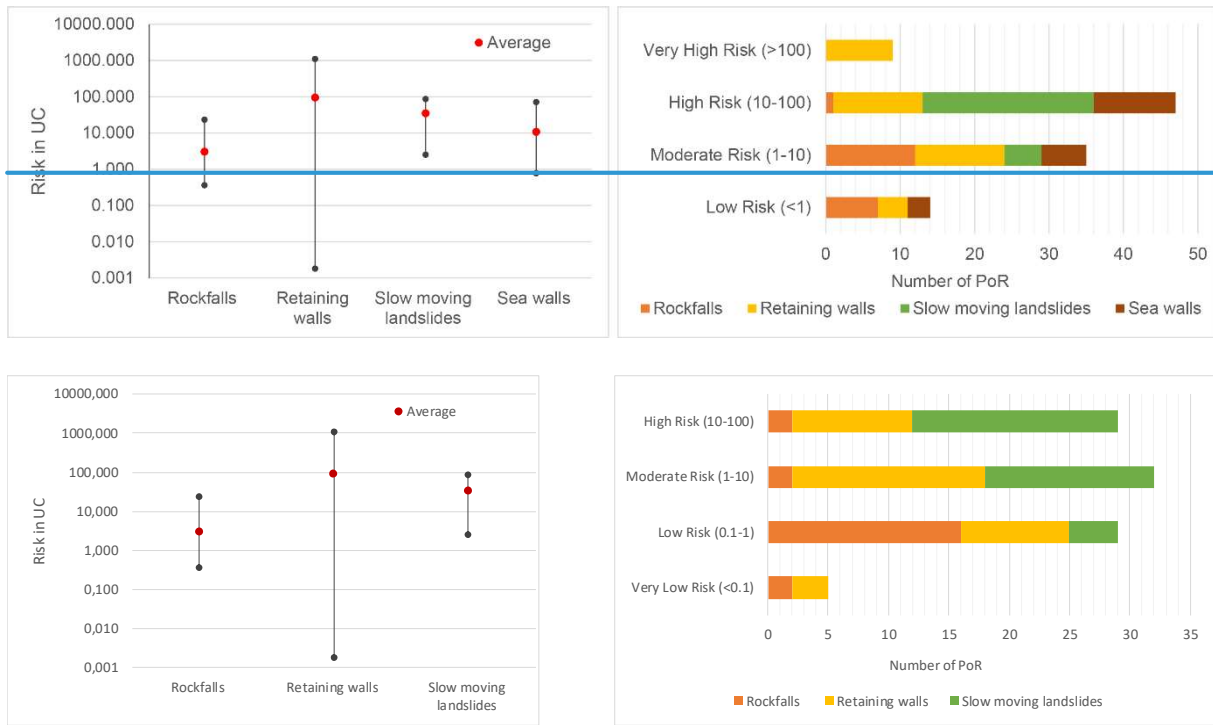


Figure 10: (left) Average, maximum and minimum calculated risk for each hazard type; (right) Number of PoR per hazard type in each risk class.

10

Figure 10 shows how the risk levels are distributed over the different hazard types. High risk areas mostly involve retaining wall failures or slow moving landslides. Rockfalls principally cause low and moderate risk and sea wall failure are of low or high risk. The risk classification highlights 42.21% of the analysed PoR being of very high risk and needing imminent protection interventions. The highest risks in the study site (above 100 UC) were observed for 9 of the retaining structures. 28.42% of the PoR fall into the class of high risk, 39.35% of moderate risk and 24.13% of low risk. Depending on the prioritization needs and the economical restrictions for the planning of the interventions, other thresholds can be used for the risk classification, in order to reduce the number of sections marked as of highest priority.

15

20

The risks corresponding to the repairs related to the failure of the retaining walls can be one order of magnitude higher than for the rest of the hazards. This is reasonable given the fact that, besides road cleaning and repair costs, the additional wall construction/repair costs are high and that for this type of events, high soil masses can be mobilized.

The calculated risks overestimate the real average annual costs, as they do not take into consideration that after the hazard is reduced and the chances of damage for the following period are much lower after protection

interventions. Moreover, in practice, low and moderate damage are not repaired each time they occur, even if required, but in larger intervals, which reduces the real repair costs.

The values calculated here for the risk components are not precise but carry a certain degree of uncertainty as also in other quantitative landslide risk studies (Jaiwsal et al. 2010, Vega et al. 2016, Corominas et al. 2014). An extensive quantification of the uncertainties and their effect on risk calculation procedure is a challenging task, and has not been included here. However, some principal sources of uncertainty are mentioned in the following with the aim to highlight steps in the procedure which present high degree of uncertainty and might have a strong effect on the final risk results.

For rockfalls, it is the attribution of large frequency values to the high magnitude classes E and F, that results in excessive costs. In any case, the definition of a maximum rockfall volume in a slope is a complicated issue, especially considering the structural geology and the existence of bridges in the rock mass with a given persistence (Corominas et al. 2018). The mobilised volume for the failure of anchored retaining walls also implies a high degree of uncertainty with a substantial effect on the final risk. When it comes to slow moving landslides, where the frequency and intensity assessment is based on the inclinometer measurements, uncertainties are associated with the location of the inclinometers in the landslide, the frequency of the measurements that also determine the precision of the velocity values, the potential existence of deeper rupture surfaces with displacements which are not registered by the actual inclinometers, and operability issues too. Through the entire procedure, the definition of different thresholds presents moderate uncertainty as these were selected to fit the best real event occurrences, with a certain coherence, as explained, respectively for each hazard, in the previous sections. The same for the association of magnitude and intensity of events with damage, as the actions acting on the road and causing its damage are complex and the roads also vary in size, materials and resistance.

The occurrence of landslides in areas intersecting transportation corridors might affect societies and the built environment in an extensive way (Remondo, 2008). The related indirect risk involves the impact on lifeline systems (e.g. water and sewage system, energy and lines of communication) in the vicinity of the roads, and present in the path of landslides. Interruption of access to and from rural and urban areas and critical transportation infrastructure like airports, ports, and bridges, as well as other medical, educational, industrial and other critical facilities, may cause important social and economic loss. Touristic, commercial, business activities, as well as real estate values are amongst the most commonly affected. Given the multiple dimensions and cascade effects that are inherent in such situations, indirect risks might entail large scale consequences, which, in monetary terms, substantially exceed the direct risks. The establishment of the links and intersections, leading from the initial hazardous process to (some of) the afore-mentioned consequences presents certain perplexity, the investigation of which is out of the scope of this work. Simplified procedures as the one presented by Corominas and Mavrouli (2015) have been proposed in the past for the study area. Despite this, the work presented here is limited to the investigation of the risk related to direct losses, and does not take indirect losses into consideration.

5. Conclusions

In this paper a procedure for the quantification of risk related to the geotechnical hazards across a road network has been presented. The studied hazards are rockfalls, failure of retaining structures, ~~and slow moving landslides, and failure of sea walls due to sea erosion.~~ The risk has been calculated in monetary terms, as multiples of a Cost of Unit set at 1000 €.

~~The application of the proposed procedure to the road network of Gipuzkoa highlights that one of the most important aspects of risk quantification is the calculation of the hazard in terms of temporal probability of an event of a given magnitude.~~ In the studied area, the extensive and periodic collection of data permitted the magnitude-frequency evaluation based on historical data and, for rockfalls, where this data lacked, the development ~~and calibration~~ of an indicator model, ~~based on local data~~, to assess it. The parameters included in this model are the joint persistence, the density of scars, the differential erosion, the number of points with potential rockfalls, and the slope mass rating SMR index.

For slow moving landslides with permanent or episodic activity, ~~the annual probability of occurrence is not relevant, and it is assumed equal to $P=1$. Instead the annual probability of reactivation of a landslide with a given intensity (low, moderate, high, very high) was used for the quantification of the hazard.~~ the landslide velocity was found to correlate well with the visible damage on the road pavement. The monthly thresholds of 3 and 10 mm and the cumulative displacement of 30 and 100 mm were used for the landslide intensity classification (see Table 13). ~~For several PoR of the study area, a good correlation of the soil movements with the daily rainfall intensity was found. This was used as a reference in order to fix the annual probability of reactivation for the landslides, considering as well their intensity, based on the return period of the extreme rainfall events of 2011 and 2013, which is about 100 years. The probabilities of occurrence, for each PoR, were then attributed for lower or higher intensity classes, according to the observed landslide pattern with reference to this value, and the maximum monthly velocity and annual displacement observed by the inclinometer measurements. The probability of reactivation for the landslides that were not found responsive to rainfall was considered higher than for the responsive ones, in order to penalize the uncertainty related to the triggering conditions.~~

~~In the study area, the number of sections is very high, not permitting the evaluation of the probability of slope/structure failure with high precision. Nevertheless the proposed procedure takes into consideration the different failure mechanisms and the factors which are relevant to the probability of failure (rainfall, deformations, and design criteria for the structures).~~ The highest risks in the study area referring to the repair cost for the damage of roads, are, in most cases associated, in descending order, with retaining structures, slow moving landslides, ~~coastal walls~~, and rockfalls. The annual repair cost for retaining wall failure presents large variation for the different PoR, ought to the variation on the maintenance conditions and working loads. Using the proposed procedure, the prioritization of interventions for all the PoR was made and the number and location of the PoR that require imminent interventions can be assessed. The thresholds defining the risk classes can be adjusted, according to financial availability for interventions, so as to point a smaller or higher number of PoR.

~~The application and calibration of the proposed methodology is an on-going procedure, as~~ Several limitations exist in the application of the methodology which are related to the availability of data in the areas, as well as the data quality. Additionally, given the inherent data uncertainties, it is recommended that that the final results are treated

as relative and not as absolute ones. Further validation and refinement, using real annual costs is necessary for improving the method, which can be realized if loss data is systematically collected. This is an on-going procedure, as in the study area inspections are made periodically for the PoR with the higher risk rates, and landslide activity or damage are being assessed on a continuous basis, especially after extreme rainfall events. Further work is needed in the following period, to adjust the methodology after the collection of new data.

The calculated risk results are conservative, as in reality low and moderate damage are not repaired each time they occur, but in larger intervals, however. The inclusion of this parameter cannot be standardized for the study area, as the repair works are not regular.

As described in the introduction, the methodology developed in this work here had as a starting point the requirements and data availability in the selected case study. Several parts of the proposed procedure for the risk assessment and ranking along road networks are strongly related to local conditions, concerning geological, geomorphological and climatic parameters and are empirical. Accordingly, the thresholds that have been selected here for the hazard descriptors and the classification of the consequences strongly depend on the expected range of frequency and magnitude/intensity of events in the study area. Moreover, the selection, scoring and weighting of the factors which are used for the calculation of the risk components have an empirical/judgmental basis are based on data collected in the study area, and as such, their use, although supported by the physical interpretation of the phenomena, can only become acceptable for the specific case study on the grounds of calibration and validation. The validation of the proposed classifications and thresholds is an iterative on-going procedure which requires observing the actual evolution of the phenomena, damage and maintenance/repair costs at the PoR.

study and cannot be transferred to other areas, without further studies. In that sense, the application of the proposed methodology to other case studies is principally suggested in terms of procedure and factors to consider for a multi-hazard integrated risk assessment for roadways. Instead Adaptation to the local conditions is needed for the scoring, and classification of the hazard parameters, and for the assessment of temporal probability values considering the intensity and recurrence of local triggering factors, as well as for the asset and cost assessments. Further applications of the procedure presented here to areas with similar or diverse data settings would be useful for its refinement, and would provide an insight for framing the conditions of its transferability to other regions.

Acknowledgments

This work has been performed with the support of project on Integrated Assessment of the Geotechnical Risk of the Gipuzkoa road network (15-ES-563/2009) funded by the Gipuzkoako Foru Aldundia and of the Project RockModels-Characterización y modelización de los desprendimientos rocosos (<https://rockmodels.upc.edu/en>) funded by the Spanish Ministry of Economy (Ref. BIA2016-75668-P, AEI/FEDER,UE).

References

Ábalos, B.: Geologic map of the Basque-Cantabrian Basin and a new tectonic interpretation of the Basque Arc, Int J Earth Sci (Geol Rundsch), 105, 2327, doi:10.1007/s00531-016-1291-6, 2016.

- Barnolas, A, and Pujalte V: La Cordillera Pirenaica: definición, límites y división. In: Vera JA (ed) Geología de España, Sociedad Geológica de España—Instituto Geológico y Minero de España, Madrid, 233–241, 2004.
- Budetta, P.: Assessment of rockfall risk along roads, *Nat Hazard Earth Sys*, 4(1), 71–81, doi: 10.5194/nhess-4-71-2004, 2004.
- 5 Bunce, C. M., Cruden, D. M., and Morgenstern, N. R.: Assessment of the hazard from rock fall on a highway, *Can Geotech J*, 34(3), 344–356, doi: 10.1139/cgj-34-3-344, 1997.
- Corominas, J., van Westen, C., Frattini, P., Cascini, L., Malet, J. P., Fotopoulou, S. Catani, F. Van Den Eeckhaut, M., Mavrouli, O., Agliardi, F., and Pitilakis, K., Winter, M. G., Pastor, M., Ferlisi, S., Tofani, V., Hervás, J., Smith, J.T.: Recommendations for the quantitative analysis of landslide risk, *B Eng Geol Environ*, 73(2), 209-263, doi:10.1007/s10064-013-0538-8, 2014.
- 10 Dai, F., Lee, C., and Ngai, Y.: Landslide risk assessment and management: an overview, *Eng Geol*, 64(1), 65–87, doi:10.1016/S0013-7952(01)00093-X, 2002.
- Eidsvig, U.M.K., Kristensen, K., and Vangelsten, B.V.: Assessing the risk posed by natural hazards to infrastructures, *Nat Hazard Earth Sys*, 17, 481–504, doi:10.5194/nhess-17-481-2017, 2017.
- 15 Fell, R., Corominas, J., Bonnard, C., Cascini, L., Leroi, E., and Savage, W. Z.: Guidelines for landslide susceptibility, hazard and risk zoning for land use planning, *Eng Geol*, 102, 85–98. doi: 10.1016/j.enggeo.2008.03.022, 2008.
- Ferlisi, S., Cascini, L., Corominas, J., Matano, F., Ferlisi, S., Cascini, Á. L., and Corominas, J.: Rockfall risk assessment to persons travelling in vehicles along a road: the case study of the Amalfi coastal road (southern Italy), *Nat Hazards*, 62, 691–721, doi: 10.1007/s11069-012-0102-z, 2012.
- 20 Ferrero, A. M., and Migliazza, M.: Landslide Transportation Network and Lifelines: Rockfall and Debris Flow. In *Landslide Science and Practice*, Berlin, Heidelberg: Springer Berlin Heidelberg, 161–170, doi: 10.1007/978-3-642-31319-6_23, 2013.
- Gharaibeh, N. G., and Lindholm, D.: A condition assessment method for roadside assets. *Struct Infrastruct E*, 10(3), 409-418, <https://doi.org/10.1080/15732479.2012.757330>, 2014.
- 25 Gómez, M., Vergés, J., Riaza, C.: Inversion tectonics of the northern margin of the Basque Cantabrian Basin, *B Soc Geol Fr*, 173:449–459, doi: 10.2113/173.5.449, 2002.
- Hungr, O., Evans, S. G., and Hazzard, J.: Magnitude and frequency of rock falls and rock slides along the main transportation corridors of southwestern British Columbia, *Can Geotech J*, 36(2), 224–238, doi:10.1139/t98-106, 1999.
- 30 Jaiswal, P., Van Westen, C. J., and Jetten, V.: Quantitative landslide hazard assessment along a transportation corridor in southern India, *Eng Geol*, doi:10.1016/j.enggeo.2010.09.005, 2010.
- Kappes, M.S., Gruber, K., Frigerio, S., Bell, R., Keiler, M., Glade, T. The MultiRISK platform: The technical concept and application of a regional-scale multihazard exposure analysis tool. *Geomorphology* 151–152: 139-155. doi.org/10.1016/j.geomorph.2012.01.024
- 35

- Mansour, M. F., Morgenstern, N. R., and Martin, C. D.: Expected damage from displacement of slow-moving slides. *Landslides*, 8(1), 117–131, doi:10.1007/s10346-010-0227-7, 2011.
- Michoud, C., Derron, M.-H., Horton, P., Jaboyedoff, M., Baillifard, F.-J., Loye, A., Nicolet, P., Pedrazzini, A., and Queyrel, A.: Rockfall hazard and risk assessments along roads at a regional scale: example in Swiss Alps, *Nat Hazard Earth Sys*, 12, 615–629, doi: 10.5194/nhess-12-615-2012, 2012.
- Nicolet, P., Jaboyedoff, M., Cloutier, C., Crosta, G. B., and Lévy, S.: Brief communication: On direct impact probability of landslides on vehicles, *Nat Hazard Earth Sys*, 16(4), 995-1004, 2016.
- Pantelidis, L.: A critical review of highway slope instability risk assessment systems, *B Eng Geol Environ*, 70(3), 395–400, doi: 10.1007/s10064-010-0328-5, 2011.
- 10 Pellicani, R., Argentiero, I., and Spilotro, G.: GIS-based predictive models for regional-scale landslide susceptibility assessment and risk mapping along road corridors, *Geomat Nat Haz Risk*, 1–22, doi: 10.1080/19475705.2017.1292411, 2017.
- Pierson L.A. and Van Vickle, R.: Rockfall Hazard Rating System. Publication No. FHWA SA-93. U.S. Department of Transportation. Federal Highway Administration. Retrieved from
15 http://www.dot.ca.gov/hq/esc/geotech/references/Rockfall_References/30_Pierson_Rockfall_Hazard_Rating_System.pdf (last accessed 3 August 2018), 1993.
- Remondo, J., Bonachea, J., and Cendrero, A.: Quantitative landslide risk assessment and mapping on the basis of recent occurrences, *Geomorphology*, 94(3–4), 496–507, doi: 10.1016/j.geomorph.2006.10.041, 2008.
- Romana, M.: SMR classification. In: International Society of Rock Mechanics (ed) Proceedings 7th International
20 Congress on Rock Mechanics, Aachen, Germany, Balkema, Rotterdam, 2, 955-960, 1991.
- Schmidt, J., Matcham, I., Reese, S., King, A., Bell, R., Henderson, R., Smart, G., Cousins, J., Smith, W., Heron, D. Quantitative multi-risk analysis for natural hazards: a framework for multi-risk modelling, *Natural Hazards* 58 (3): 1169- 1192. doi.org/10.1007/s11069-011-9721-z, 2011
- Silva, F., Lambe, T. W., and Marr, W. A.: Probability and Risk of Slope Failure, *J Geotech Geoenviron*, 34(12),
25 1691–1699, doi:10.1061/(ASCE)1090-0241(2008)134:12(1691), 2008.
- Tugend, J., Manatschal, G., Kuzsnir, N.J., Masini, E., Mohn, G., and Thion I: Formation and deformation of hyperextended rift systems: insights from rift domain mapping in the Bay of Biscay-Pyrenees, *Tectonics*, 33,1239–1276, doi: 10.1002/2014TC003529, 2014.
- 30 [Vega, J. A., and Hidalgo, C. A.: Quantitative risk assessment of landslides triggered by earthquakes and rainfall based on direct costs of urban buildings. *Geomorphology*, 273, 217-235, doi: 10.1016/j.geomorph.2016.07.032, 2016.](#)
- Zêzere, J. L., Garcia, R. A. C., Oliveira, S. C., and Reis, E.: Probabilistic landslide risk analysis considering direct costs in the area north of Lisbon (Portugal), *Geomorphology*, 94(3–4), 467–495, doi: 10.1016/j.geomorph.2006.10.040, 2008.

Appendix - Table 4413: Consequence classification and costs for each hazard type (source of costs Ikerlur and Gipuzkoako Foru Aldundia).

Hazard type and variable for consequence classification	Class	Principal consequences and disruption	Actions	Cost (in UC)
RF - Rockfall magnitude (m ³)	A (<1)	platform not/partially occupied, no/partial disruption	(Alternative pass + removal debris)	0.8
	B (1-5)	platform partially occupied, partial disruption	(Alternative pass) + removal debris	1.5
	C (5-50)	platform occupied, disruption	Alternative pass + removal debris	3.9
	D (50-500)	platform occupied, disruption	Interruption road + removal debris + slope scaling	17.5
	E (50-5,000)	platform occupied and damaged, disruption	Interruption road + removal debris + repair road + intensive scaling	117.2
	F (>5,000)	platform occupied and damaged, disruption	Interruption road + removal debris + repair road + intensive scaling	172.4
RS - Wall structure failure extent	Partial failure of small wall	no damage, no/partial disruption	Removal + slope scaling	20.9 (per 10 m wall)
	Height wall: ≤ 6 m	platform occupied and damaged, disruption	Removal + slope scaling + stabilization + reconstruction wall + repair road	70.3 (per 10 m wall)
	Height wall: > 6 m	platform occupied and damaged, disruption	Removal + slope scaling + stabilization + reconstruction wall + repair road	121.0 (per 10 m wall)
SL - Max rate of terrain displacement (mm/month) and instability indicators	$v_A < 3$	Without/slight damage, no disruption	Repair road	1.4 (per 10 m damaged road)
	$3 < v_B < 10$	Moderate damage, no disruption	Repair road	15.0 (per 10 m damaged road)
	$v_C > 10$	Severe damage, no/partial disruption	Repair road + stabilization	37.4 (per 10 m damaged road)
	$v_D > 10$ and presence of scarp or developed shear displacements	Partial/total destruction, disruption	Interruption road + scaling slope + stabilization	45.4 (per 10 m damaged road)