Estimating building inventory for rapid seismic vulnerability assessment in Bishkek, Kyrgyzstan: an integrated approach based on multi-source imaging and GIS

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Abstract
A crucial basis for disaster risk reduction forms the analysis of the existing building inventory with respect to its vulnerability. Traditional approaches using in-situ field-observations by civil-engineers proofed to be highly sufficient in determining the vulnerability of buildings, but are very time- and cost-consuming. Given the high rate of urbanization of Bishkek it becomes impossible to provide a complete earthquake vulnerability assessment of the whole city using a traditional civil-engineering approach. Therefore we propose an integrated approach, which aims at providing a comparatively cost- and time-efficient way to assess building inventory and thus structural vulnerability over large areas. The approach focuses on a new multi-source evaluation of structural vulnerability based on satellite remote sensing and ground-based omnidirectional imaging. It can be easily applied to different urban environments and efficiently be scaled depending on the desired level of detail. Latest image processing algorithms as well as computer vision and Geographical Information System (GIS) techniques are used on multiple imaging sources in the framework of an integrated sampling scheme. Each imaging source and technique is used to infer specific, scale-dependent information. To account for the requirements of the Global Earthquake Model (GEM) we prefer globally available low-cost data-sources and tools are developed on an open-source basis. An easily deployable omnidirectional camera-system is introduced for ground-based data-capturing. Preliminary results from a first application to our study site Bishkek, Kyrgyzstan, are shown.

Keywords: Seismic Vulnerability, Remote Sensing, Computer Vision, GIS, Omnidirectional

1. INTRODUCTION

The activities presented within this paper are part of the Global Earthquake Model (GEM) regional program Earthquake Model Central Asia (EMCA), which is coordinated by the GFZ. EMCA aims at cross-border assessment of seismic risk in Central Asia, by working together with institutions and experts in the region. The activities are subdivided into “Seismic hazard assessment and Microzonation”, “Seismic Vulnerability”, and “Earthquake Risk”. In order to provide an efficient approach that allows seismic risk monitoring, and considering the rapid growth of the main Central Asian urban areas, the use of remote sensing data and other imaging sources is tested and applied within EMCA. These activities also fully comply with the aim of the GEM Inventory Data Capture Tools (GEM-IDCT). A first test related to estimating building inventory for rapid seismic vulnerability assessment is ongoing in Bishkek and preliminary results are shown within this paper.

2. OBJECTIVES AND METHODOLOGY

Bishkek, the capital of Kyrgyzstan, is situated in one of the most seismically hazardous zones in Central Asia. Taking into account the centralized design and construction practices in the former Soviet Union, the buildings in Bishkek are moreover highly vulnerable to earthquake hazard. According to the conclusions of the Advanced Research Workshop in Almaty, Kazakhstan, an earthquake with similar intensity as the Armenian or Sakhalin earthquakes will cause approximately 40.000 deaths and 160.000 injuries in Bishkek [1]. Therefore it becomes imperative that certain preparedness measures are conducted to
reduce the negative consequences of earthquake hazard in the city of Bishkek. A crucial basis for disaster risk reduction forms the analysis of the existing building inventory with respect to its vulnerability. Traditional approaches using in-situ field-observations by local civil-engineers proofed to be highly sufficient in determining the vulnerability of buildings, but are highly time- and cost-consuming. Given the high rate of urbanization of Bishkek it becomes impossible to provide a complete earthquake vulnerability assessment of the whole city using a traditional civil-engineering approach. Therefore we propose an integrated approach to multi-scale seismic vulnerability assessment which can be easily applied to different urban environments and efficiently be scaled based on the desired level of detail (fig. 1). The approach is focused on a novel multi-source evaluation of structural vulnerability based on satellite remote sensing, ground-based omnidirectional imaging and Geographical Information System (GIS).

![Fig. 1: Integrated approach to estimating building inventory using multi-source imaging](image)

On urban footprint and district level an analysis of urban structures on the basis of medium-resolution satellite images is performed. Using image segmentation, multi-temporal change detection and machine learning based image classification the urban environment can be delineated into areas of homogeneous urban structure types. These analysis can provide a first estimate of value and distribution of crucial vulnerability indicators, such as pre-dominant building-type, building-age or urban growth rate and distribution. Furthermore the outputs are used to identify representative sample areas for a more detailed analysis of the building stock with ground-based omnidirectional imaging and high-resolution satellite images.

On building footprint level a rapid survey of the representative samples is then performed using high-resolution satellite images and an omnidirectional imaging system driven around with a car. Automatic processing of the acquired images provides with vulnerability relevant features and an estimate of the most likely vulnerability class, following EMS-98 scale [2], for each building successfully located. The dominant vulnerability class can then be associated to the corresponding homogeneous cluster for extrapolating the high-resolution vulnerability information to district level and therefore provide a detailed vulnerability classification for a complete city.

Following the requirements of GEM globally available low-cost data-sources are preferred and tools are developed on an open-source basis to allow for a high degree of transferability and usability.

### 3. Analysis of Urban Structure Types Using Medium-Resolution Satellite Images

Urban structure types are in this study defined as spatial units on block scale, that are homogeneous in medium-resolution satellite images in terms of their physical appearance (landcover) and usage (landuse) as well as their approximate age. The delineation of a city
into areas of homogeneous urban structure forms the strata for a sampling scheme to identify representative areas for a more detailed local assessment of the building stock. The analysis of urban structures from remote sensing on block scale is carried out in three hierarchical stages of stratification (fig. 2). We take images of Landsat Thematic Mapper (TM) and Multispectral Scanner (MSS), with 30m spatial resolution for TM and 60m respectively for MSS as input for the analysis. Both satellite sensors have a large swath-width and allow for capturing a city like Bishkek within just one image. Furthermore they are characterized by a high temporal repetition rate, worldwide coverage and a publicly, free-of-charge image archive, which dates back until 1972.

A first stage of stratification is image segmentation based on the brightness values of the image pixels in six spectral bands of Landsat TM. We use an efficient graph-based image segmentation algorithm developed by [3]. The segmentation delineates areas, which are homogeneous in terms of their spectral response in the satellite image and therefore clusters the image pixels into superpixels, also referred to as segments.

In a second stratification stage the segments are labelled concerning their predominant landuse/landcover (LULC) and approximate age of built-up areas. LULC provides us with information about the predominant building-type and is extracted by carrying out an object-oriented LULC classification. In a supervised classification process we use Support Vector Machines (SVM) learning algorithm to recognize the desired classes and to determine decision boundaries which partition the feature space according to the properties of selected training samples. Following an object-oriented approach to classification, we label segments instead of single pixels. Therefore, in addition to multispectral information, also geometrical and textural information, which take into account neighbourhood relations between pixels, can be used as input features for classification. This is of particular importance when analysing the urban landscape, where LULC classes are mainly defined by the alignment of buildings, streets and open-spaces and therefore can not sufficiently be described by just the spectral values of a single pixel.

To assess changes in the urban environment for getting information about the approximate age of built-up structures, we use multi-temporal change detection. As input we use Landsat TM and MSS images, which cover the same spatial extent but are taken at three different times (1977, 1994 and 2009). Post classification comparison was found to be the most suitable change detection method, because it directly gives information about the spatial distribution, the rate of change and also the change direction. Within this change detection method LULC classifications, which distinguish built-up from non-built-up areas, for individual Landsat images are compared on pixel basis and a change matrix is generated. This change matrix provides the “from-to” information of every LULC class, which allows for identifying and analysing changes separately, depending on the objective of the study. Given the three time steps of the input images we can derive three different age classes (before 1977, 1977-1994, 1994-2009).

In a third stage the LULC classification is combined with the age of built-up areas into a new thematic layer. Intersection of the layers is done using GIS. The final output of this stage is representing urban structures, which are on a block scale homogeneous in terms of LULC and approximate age. In terms of a stratified sampling approach this layer represents the final strata for automatically identifying a representative sample for each urban structure type.

The sampling process itself is based on a proportional allocation scheme where in a first step the largest segment of each stratum is selected for a closer inspection. The selected representative segment is then further analysed in a second step to define the final sample area for the related stratum. The size of a sample area is chosen proportionally to the size of the stratum, whereas its shape is defined as a square. The location of the sample area inside the representative segment is chosen randomly.
4. EFFICIENT GROUND-BASED DATA-CAPTURING USING ROUTING AND OMNIDIRECTIONAL CAMERA

Once representative sample areas are identified, optimal driving routes for a ground-based omnidirectional imaging survey need to be calculated within these areas. Optimal in the context of this study means a route, which covers all street-segments in a sample area with the shortest overall driving length to minimize costs and time for a ground-based camera survey. Pre-calculated driving routes furthermore can help to reduce data gaps and overlaps and therefore optimize disk space by avoiding the capture of redundant data. We use freely available digital street-data in vector-format from the OpenStreetMap project (OSM) [4] as basis for routing. In the context of this study the routing problem can be reduced to the common Travelling Salesman Problem (TSP). The TSP is a well-studied combinatorial optimization problem, in which a traveller is required to minimize the total travelling distance in order to visit all the stops on his list only once. To approach this problem we use the ArcGIS network analyst route solver tool. Its underlying algorithm determines the best route through a set of stops with a minimum cost by using a modified Dijkstra algorithm [5]. It first computes an origin-destination cost matrix holding the travel times between the stops using the Dijkstra algorithm and then uses a tabu-search algorithm to find the best sequence of visiting the stops. The calculated routes are used during the field-survey in combination with real time GPS-tracking to navigate a car with the omnidirectional imaging system through the pre-selected sample areas in the most efficient way.

Besides the navigation unit, the data-capturing system is composed by a camera, a GPS receiver and a laptop. We use a Ladybug3 omnidirectional camera from Point Grey Research Ltd, composed by 6 colour CMOS cameras. Omnidirectional images are by construction projections of a spherical field of view onto a central point [6]. Usually omnidirectional images are projected onto a planar, equirectangular map representation. This representation can be processed similar to a satellite image, keeping into account that the spatial resolution of the image is different from point to point and that there is a strong distortion around the poles. Omnidirectional imaging is particularly convenient, because it allows for capturing at once everything, which is surrounding the camera (360° horizontally and almost 180° vertically). Therefore an operator does not have to choose what to capture in a phase where, typically, it has not yet been established. This increases the overall speed of the survey operation and also erases uncertainties coming from subjective scene interpretation. Image sequences have been captured at 10Hz sampling rate in full resolution (5700x2700 pixels) colour JPEG format. The images are automatically georeferenced using the GPS signal. A custom software application has been developed to capture, synchronize...
and save the different data streams coming from the camera and the GPS. The actual image capturing process is performed almost automatically by driving along the pre-calculated routes with the camera system fixed onto the roof of a car. A flexible mounting system and a light hardware set-up makes the system easily deployable even by non-skilled operators.

5. EXTRACTION OF VULNERABILITY RELEVANT FEATURES FROM HIGH-RESOLUTION SATELLITE IMAGES AND OMNIDIRECTIONAL IMAGES

Image processing applied to high-resolution satellite images and omnidirectional imaging is a potential source of information related to seismic vulnerability on building scale. Many features that can influence the seismic performance of a building are visible from the outside, and therefore subject to a suitable quantification by means of a possibly automatic, visual assessment.

Features, which are best assessed from the topview using satellite images, are for example location, building footprint, roof-type, building age and accessibility. Fig. 3 shows an example from Bishkek of the automated extraction of the location and footprints of buildings on the basis of a Quickbird image (0.6m spatial resolution). For this first step in feature extraction we used an optimized multi-scale segmentation procedure followed by a supervised classification based on SVM.

Fig. 3: automatically extracted building footprints and location.

Features, which are best assessed from the streetview using omnidirectional images, are for example height, number of storeys, presence of weak/soft storeys, number and distribution of openings (windows and doors), 3D-shape, symmetry and distribution of vertical and horizontal elements. An extensive assessment of the application of advanced computer vision techniques to the task of automatically extracting such features from a omnidirectional image stream is currently undergoing. An example for feature extraction is shown in fig. 4. It can be seen, that it is possible to obtain a fairly accurate 3D reconstruction of a building facade from three contiguous omnidirectional images using optical flow measures. Optical flow means the vector field describing the apparent displacement of each pixel between two images [7]. The 3D reconstruction is defined in the reference system of the camera relative to the first image of the subsequence. Since we know from the GPS track the position and the aim of the camera at the same time frame, we can define the 3D coordinates of the reconstructed points in an external reference frame.
Due to automated georeferencing, the information extracted from the omnidirectional images can be easily crossed in a GIS environment with the building footprints and other features extracted from high-resolution satellite images. The estimated height of the buildings is mapped as a 2D distribution on a georeferenced satellite image (fig. 5). Height estimation from images is consistent with the manually assessed number of storeys of the identified buildings.

6. CONCLUSIONS

The integrated combination of satellite-based remote sensing and ground-based omnidirectional imaging allows for a rich visual description of the urban environment on different spatial scales, which can be easily updated on regular basis and in a standardized way due to the high temporal resolution of the input data and the speed of the ground-based survey. The proposed approach can be easily applied to different urban environments, and the underlying multi-scale structure eases the task of integrating information coming from different sources and at different levels of detail. Automated feature extraction from both high-resolution satellite and ground-based omnidirectional images for the city of Bishkek is in progress. Next steps include automated vulnerability classification of the identified buildings under consideration of uncertainties as well as the extrapolation of the results on building scale to block scale covering all of Bishkek. Furthermore the derived probabilistic vulnerability map for Bishkek will be combined with the results of seismic hazard analysis [8] to update and improve risk scenarios for the city of Bishkek [9] in a fully probabilistic framework.

REFERENCES


