Stochastic approach for karst risk assessment in a motorway project

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ABSTRACT: Sinkholes and subsidences related to karst features in motorway projects causes significant direct and indirect economic losses. A stochastic approach has been used to evaluate different scenarios of hazards for karst risk assessment. The process involves an initial phase, where karst related information is collected, based on ground evidence, aerial and satellite data. Based on this data we reconstruct a ground level statistical model of karst features and successively a rock bed karst spatial stochastic model by means of python PYMC3 package. The latter is used to elaborate a stochastic model of surface sinkholes and subsidences, based on analytical formulations. Each stochastic run is a scenario, and the sum of all scenarios can be used to statistically define the rate of occurrence, which represent a measure of the hazard, and successively identify the applicable countermeasure used to reduce the hazard. This article presents a concrete application of the methodology, for a motorway project in karst areas, however the versatility of the method allows for a wide field of applicability. The results are presented in form of tables and graphs showing many scenarios, optimistic, baseline, pessimistic and extremely pessimistic, representing the 25th, 50th,75th and 95th quantiles of the stochastic analysis.

Keywords: Karst hazard, stochastic analysis, python, PYMC3, motorway

1 Introduction

This study is as a part of a 750Km motorway design on the Southwest of Russia linking Moscov to Kazan. Part of the road alignment crosses the Nizhny Novgorod area a land affected by karstic phenomena for 110km.

There are two main types of damaging surface features from the kinematic and management perspective: (1) features characterized by progressive subsidence resulting in the development of large potholes that require frequent re-levelling works, and (2) collapse sinkholes that typically occur in a sudden way without noticeable precursory signs of instability. The latter have a higher capability. to cause damage due to their unforeseeable and catastrophic character. Long road closures and accidents on roads and railways caused by sinkhole activity have been documented in many karst regions of the world. Several mitigation strategies may be applied to avoid or reduce sinkhole-related damage on transportation infrastructure built upon karst areas: (1) Prevent the sinkhole hazard by selecting a route that evades the subsidence-prone zones; (2) Minimize the hazard interfering with the processes and factors involved in sinkhole development (3) Reduce the vulnerability of the structure through the incorporation of sinkhole-resistant designs.

The safest mitigation strategy may involve the extensive application of costly corrective measures. However, in a world of limited resources, the extra cost of the mitigation should be affordable and justifiable by the expected damage reduction.

Cost–Benefit Analyses (CBA) based on hazard assessments of “with mitigation” and “without mitigation” scenarios are a widely used approach to evaluate expenditures and optimize resources. This method allows assessing the cost-effectiveness of different mitigation strategies and identifying the most favorable one from the economic profitability perspective.

This article illustrates an evolution of this method by creating a stochastic statistical model capable to deliver a posterior statistical distribution of the solution and mitigation measures rather than a finite series of scenarios.

2 Geological and geomorphological setting of the study area

The geological framework of the area is mainly represented by deposits of Permian (P), Jurassic (J), Cretaceous (K) systems, covered by Quaternary (Q) deposits. The geological formations affected by karst processes are mainly represented by carbonate-sulphatic deposits consisting of limestones and dolomites of the Kazanskiy plane of the Middle Permian (P2kz), as well as gypsum and anhydrites of the Sakmarskiy plane of the Lower Permian (P1s + a).

The karst phenomena observed in the area, both hypogean and epigean, are associated with water infiltration and circulation within the limestone-dolomite and sulphate complexes of the Permian substrate. In these areas, the processes of chemical-physical dissolution of the soluble rocks and mechanical degradation are activated which determine the formation of typical forms such as fractures, well cavities, dissolution channels, funnels.

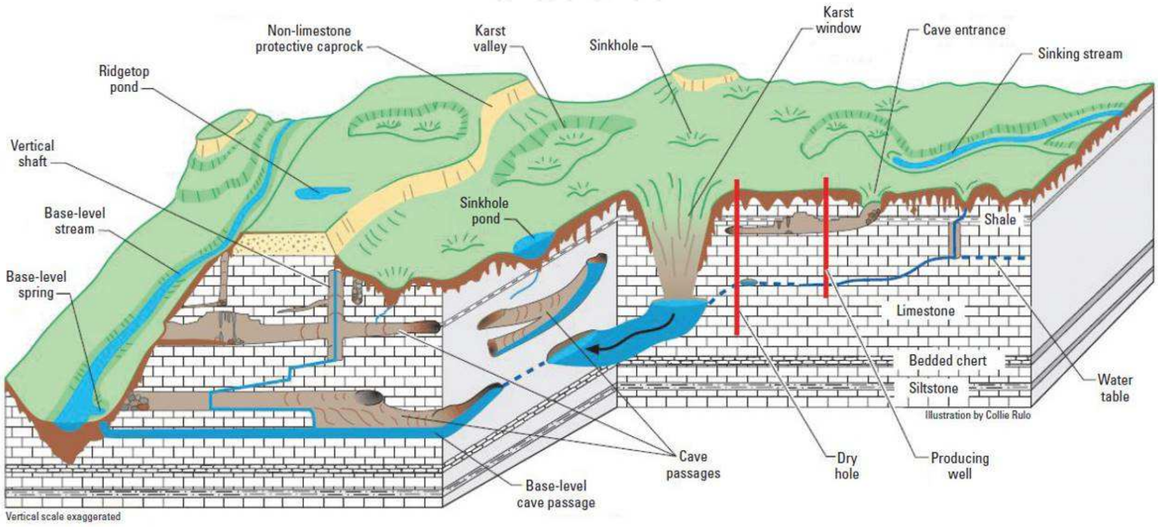

Figure 1. Hydrogeologic characterization and methods used in the investigation of karst hydrology. US Geological Survey (2008)

3 Calculation methodology

3.1 Project input data

In the project area more than 3000 sinkhole and depression where identified based on field observations and remote sensing analysis. Topographic and orographic features are obtained from the Digital Elevation Model DEM (30x30m grid) and high-resolution topographic data SRTM (NASA's Shuttle Radar Topography Mission). A spatial database in GIS environment was set out to collect, process and harmonize different geodata layers. Cartography, field observations and ground investigation were used to collect hydrogeological information. Geotechnical characterization of each unit was based on geological bibliography and preliminary geotechnical investigation data.

3.2 Surface karst feature forecast model

The karstification process in the project area is a broad problem that concerns several variables, each of which presents an intrinsic degree of variability. The problem that arises is to predict the hazards during the construction and maintenance phase of the work during its useful life. Being a multivariable problem, the proposed approach is that of the stochastic process.

The process provides, after careful analysis of the project and bibliography data, a statistical model for each variable. These models will constitute the input of stochastic processes, such as Markov Chain Montecarlo (MCM), for the creation of a probabilistic spatial model of hazards.

As regards the definition of the surface funnels that can form during the useful life of the work, the empirical formulations provided by the Russian legislation and the propagation models of karst openings defined by Anikeev (2017) will be considered. Through a decision-making algorithm, the stochastic model will be used to define the most appropriate countermeasures for each case study.

Based on this process, it will be possible to define a probabilistic distribution of the countermeasures and therefore of the costs. The model will also be usable during the construction phase, allowing the evidence of the construction phase to be entered as an input, allowing it to iteratively recreate models as they progress with gradually lower degrees of uncertainty.

The proposed approaches are two:

1) Reconstruction of the karst distribution based on surface evidence (backward analysis) which will be used as a preliminary model pending the progress of the geotechnical campaign (steps 1a-1c, blue).
2) Direct analysis starting from the data of the survey columns. This approach will gradually become more reliable with the increase in surveys carried out. In the long run it will become the role model. To support this analysis, the results of the seismic surveys will also be used (steps 2a-2c, green).

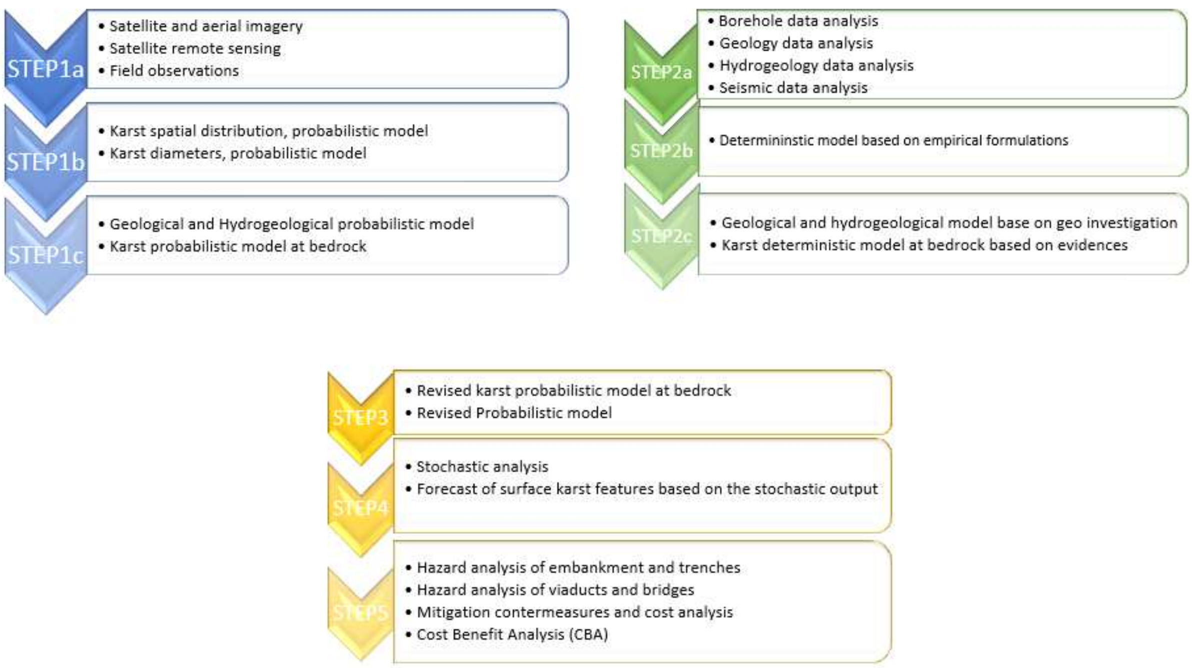

Figure 2. Calculation model flow chart

On the step 1 a subsurface karst distribution model, based on surface evidence, was recreated. This model considers the fact that surface evidence represents only a minimal part of real subsurface karstification. The use of a statistical truncated exponential model was used to estimate dimension and quantities of the remaining portion of karsts not leading to surface features.

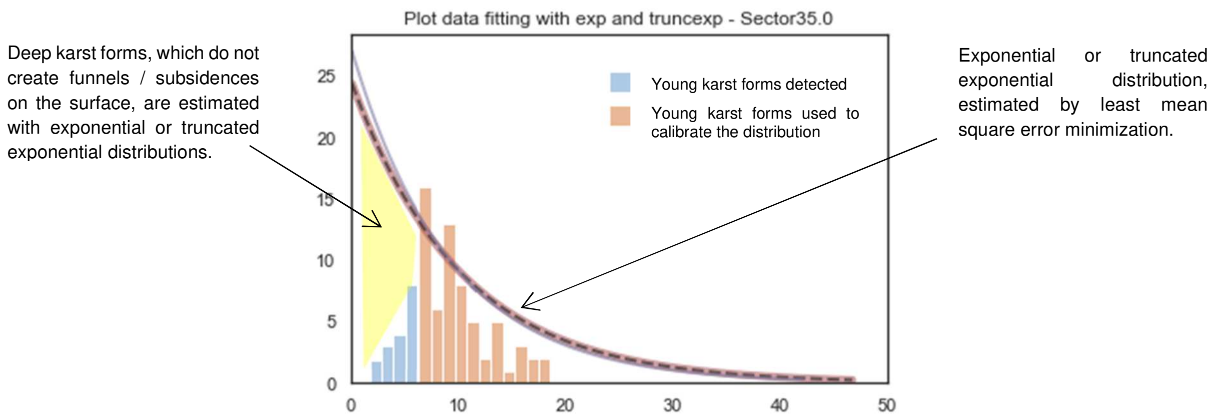

Figure 3. Statistical estimation of subsurface karst model

Step 2 runs parallel to step1 but rely on subsurface evidence retrieved from geophysical, ground field boreholes and excavations evidence.

The Step 3 uses the subsurface model recreated by step 1 and step2 and recreate a prediction surface karst feature model that will be used to estimate karst occurrence during the project life span life. In total 10000 stochastic different scenarios are evaluated.

The approach used to calculate the surface karst evolution is the one proposed by Anikeev (2017) allow for the estimation of the karst diameter at surface starting from the cavity located at the interface between the rock bed and the quaternary deposit. The formulations proposed derives from the limit analysis theory and the failures schemas are resumed in the picture below:

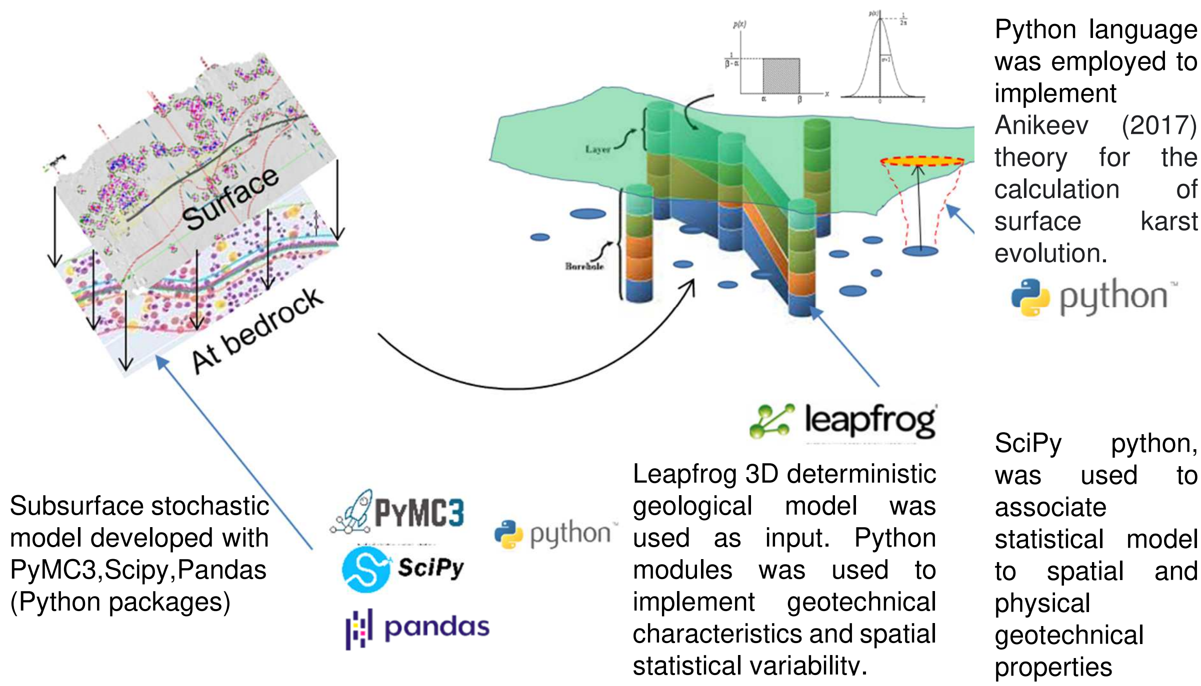

Figure 4. Calculation model pictorial flow chart

A probability of occurrence (Pds) can be evaluated for each karst feature. If the calculated probability is greater than 10%, the feature is associated to sinkhole formation.

In correspondence of the areas with clayey cover and probability of collapse Pds <10%, a phenomenon of subsidence is associated with the cavity.

For probabilities lower than 1%, the hazard is considered negligible. It is observed that for quaternary coverings, distance of the ground level from the karst substratum, greater than 50m, the hazard of karst occurrences is practically nil. To highlight this aspect, a graph is provided in the figure 5. In the areas where the quaternary layer (light blue line) is greater than 50m (horizontal blue line) the karst features (dark blue dots) at the surface decreases considerably.

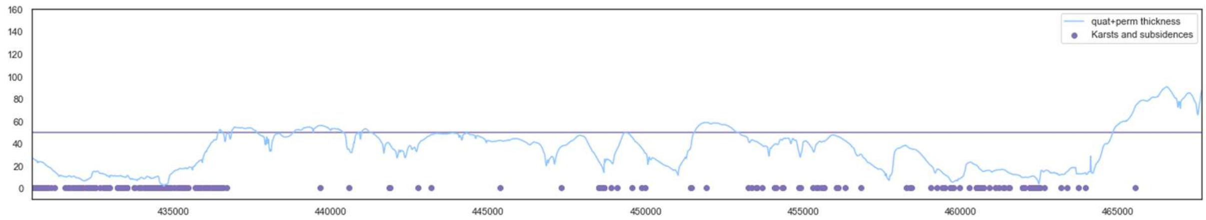

Figure 5. Correlation between the quaternary thickness and the surface karst features.

3.3 Countermeasure's evaluation

The mitigation measure is evaluated based on the density of karst occurrence. For each sector of one kilometer the intensity of occurrence λ is expressed as the number of karst forms (n) per square kilometer (S) over 100 years (t):

$$\lambda = \frac{n}{S \cdot t}$$

The parameter λ is estimated on a band of 2500m from the road axis (respectively to the north and south of the same). As previously stated, the density of karst at the surface, is a function of the lithology geotechnical parameters and the thickness of the cover layer (distance from the support plane of the embankment from the karst substrate). Successively an attribution map of the karst countermeasure is drawn up to manage the hazard according to general geotechnical aspects (for example prevalence of cover in sandy or clayey materials). The parameters influencing the decision-making choice vary according to the scenario and are extrapolated directly from the density graphs.

The main types of mitigation measure foreseen are:

- Reinforced concrete lattice plate.
- Vibroflotation.
- Dynamic compaction.
- Compaction grouting
- Reinforced embankment with reinforced Geogrid / geotextile

The above interventions can be coupled with an intervention aimed to mitigate the hydrogeological hazard:

- Vertical drains on the sides of the embankment.
- Lateral draining trenches longitudinal to the route

The type of solution is chosen according to the intensity of density and the geological and hydrogeological conditions, for this a series of flow chart have been used as guideline for the choice of the most suitable mitigation measure.

The final quantities are not deterministic but are expressed as statistical distribution by means of kernel functions. The results were presented considering 4 quantiles of the calculated distribution.

The image below shows how karst occurrences are managed for each sector, based on 3 scenarios:

- Optimistic: 25% percentile (green line)
- Baseline: 50% percentile (black line)
- Pessimistic: 75% percentile (orange line)
- Extreme: 95% percentile (red line)

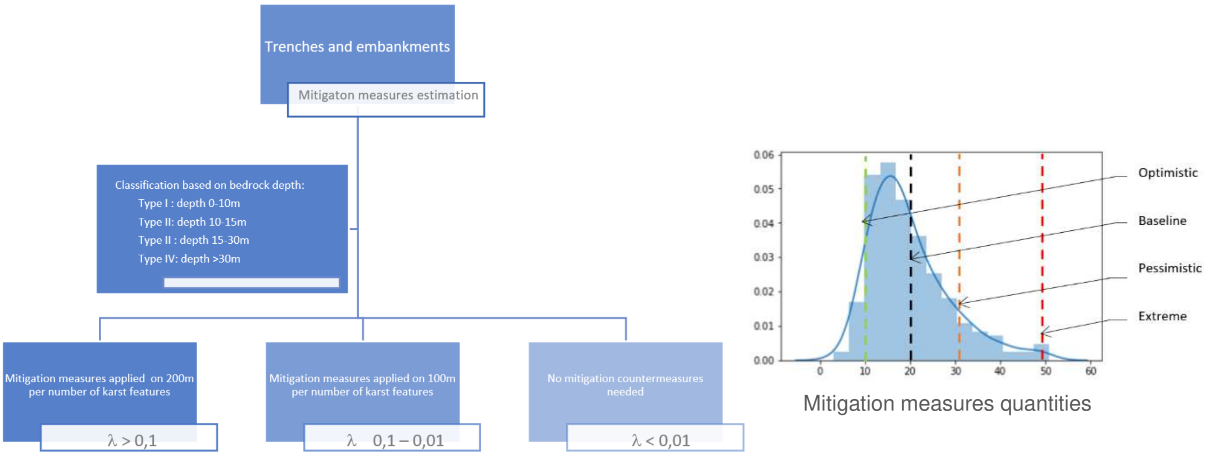

Figure 6. Flow chart and mitigation measure distribution examples

4 Calculation results

The outcome from step 1 and 2 is the stochastic model of surface karst features. Each simulation provides for a stochastic distribution of karst features associated with a sinkhole or surface subsidence with a certain probability of occurrence. The image below shows the results of karst features issued from 1 stochastic simulation. The features are filtered by a probability of occurrence greater than 0.1 regrouping only sinkhole associated features. The color expresses the probability of occurrence the size the dimension of the cavity at the surface (the size is qualitative).

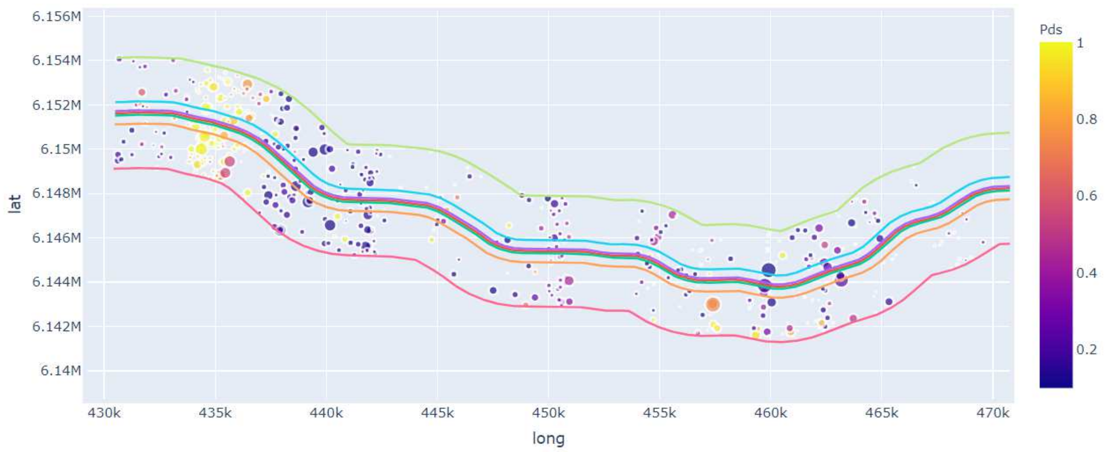

Figure 7. Result of 1 simulation filtered by : Pds > 0.1 (sinkholes and funnels)

The next image shows the results of karst features issued from 100 stochastic simulations. The features are filtered by a probability of occurrence greater than 0.01 regrouping both sinkholes and subsidences. The color and the size express the dimension of the cavity or the subsidence diameter at the surface (the size is qualitative).

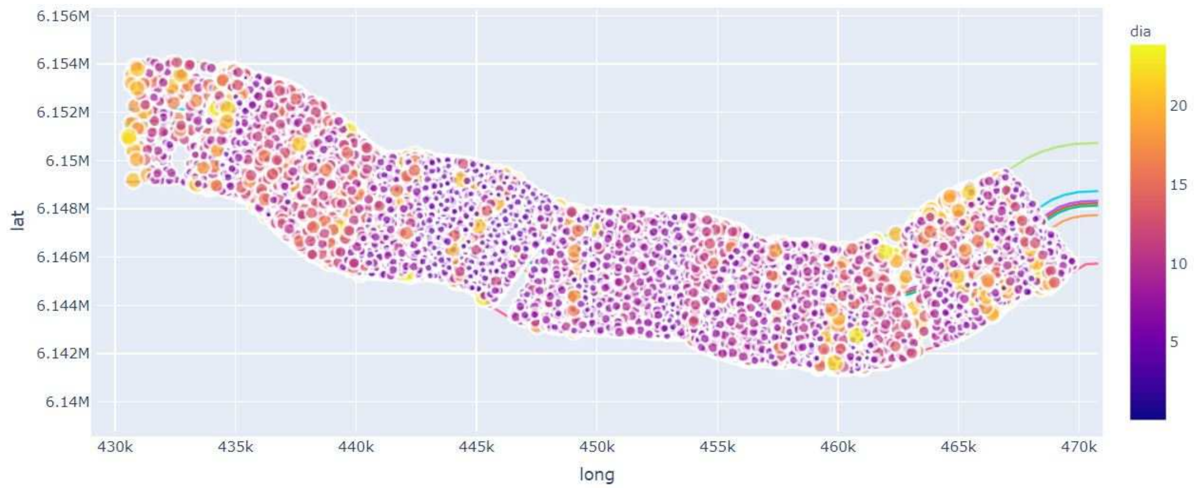

Figure 8. Result of 100 simulation filtered by : Pds > 0.01 (sinkholes funnels and subsidences) the color expresses the estimated karst feature diameter at the surface

In the image below, the parameters λ (intensity of occurrence) are plotted for sectors (chainages of one kilometer length).

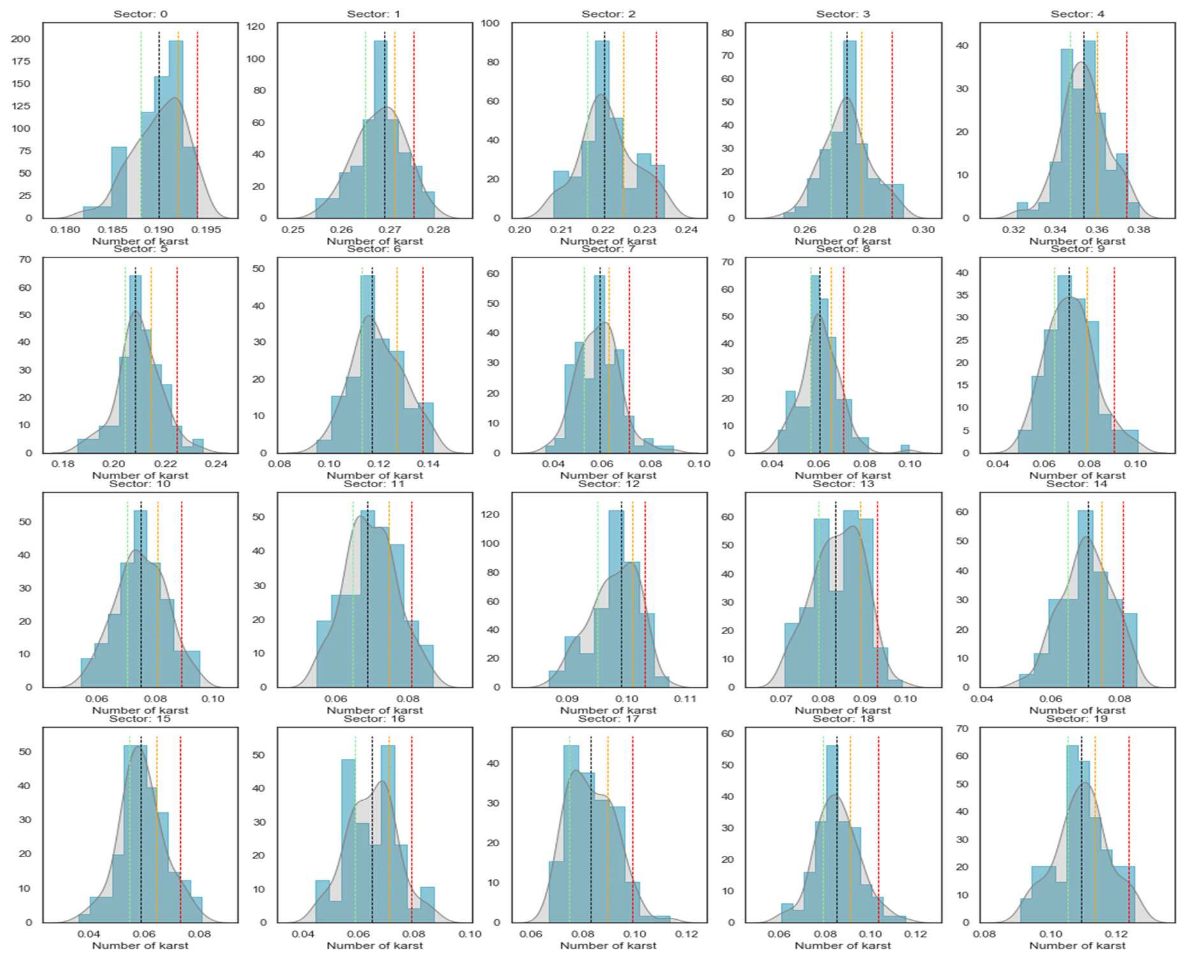

Figure 9. Representation of the variation of the intensity of occurrence parameter λ (x axis) calculated on the strip with 2500m offset from the road axis, expressed in number of karst forms per km^2 per 100 years, each plot represents a sector of 1 Km.

5 Conclusions

Risk related projects necessitate an accurate Cost–benefit analyses (CBA) based on hazard assessments. The easiest way to perform such analysis is by calculating 2 scenarios “with mitigation” and “without mitigation to evaluate expenditures and optimize resources. This method is often based on a determinist approach of the cost-effectiveness evaluation for different mitigation strategies. The proposed method in an evolution of this approach. It relies on statistical stochastics simulation to recreate a posterior distribution of the scenarios. The advantage of a result based on a distribution rather than deterministic scenarios, relies on the possibility of evaluating a worst-case economic reservoir useful in the preliminary stage of the project. During construction the countermeasure are determined according to site evidence. Being the forecast evaluated as a continuous kernel function, it allows to compare the level of the actual expenses with the forecast. This can be done for each sector and allows for a continuous revision of initial assumed scenario probability level to refine the final cost forecast. The use of versatile code languages such as python allows for the use of open source third party efficient and tested statistical packages. During the construction phase, and with the advancing of ground field investigations, the geotechnical and hydrogeological variables will reduce their uncertainties, thus updated models can be constantly evaluated.

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