From national landslide database to national hazard assessment

M. Jemec & M. Komac
Geological Survey of Slovenia, Slovenia

Abstract

The territory of Slovenia is, geologically speaking, very diverse and mainly composed of sediments or sedimentary rocks. Slope mass movements occur in almost all parts of the country. In the Alpine carbonate areas of the northern part of Slovenia rockfalls, rock slides and even debris flows can be triggered. In the mountainous regions of central Slovenia composed from different clastic rocks, large soil landslides are quite common, and in the young soil sediments of the eastern part of Slovenia there is a large density of small soil landslides. The damage caused by slope mass movements is high, but still no common strategy and regulations to tackle this unwanted event, especially from the aspect of prevention, have been developed. One of the first steps towards an effective strategy of combating landslides and other slope mass movements is a central landslide database, where ideally all known landslide occurrences would be reported and described in as much detail as possible. At the end of the project of compiling the National Landslide Database (May 2005) there were more than 6,600 registered landslides, of which almost half occurred at a known location and were accompanied with the main characteristic descriptions. Based on the landslide database described, a Landslide Susceptibility Map of Slovenia at a scale 1:250,000 was completed. Of 3,257 landslides with a known location, a random but representative 65% were selected and used for the statistical analysis of landslide occurrence, the rest of the landslide population (35%) being used for model validation. The most suitable susceptibility model was used for the anthroposphere exposure assessment due to potential landslide processes on a national scale. These analyses included a population census, building locations, land use, road type and railways. The results have shown that almost 19% of the population lives in one quarter of the area of Slovenia that is highly exposed to landslide occurrence. This is clearly an indication that better spatial and urban planning is needed on a national scale.

Keywords: landslide, slope mass movements, hazard, database, Slovenia.

WIT Transactions on The Built Environment, Vol 110, © 2009 WIT Press
www.witpress.com, ISSN 1743-3509 (on-line)
doi:10.2495/DMAN090221

1 Introduction

Based on research conducted in the early nineties, [1] estimated that there could be between 7,000 and 10,000 active landslides in Slovenia (or 0.3-0.5/km2). To put it more illustratively, there is one landslide per 1.46 square kilometres in Slovenia, excluding flat terrain. In the years 1994 to 2006, the damage caused by landslides (and avalanches) amounted to €94.2 million [2], excluding remediation costs. In the past decade global climate changes probably caused several extremely large landslide events on the territory of Slovenia, which had not been observed before. The latter represents an additional, much higher burden on the state and municipal budgets. In rare, but extreme circumstances, the landslides resulted in human casualties.

The newly arisen conditions due to climate changes demand a more strategic approach in tackling the problems related to slope mass movements. This is especially important in mountainous areas which occupy roughly one third of Slovenia. Worldwide there are numerous landslide databases, all of them with a common prerogative – landslide databases are constructed to study the evolution of landscapes, and are mandatory to ascertain landslide susceptibility, hazard and risk. In Europe, landslide databases can be found in Italy [3] and France [4], to name just a few countries. In Asia and Oceania similar projects are under way in Japan [5], Taiwan [6], Hong Kong [7], and Australia [8], while in America such projects exist in USA [9] and Canada [10]. The basis for the worldwide landslide database has been set by UNESCO [11–13]. Based on the 2006 Tokyo Action Plan, the International Programme on Landslides (IPL) Global Promotion Committee was established by the International Consortium on Landslide (ICL) members and ICL supporting organizations [14]. One of the Consortium's main goals is to maintain a database of the world's landslides [15].

2 National landslide database in Slovenia

With an awareness that Slovenia is highly exposed to landslides or rather several types of slope mass movements, several Slovenian Ministries expressed the will to finance the construction of the National Landslide DataBase [16, 17] which includes events of landslides, rockfalls and debris flows. In the following text a landslide database is referred to; the word landslide in the text should be considered as slope mass movements in general. Some of the pioneering work was done in the 1990s with pilot projects [1]. Nowadays, an up-to-date landslide database is vital for the activity of the Ministry of the Environment and Spatial Planning for gathering data on imminent danger (geohazard maps) and coping with the issues of prevention and remediation due to slope mass movement events. Usually there are huge costs related to the remediation of the consequences due to slope mass movement occurrence, which are partly compensated by the state. Additionally, the Administration of the Republic of Slovenia for Civil Protection and Disaster Relief deals with the disaster impacts on the population and their property.

The project goals were: (a) to establish an up-to-date central landslide database, (b) the construction of an information system that would allow data management by different users via the internet application. The database would represent (c) the basis for spatial analysis of slope mass movement distribution, and (d) the slope mass movement data could be distributed very fast to different users in accordance with their privileges/rights. Furthermore, the database would serve as a foundation for the modelling and production of geohazard and georisk maps of different scales (e).

The existing slope mass movement data that were acquired from different sources in different formats were analysed and merged into the centralised database with the duplicates removed. The quality is questionable to a certain degree, since the separate databases were rarely maintained. The dominating problems were different database attributes and missing or multiplied data [18]. At the end of the project there were 6,602 slope mass movements in the database, while 3,257 of them were geolocated (Fig. 1).

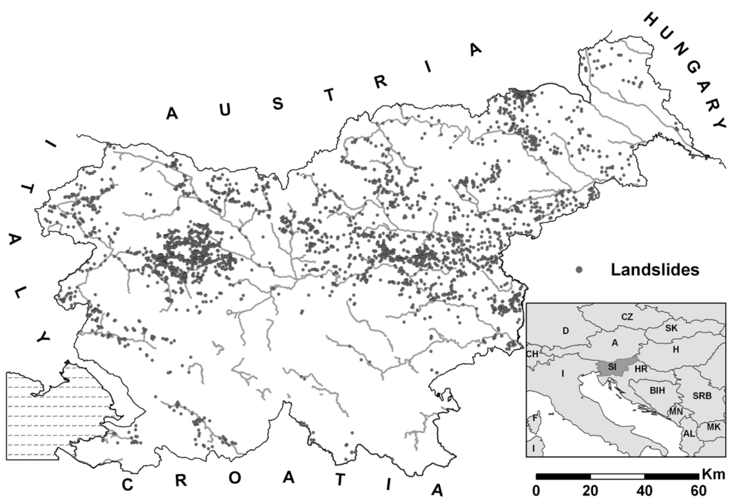

Figure 1: Known landslide distribution in Slovenia.

The Landslide DataBase is made up of the following types of data: a) Basic data (Code, Name, Location, Date of occurrence), b) Register of spatial data (Municipality, Settlement), c) Coordinates, d) Landslide conditions (Status, Speed, Dimensions, Geology), e) Remediation of Landslide, f) Costs of remediation, g) Priority, h) Documentation, i) Activities on Landslide, j) Landslide occurrence consequences (Damaged and threatened objects, Roads, Buildings, Public Infrastructure, Land).

Three different modules, the Authorization module (Managing users and their rights [user name and password], Access to application, Controlling digital certificates), the Attribute module (Landslide registration, Landslide data modification, Managing landslide events, Search and query, Managing attribute data), and the Spatial module (Viewing and checking different graphical layers, Zoom, Identification, Measuring distance, Selecting graphical objects and their transfer to the attribute module; Fig. 2) constitute the Landslide Information System (LIS). Applications supporting the users' work consist of attribute (for tabular data) and GIS (for graphical spatial data) modules connected to one system. Both modules are based on multitier internet technology. The attribute module is created with the JSP (Java Server Pages) and runs on the Apache application server with installed Oracle Container for JAVA (OC4J) and attributes are stored in Oracle database 9i2R. The GIS WEB module is developed within the Delphi environment with the ESRI MapObjects components for GIS while Oracle Spatial is used for storing the location of slope mass movements. Other spatial data used in the system are stored on the file server (background maps, digital orthophoto, etc), or in Oracle Spatial (vector data such as land and building cadastre, infrastructure, etc). Also the Internet Map Server was implemented to support communication between users and the GIS WEB module. At the user level the thin client in Java supports the GIS functionality. The users of the system can be divided into three segments: the administrator, internal users and external users (Fig. 2). All the events on the slope mass movements are stored in the History of Events files. In this way the system enables tracking of all the events on every slope mass movement entered by users in the slope mass movement registry until now. Prior to modifying the data, the type of event, reason for the change and the change date have to be defined. Every event is managed as an independent entity and can be recalled in the same form as was entered.

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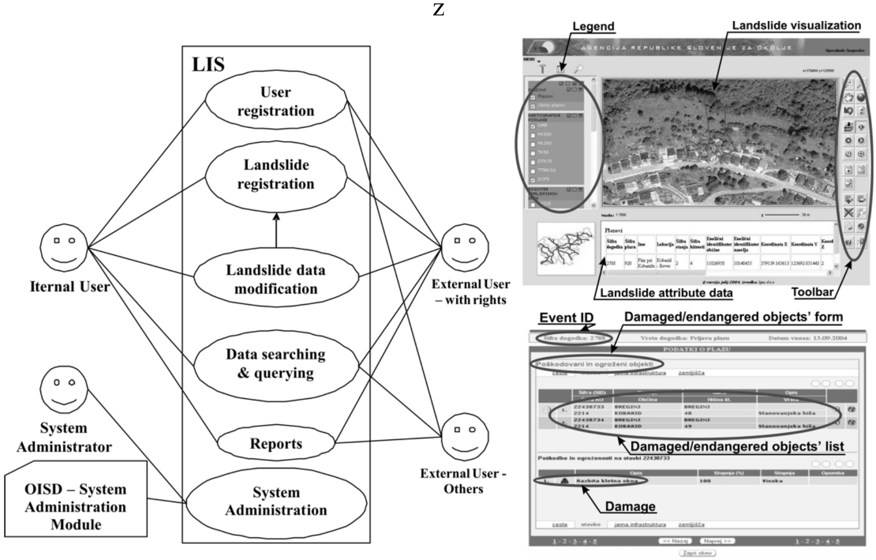

Figure 2: Flowchart of the Landslide Information System (LIS) and a part of the Attribute module (below) and Spatial module (above).

3 Methodology

3.1 National landslide susceptibility map

The constructed database enabled the spatial and temporal analyses of landslide occurrence in relation to spatio-temporal factors, and based on these results the landslide susceptibility map at a scale of 1:250,000 for the area of Slovenia was produced. All the analyses were conducted in the GIS with 25×25 m pixel resolution and the results were statistically analysed employing the χ^2 method. For the landslide susceptibility map a linear model of weighted spatial factors was used.

For the purpose of model development, the spatial factor data that had already been proven to be relevant to landslide susceptibility by many authors [19–22] were gathered. The landslide data were obtained from the National Landslide Database. Approximately 2/3 of landslides (2,176) were randomly, but representatively selected from the population for each geological engineering unit for the landslide susceptibility model training phase. The remaining 1,081 landslides were used for model evaluation. Where less than 40 landslides occurred in a specific geological engineering unit, the landslide occurrence served as an indication that assisted the expert to make the right classification decision of landslide occurrence probability for a given unit. The digital elevation model (DEM) data were obtained from the national 25 m resolution InSAR DEM 25 [23]. All the additional data on the terrain morphology (curvature, elevation, slope, aspect) were derived from the DEM. The Geological Map of Slovenia at a scale of 1:250,000 [24] served as a source for the geological engineering data [18, 25]. For land use and vegetation cover CORINE land cover data were used [26]. The surface water data were obtained from ARSO [27] and are at a scale of 1:25,000.

To understand the natural processes, the influencing spatio-temporal factors on the observed process have to be defined and their interaction addressed. The most appropriate way to understand the “back-stage” of natural processes is to analyse the factors or their approximations. The better the understanding, the better can be the prediction of future events. The groups of influencing factors on landslide occurrence in Slovenia were selected based on previous research [28, 29]. The analyses were conducted on the landslide population for all of the spatio-temporal factors for the whole of Slovenia, and additionally on the landslide population for all of the spatio-temporal factors for each of the 29 geological engineering units.

Several authors [30, 31] showed the applicability of the χ^2 (Chi-square) method for testing normally distributed discrete variables. The χ^2 method is based on a comparison of observed and expected frequencies of the phenomenon [32]. For the purpose of model development the categorical variables were transformed into numerical form on the basis of relative landslide occurrence probability of phenomenon occurrence calculated from the χ^2 values for a specific class of variable. In short, they were ordered, but one has to consider that such an ordinal scale does not comply strictly with the law of continuity.

Where obvious discrepancies of class order occurred, an expert decision was made to correct the error. Before the inclusion of relevant factors in the model development, the values of each factor were normalised. This was a necessary step to equalise the different class numbers in factors, the goal being that the weights in the models represented the real influence of a given factor. Normalisation was done using the eqn (1):

$$NV = \frac{5 * (OV - \min)}{\max - \min}, \tag{1}$$

where NV stands for a normalised value, OV represents original (nominal) value, and the difference between maximum (max) and minimum (min) is always one less than the original number of classes. The normalised values ranged from 0 to 5.

The normalised factors were used to develop the optimum landslide susceptibility model. The models were developed using the linear weighted sum [33]. The result is standardised landslide susceptibility, calculated from the eqn (2):

$$H = \sum_{j=1}^{n} w_j \times f_{ij}, \tag{2}$$

Table 1: Weights of spatio-temporal factors of ten models used for the landslide susceptibility calculation. The “Success rate” of model is calculated from the proportion of landslides in the two lowest classes of landslide susceptibility.

MODEL	M_01	M_02	M_03	M_04	M_05	M_06	M_07	M_08	M_09	M_10	M_11 _3F
Engineering-geological properties	0,3	0,3	0,25	0,4	0,1	0,166	0	0,2	0,3	0,3	0,41
Slope	0,2	0,25	0,25	0,2	0,1	0,166	0,2	0,2	0,25	0,3	0,26
Curvature	0,1	0,1	0,05	0,05	0,1	0,166	0,2	0,2	0,1	0,05	0
Aspect	0,05	0,05	0,05	0,05	0,1	0,166	0,2	0,2	0,05	0,05	0
Landcover type	0,3	0,25	0,35	0,25	0,5	0,166	0,2	0	0,1	0,25	0,33
Distance to struct. elements	0,05	0,05	0,05	0,05	0,1	0,166	0,2	0,2	0,2	0,05	0
Success rate	12,1%	10,6%	12,8%	11,3%	14%	14,3%	18,5%	19,7%	14%	13,3%	12,3%

where H represents standardised relative landslide susceptibility (0-5), w_j represents weight for a given factor and f_{ij} represents the value of continuous or discrete variable. The weight values for different factors were defined based on previous research [28] and modified or adapted to some extent by an expert decision. Altogether ten models plus one generic for the whole of Slovenia were calculated using different weight combinations (Table 1). In order to select the optimum model, a comparison of their prediction success was necessary. This comparison was based on the equal area method to avoid the differences between the model value distributions. Every model was divided into 100 classes, 1% of the area per class. The criterion for model success was the number of successive classes in which a statistically significant proportion of landslides from the test set occur. The lower the number of classes, representing the landslide susceptible area, and the higher the proportion of test landslides in the landslide susceptible area, the better the model.

Based on the analysis results a mathematical model was developed and the results represented in the form of a GIS data set and in a map. The Landslide Susceptibility Map of Slovenia at a scale of 1:250,000 is a final product of linear mathematical modelling of spatio-temporal factors that govern landslide occurrence and hence landslide susceptibility. Based on an expert decision, the areas with slopes less than 5º were excluded from the modelling and the lowest possible susceptibility was assigned to them. In areas with slopes of less than 5º, where no landslides should occur, 55 or roughly 5% of these phenomena from the testing set are present. The error is present in all of the models.

3.2 Landslide hazard assessment

The results of landslide susceptibility modelling and its spatial distribution permitted an analysis of landslide hazard distribution on a national scale. Using the landslide susceptibility model and data of spatial distribution of anthropogenic components (census, land use, infrastructure), an estimation of the hazard was performed. This cross validation enabled the assessment of component exposure to possible landslide occurrences. Although the scale is very general, the results are a very informative indicator of anthropogenic exposure to slope mass movement and an indication of whether natural processes were considered in the spatial planning process. The analyses were conducted in GIS in a 25×25 m cell. Due to the cell based analyses the results can deviate by up to 0.4% from the values shown.

4 Results and discussion

4.1 Landslide susceptibility model

The worst results in calculating the landslide susceptibility models were given by models where geological engineering properties (M_07) or landcover type were excluded (M_08). Slightly better results were achieved with the model M_06, where all of the factors were assigned equal weights. Next by performance was model M_09, where distance to structural elements was given an important role and the role of the landcover type was minimised. With model M_05 the landcover type was given a very important role and the rest was split among other factors. The success rates of the rest (models M_01, M_02, M_04, M_10) were very similar. Model M_02 was chosen for the most successful and suitable landslide susceptibility model, based on a good landslide to area ratio and the expert knowledge (and logic) of importance of spatio-temporal factors. In only 18% of area, 61.5% of landslides occur, and in less than 1/3 of area (29%), 76% of landslides occur. Split in half, to landslide susceptible and landslide "safe" areas, in landslide susceptible areas 88.2% of landslides occur. Table 2 represents the basic characteristics of model M_02. The reclassification of model M_02 values into landslide susceptibility classes, which are shown in the form of the Landslide Susceptibility Map of Slovenia at a scale of 1:250,000, are based on actual landslide occurrences compared to expected ones. In the class of highest landslide susceptibility, the areas where six times more landslides occurred than expected were classified. This class represents the top 7% of area according to landslide susceptibility, and comprises 43.3% of landslides. All areas where the proportion of landslides to that of area ratio is greater than one were joined to the class of high landslide susceptibility. 27% of landslides were located in an area of 17%. The class of medium landslide susceptibility comprises areas where the proportion of landslides to that of area ratio is near or equal to one. In this class, which spreads over 10% of the total area, 10.5% of landslides occurred. In areas with low landslide susceptibility that cover 21% of the total area, 8.5% of landslides occur, and in areas with very low, but still some landslide susceptibility, which cover 17% of the total area of Slovenia, 5.5% of landslides occur. Other areas belongs to the "landslide safe" zone where 5.1% of landslides occur. This error is most probably a result of digital elevation model generalisation (the possible generalisation of transitions between terraces) and due to the fact that analyses were conducted at a scale of 1:250,000. Cumulatively in the first class 43.3%, in the first two 70%, in the first three 80%, and in the upper four susceptibility classes 90% of landslides occur. In each of the lowest two landslide susceptible classes 5% of landslides occur.

Table 2: Distribution of landslide susceptibility class areas for model M_02. "A" represents the proportion of the area covered by a given class ("Class"). "Reclassified classes by area proportion" represents the area proportion of landslide susceptibility classes, "Model values" represents the range of model values for a given class in model M_02, "Landslide susceptibility" defines the description of susceptibility, and "Landslide proportion" states the proportion of landslides in a given class.

Class	A (%)	Reclassified classes by area proportion	Model values	Landslide susceptibility	Landslide proportion
1	28.00%	0 - 28	0 – 0.57	None	5.1%
2	17.03%	28 - 45	0.57 – 3.19	Very low	5.5%
3	20.99%	45 - 66	3.19 – 4.59	Low	8.5%
4	10.00%	66 - 76	4.59 – 5.42	Medium	11.4%
5	17.00%	76 - 93	5.42 – 7.16	High	26.2%
6	6.97%	93 - 100	7.17 – 9.88	Very high	43.3%

The analysis results indicated one particular characteristic, the importance of three spatio-temporal factors, lithological or geological engineering characteristics of rocks and soils, slope inclination, and landcover type. Using only these three factors, models would not achieve such prediction performances as in the cases presented above since the prediction would be of lower detail, but

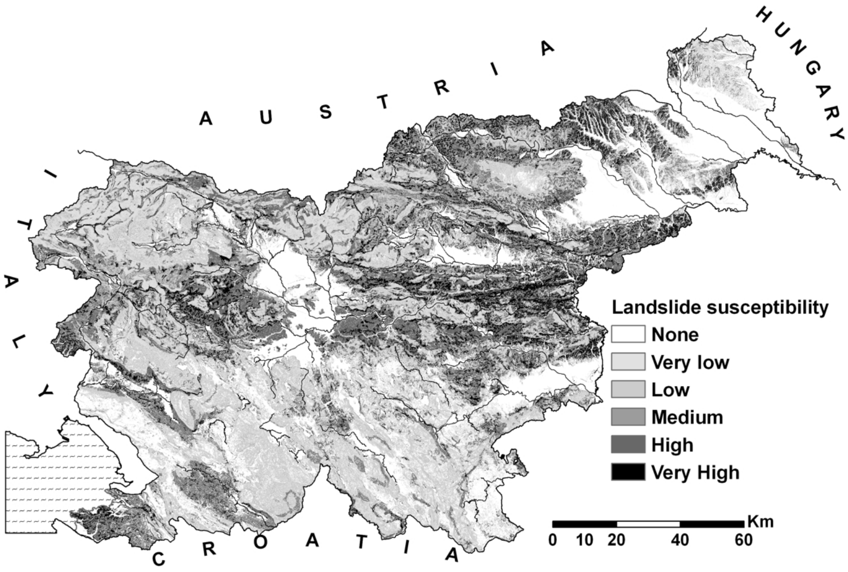

Figure 3: Landslide susceptibility map of Slovenia at a scale of 1:250,000.

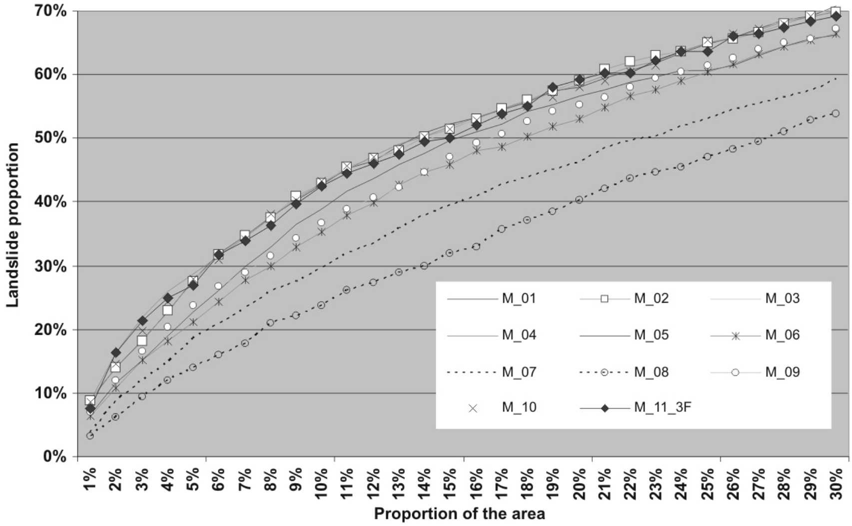

Figure 4: Cumulative distribution of landslides according to area proportion for each of eleven models. Legend represents labels for each of the linear models.

the results would still be satisfactory. The success rate analyses for these three factors revealed that the error for the ideal combination of factors in model M_11_3F (lithology, 0.41; slope inclination, 0.26; landcover, 0.33) is 12.3%, while in the chosen model M_02 the prediction error is 10.6%. The "ideal" weight values of the three factors were derived from the average of the best ten weight values for each of the factors when factor influences were analysed individually for each factor. The averaging approach was selected to reduce potential extreme variations caused by different factor weights. The comparison between model M_02 and model M_11_3F poses a reasonable question of developing complex landslide susceptibility models. This question, of course, has no solid foundations, since the quality of models is augmented with the inclusion of a reasonably higher number of spatio-temporal factors. Moreover, when the safety of inhabitants or property is concerned, every percentage point counts.

4.2 Exposure to landslides and hazard assessment

The majority, almost two thirds, of the population [34] lives in areas of neglected landslide susceptibility, while 7.8% of the population inhabits areas of very high landslide susceptibility. The difference between the proportion of inhabitants and the proportion of area is statistically significant. Almost 19% of the Slovenian population lives in areas of high or very high landslide susceptibility. It can be concluded that inhabitants do not take landslide susceptibility into consideration when planning locations for their homes.

When analysing the distribution of buildings [34] in relation to landslide susceptibility in Slovenia, it can be concluded that the relative high proportion of buildings in the upper two classes of landslide susceptibility are the result of numerous leisure homes in hilly areas (buildings with no permanent inhabitants). The total proportion of buildings in the area with high susceptibility is twice as high as the area proportion of this class. This again shows the great negligence of past processes concerning slope mass movements when choosing building locations.

The analysis of landcover type exposure to landslides was performed on the data obtained from the Ministry of Agriculture, Forestry and Food [35]. With regard to farmland, almost twice as much area is located in the most exposed class to landslides than expected. A more detailed analysis reveals that the major contributors to landslide occurrence on farmland are meadows where grass with its shallow root system acts as a poor preventive action against landslides. The proportion of forests is, as expected, lower in areas where landslide susceptibility is negligible since these areas are occupied by other landcover types (farmland, built areas, etc). The relatively small proportion of forests in areas of very high landslide susceptibility is most probably related to the protection function of the tree root system against landsliding. As expected, built-up areas have a similar distribution to building distribution. The distributions of water and open marshland are also as expected since the majority is located in areas of negligible landslide susceptibility. The small proportion of water-related landcover types in areas of high landslide susceptibility is most probably a consequence of the generalised digital elevation model. Open land with no or insignificant vegetation is mainly situated in higher or even mountainous areas where the probability of landsliding is higher, but at the same time not extremely high since these areas most probably consist of harder rocks.

Table 3: Distribution of anthropogenic components according to landslide susceptibility classes in Slovenia.

Landslide susceptibility	None	Very low	Low	Medium	High	Very high
Population proportion	65.9%	3.3%	6.4%	5.5%	11.0%	7.8%
Building proportion	53.1%	3.9%	8.4%	7.2%	15.5%	11.9%
Farmland	48.4%	5.6%	9.7%	6.8%	15.8%	13.7%
Forest and similar landcover	14%	23.8%	28.4%	12.2%	18.4%	3.2%
Built and similar sites	55.2%	4.7%	9.1%	6.8%	14.3%	10%
Open marsh land	94.5%	1.9%	1.6%	0.6%	1.1%	0.2%
Open land with no or insignif. veget.	2.31%	53.7%	30.2%	7.5%	5.7%	0.5%
Water	80.7%	5.6%	6.5%	2.3%	3.9%	1.1%
Highway	68.3%	7.2%	8.2%	4.8%	8.5%	2.9%
Fast road	73.1%	5.4%	7.2%	5.5%	7.3%	1.6%
Regional road	25.8%	16.3%	25%	10.4%	16.7%	5.9%
Local road	36.2%	7.2%	14.2%	9.6%	20.2%	12.7%
High street	89.7%	3.0%	3.2%	1.8%	1.8%	0.4%
Main city street	79.2%	3.8%	5.2%	3.7%	5.5%	2.6%
City street	78.9%	3.3%	4.7%	3.8%	6.3%	3.0%
Public path	41.74%	5.8%	11.3%	8.6%	19.3%	13.3%
Cycling path	65.3%	3.9%	6.0%	6.3%	12.1%	6.3%
Railway	60.6%	9.7%	12.6%	6.0%	8.36%	2.7%
Class area (km^2)	5675	3451.61	4254.2	2026.8	3445.5	1412.67
Class area proportion	28.0%	17.0%	21%	10.0%	17.0%	6.97%

Regarding the exposure analyses of road infrastructure [36] in Slovenia, the distributions of highways, fast roads, regional roads, high streets, main city streets and cycling paths indicate very good infrastructure planning in relation to landslide susceptibility. The distribution of regional roads is very similar to the distribution of landslide susceptibility classes, which indicates that this type of road is built regardless of landslide susceptibility. The main reason for this phenomenon is most probably the importance of these roads which connect the most distant settlements regardless of unfavourable natural conditions. The relatively high proportions of local roads and public paths in the two most exposed classes to landsliding are probably the result of their specific use (logging and transportation of wood, footpaths, etc).

The railway network is mainly situated on flat or gently sloping terrain. When crossing hilly or mountainous areas, the railway is cut into hard rock, and when crossing soft rock, they are usually protected by tunnels, entrenchments and similar constructions. The distribution of the railway network indicates that its positioning was very prudent when taking landsliding into consideration.

5 Conclusions

Landslides are the most common local geohazard problem in Slovenia. A holistic national landslide protection approach consists of several stages. In the first stage the collection of data is necessary, followed by analyses of the available data. The existence and use of the Slovenian National Landslide DataBase bring great progress to the quick response to slope mass movement threats and the field of slope mass movement prevention. Furthermore, various useful scientific results can be achieved on the basis of an analysis of slope mass movement data. The data, stored in the Landslide DataBase, serve as a basis for a better understanding of slope mass movements and assist experts in building improved prediction models of these phenomena. The data and results based on these data further serve for the production of geohazard and georisk maps, which may, with regular updating of the database, gradually improve by providing better prediction levels. Spatial mathematical modelling of natural phenomena enables the assessment of their occurrence and hence the exposure of the environment to their impact. Based on the analytical results, the legislative stage has a responsibility to conclude the circle of protection approach, but this field is following very slowly. The holistic approach does not stop at the legislative level, but involves a live, continuous process that improves with every repeated circle.

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