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Earthquake Hazard Analysis and Building Vulnerability Assessment to Determine the Seismic Risk of Existing Buildings in an Urban Area

PhD Thesis Pamphlet

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Introduction and background

Recent earthquakes with high number of casualties and enormous devastation proved that the hazard of natural disasters should not be neglected. Preventive approaches have received greater attention recently. Research in earthquake hazard mitigation has focused on evaluating possible damage scenarios for different magnitude events (Luco et al 2007; Committee on National Earthquake Resilience 2011). Two widely different approaches exist; one considers the effect of previous earthquakes, listing the damaged buildings and casualties. The other offers a method to evaluate possible damages prior to an event. The latter method facilitates prevention by gathering information about the state of the building stock and the expected damages, so the authorities can strengthen the most vulnerable buildings in order to mitigate risk.

The challenge with this method is that many uncertainties must be taken into consideration. In order to determine earthquake risk within towns a fast and simple method should be developed. Otherwise it would be very time-consuming and require too much expert participation. The steps are the following:

- determine the hazard and the expectance of an earthquake,
- assess building stock.

With given input parameters of subsoil and PGA (peak ground acceleration) and the examined vulnerability, the damage based on building classes can be obtained, and earthquake scenarios can be derived. The vulnerability increases with extending urban areas. To reduce the potential damage, a comprehensive assessment of the seismic risk followed by a package of relevant remedial measures is needed. Earthquake risk can be assessed as:

$$\mathrm{RISK} = \mathrm{HAZARD} \times \mathrm{VULNERABILTY}$$

The “multiplication” should be considered a convolution of two large sets of data: the earthquake hazard data which describes the intensity and probability of an earthquake event and the vulnerability data that estimate the performance of a variety of building types to different levels of seismic loading. The risk is then the proportion of buildings that are likely to fail (considered as collapse, structural damage, or loss of operation).

This concept is suitable even in Hungary. Here there are about 100-120 smaller earthquakes per year; which are below the perceptible level, and 4-5 perceptible earthquakes per year (Earthquake Information System / www.foldrenges.hu). Earthquakes with a greater effect, causing structural damages can be expected every 15-20 years, and in 40-50 years major earthquakes with high economic and social effects. With this earthquake hazard level, Hungary ranks with the medium-hazardous countries. Hungary has experienced destructive earthquakes in the past, most significant was the event of 1763 in Komárom (Varga, 2014) with estimated intensity of IX, and an intensity of VII-VIII in Győr according to European Macroseismic Scale. Although such events are very rare, their intensity is comparable to the major earthquakes such Northridge earthquake (California 1994) with an intensity of IX according to Modified Mercalli Intensity Scale (Southern California Earthquake Center, 2001)

Scientist around the world have made a great effort concerning seismic hazard assessment, vulnerability evaluation and risk management in order to mitigate the consequences of a possible earthquake. Several projects have been funded by the European Commission in order to evaluate seismic hazard, vulnerability and risk across Europe. These topics have become more important in the last 10 to 20 years. Ongoing projects (NERIES, 2006-2010) (SYNER-G, 2009-2012) emphasize that this is a topic the research community works on worldwide. The next quote clearly states the importance of the work in seismic risk assessment: *"The fundamental role of the seismic risk assessment for the society is to provide all the information for each community or organizations to support the risk mitigation decision-making. These decisions are generally related to the likelihood and significance of structural collapse to the life-safety or business interruption. Hence a high risk of structural collapse is not accepted by the current standards and there are various methods available for making decisions to reduce that risk."* (ETH Zurich, 2013)

The results of seismic hazard assessments are further used by engineers to appropriately design any type of building, thus the results are widely used and important information. Taking into account the Hungarian situation according to seismic risk the other major issue is related to the built environment. It is important to note that a greater part of Hungarian buildings were not designed to resist earthquake loads. The first buildings to be designed taking into account the seismic loads were the large panel cast buildings in the seventies. The rest of the buildings of this era and earlier were designed only to resist wind load. It is obvious that the seismic hazard, vulnerability and earthquake risk is underestimated by both engineers and authorities or not properly quantified.

It is high time for Hungarian scientist and engineers to determine the seismic risk of those major cities, which have experienced destroying earthquakes in the past. In Hungary, the goal should be the reduction of the expected damage during an earthquake. This provides an economic motivation for funding and executing seismic engineering research.

1. Objectives and motivation

Determining the earthquake risk of buildings in a town or settlement has lately become a more prominent issue. The process can provide important data for governments, authorities, disaster management and insurance companies to better understand risks to many buildings and engineering systems rather than a single building. By this assessment process they can make better decisions about remedial actions, insurance underwriting, and evacuation and rescue.

This research addresses the rapid evaluation of a large number of similar buildings in the area of Győr. The steps involve determination of the hazard, assessing building stock, and computing vulnerability with different methods.

Objectives concerning the research are:

- review the literature concerning seismic hazard, vulnerability and earthquake risk assessment;
- review the geographical, geomorphological and tectonic formation of the investigated territory;
- review the development of the city and the typical building construction periods;
- develop data collection and validation procedure in a very specific Hungarian context;
- collect data about the soil profile of Győr in order to determine the seismic hazard of the town;
- collect data about the building stock of Győr in order to determine the vulnerability of the buildings;
- analyze data of soil parameters to define the effect of local soil profile;
- develop the method for seismic risk analysis of a town, taking into account local soil effects and behavior of the buildings;
- analyze data of building to determine the vulnerability;
- perform the zonation of the appointed area of research;
- evaluate the seismic risk of the selected building stock.

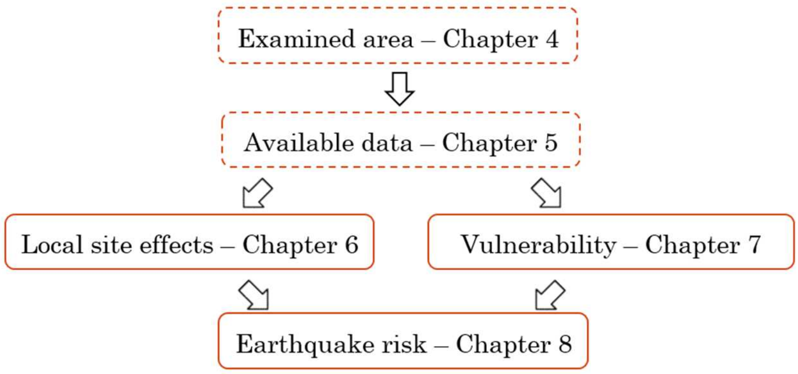
In order to achieve the goals of the research it was necessary to build up a method to fulfill the requirements of being accurate enough but reach the aims within an acceptable period of time using little resources. Compared to other methods, it should give a more accurate overview of the local site effects and should take into account the factors that contribute to the dynamic properties of the buildings.

2. Research methodology

In order to be able to determine the earthquake hazard of the area, the vulnerability of the buildings and the earthquake risk of the city a huge database is needed. Concerning data collection two very important expectations had to be fulfilled: the data should be accurate suitable for the given goals within an acceptable period of time nevertheless using low budget. One goal of the research was to develop the method of data collection that fulfills the above requirement in order to give a reproducible chain of process for risk analysis.

Firstly I have reviewed the literature concerning seismic hazard, vulnerability and earthquake risk assessment and compared my outcomes with results published in literature. The literature overview is presented in Chapter 2 and Chapter 3.

Secondly I studied the area of research more closely. On one hand I get acquainted with the geologic formation, the tectonics and geomorphology of the area and compared with the results from soil profile assessment. On the other hand I gathered information on the built environment to be able to determine the most used construction methods in the town furthermore the age and extension of different building types in different districts of the town. These formed the base of the preparation of the checklist and further investigation (Chapter 4).



A great part of the work has been in processing the data and in determining and performing validation. I performed MASW measurements to determine the v_s (shear wave velocity) profiles of the various soil types in and around Győr. I processed CPT data based on Wair et al (2012) to obtain v_s profile of the sites. I compared MASW results to CPT results. The correlations were very good. Based on measured v_s data I determined baseline v_s values for soil types in Győr. I used a regression technique to determine the variation of v_s parameters with depth. Using three different methods, I determined the v_s profile for each set of borings and compared them to the measured data. Finally, I was able to determine a pattern of soil layer distribution and delineate several different soil zones for Győr. Based on the zoning, I performed one dimensional site response analysis and compared the result to the standards of EC8. I was able to differentiate between levels of hazard concerning Győr even though almost all territory of Győr belongs to soil category C based on EC8. This is presented in Chapter 6.

Another part of the work has dealt with built environment placing emphasis on residential and public buildings. I developed a checklist and with the help of trained staff we collected structural data from more than 5000 buildings, based on screening methods. The buildings were scored to assess their seismic vulnerability. I carried out more detailed push over analyses of typical buildings to compare to the score assignment results. Based on building vulnerability properties I divided the city district further into smaller zones (Chapter 7).

Finally I evaluated the overall seismic risk of the designated area based on different scenarios. Two maps, one depicting seismic hazard, the other displaying building vulnerability were overlaid resulting in a detailed zonation of seismic risk (Chapter 8). Based on this visualization, engineers can better plan to make improvements to infrastructure, determine insurance rates for protection, and plan for emergency activities in case of a seismic event.

The research methods consisted of:

- Hazard activities
  - collecting historical soil data throughout Győr;
  - processing and validating historical soil data with present day information;
  - measuring soil shear wave velocity at selected locations;
  - extending shear wave velocity estimates throughout the city by correlating measured data to historical data;
  - modeling site response by one dimensional response analysis;
  - comparing response analysis to code (EC8) profiles;
  - using site response analysis to determine seismic demand;
- Vulnerability activities
  - designing methods to collect building data then actually collecting it;
  - processing and validating building data;
  - analyzing typical buildings to generate vulnerability functions;
- Risk activities
  - comparing seismic demand to vulnerability to determine risk;
  - mapping risk for different areas of the city and scenarios.

My overall goal was to develop and evaluate a method for seismic risk analysis. This implied the processes and necessary data for completing the analysis.

I developed skills concerning field seismic testing and software implementation during the research. I prepared papers about the research and had presentations at international conferences. I organized a workshop for undergraduate students dealing with dynamic analysis of structures and soil as well as building assessment for seismic performance.

3. New scientific results

3.1. Thesis I (Chapter 6)

I determined and mapped the local soil effect for seismic hazard determination in the area of Győr.

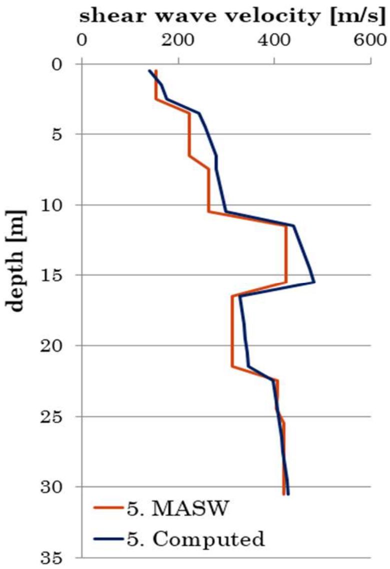
3.1.1. Thesis I/a

I determined the shear wave velocity profiles for different soil categories in Győr using MASW.

Depth [m]	MED v_s [m/s]						MIN v_s [m/s]						MAX v_s [m/s]					
		169.79	178.69		183.09	162.89		131.44	140.07		131.44	134.13		204.00	193.09		215.58	201.31
		190.93	233.00		185.86	207.79		159.80	202.15		163.31	200.57		222.73	257.04		208.40	215.00
		194.36	212.11		-	-		194.36	167.04		-	-		236.49	251.27		-	-
		-	-		192.94	235.83		-	-		183.68	212.15		-	-		202.20	259.50
1-5		203.81	256.09		191.80	192.67		187.06	160.00		159.80	155.97		270.82	324.59		215.58	251.86
		193.06	219.23		321.33	275.30		169.22	198.83		309.66	247.95		210.43	285.95		333.00	302.66
		220.10	276.33		208.40	224.35		218.34	268.57		208.40	220.15		222.73	287.41		208.40	228.37
		238.85	273.87		324.49	295.74		236.49	260.82		324.49	292.23		242.00	282.80		324.49	299.26
		263.29	282.74		220.79	274.50		261.61	262.21		183.68	221.22		266.20	293.23		267.23	299.09
5-10		316.22	381.09		345.64	319.17		270.82	346.25		329.40	313.37		384.32	412.86		378.12	322.07
		235.65	223.98		292.98	275.04		210.43	218.53		264.63	253.18		252.47	229.08		333.00	309.35
		-	-		264.69	262.04		-	-		248.55	244.79		-	-		309.66	309.66
		315.20	294.06		324.49	311.59		248.55	246.86		324.49	305.72		333.00	312.30		324.49	317.33
		284.93	305.51		267.23	312.45		261.61	294.12		267.23	304.83		333.77	319.73		267.23	319.74
10-15		428.67	453.03		359.21	345.87		384.32	426.38		329.40	330.11		463.43	473.08		378.12	357.42
		252.47	232.38		264.63	278.17		252.47	231.32		264.63	274.62		252.47	233.44		264.63	281.66
		381.49	354.19	Kismegyer	538.58	523.98		371.71	354.19	Kismegyer	538.58	514.32		391.27	354.19	Kismegyer	538.58	533.53
		318.27	328.74		249.32	250.97		312.05	316.20		248.55	246.86		330.72	339.71		250.28	254.07
		343.64	334.25		329.97	335.73		326.40	324.12		329.97	328.24		378.52	339.71		329.97	342.88
15-20		450.55	486.62		370.98	375.66		424.77	483.34		344.00	363.34		463.43	493.17		443.05	384.47
		-	-		-	-		-	-		-	-		-	-		-	-
		381.49	358.08	Kismegyer	538.58	551.38		371.71	358.08	Kismegyer	538.58	542.64		391.27	358.08	Kismegyer	538.58	560.03
		337.35	341.76		364.84	361.40		312.05	336.02		338.41	356.31		350.00	346.57		391.27	366.39
		369.25	349.69		417.52	353.16		326.40	343.20		329.97	346.15		378.52	355.95		461.29	358.08
20-25		656.53	556.38		396.72	398.12		656.53	552.64		370.00	389.24		656.53	560.11		370.00	389.24
		-	-		-	-		-	-		-	-		-	-		-	-
		392.91	380.98		-	-		390.55	375.59		-	-		400.00	387.74		-	-
		362.22	352.21		365.81	375.10		360.00	346.85		338.41	369.53		370.00	356.37		391.27	381.22
		369.47	365.00		-	-		365.19	358.88		-	-		370.00	369.74		-	-
25-30		617.87	584.07		416.12	417.29		521.23	567.37		390.00	410.73		656.53	594.62		430.00	425.74

3.1.2. Thesis I/b

I correlated the measured MASW data to CPT and soil boring data and developed empirical relationships between soil types, soil depth and shear wave velocity.

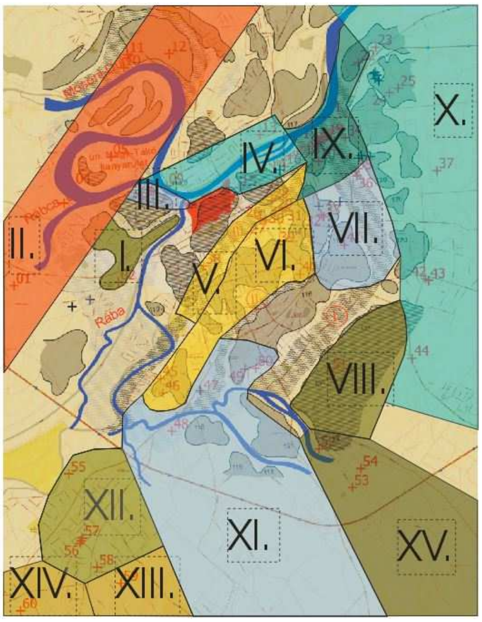


Predictive equation: $v_{s,i} = a \cdot D^b$

Based on MASW measurements		Based on literature and optimization	
Soil type	Predictive equation	Soil type	Predictive equation
Cl	$v_{s,i} = 190 \cdot D^{0.1858}$	Ss	$v_{s,i} = 250 \cdot D^{0.3500}$
Si	$v_{s,i} = 180 \cdot D^{0.1181}$	Cls	$v_{s,i} = 200 \cdot D^{0.2700}$
siSa	$v_{s,i} = 155 \cdot D^{0.2087}$	clSa	$v_{s,i} = 185 \cdot D^{0.2136}$
Sa	$v_{s,i} = 185 \cdot D^{0.2186}$	Gr	$v_{s,i} = 180 \cdot D^{0.2200}$
grSa	$v_{s,i} = 155 \cdot D^{0.1461}$	saGr	$v_{s,i} = 195 \cdot D^{0.1900}$
siCl	$v_{s,i} = 185 \cdot D^{0.2046}$	stiffCl	$v_{s,i} = 200 \cdot D^{0.3219}$
saCl	$v_{s,i} = 185 \cdot D^{0.2463}$	stiffclSa	$v_{s,i} = 195 \cdot D^{0.3388}$

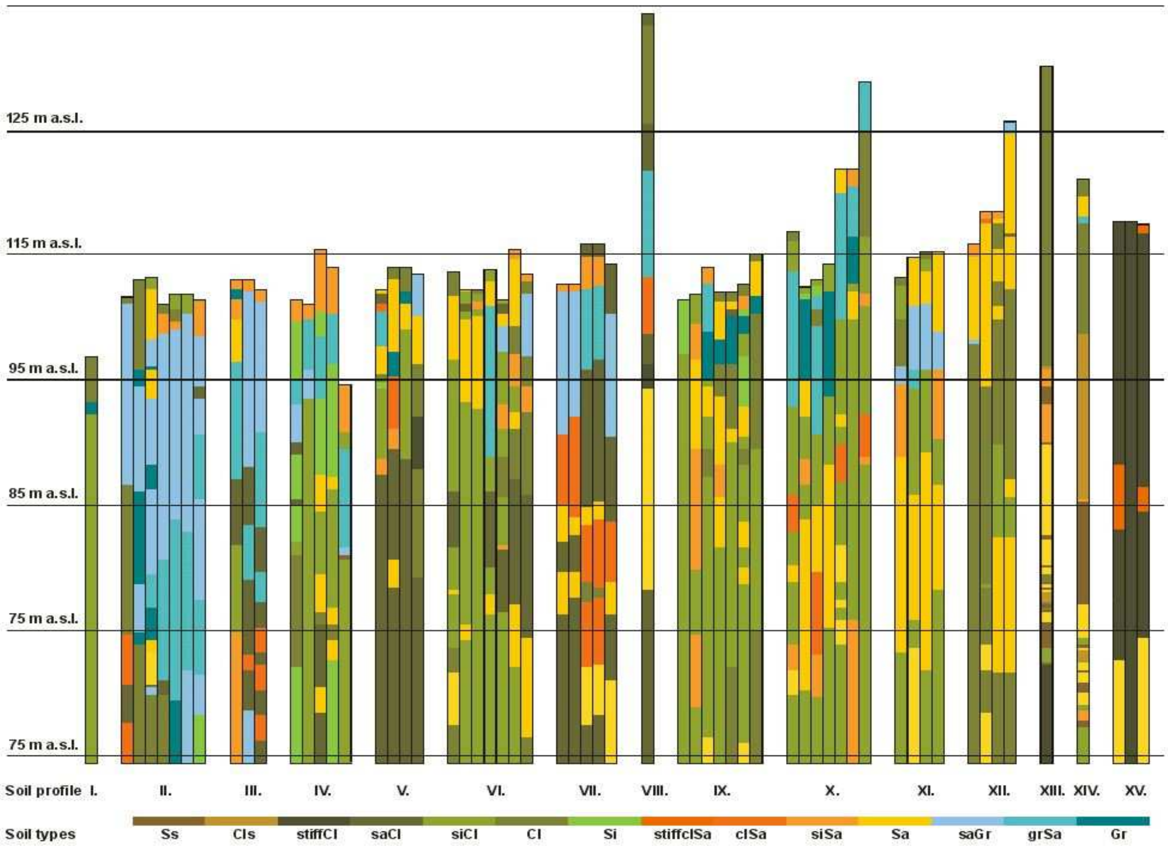
3.1.3. Thesis I/c

Using the correlations I was able to create a soil profile map for the Győr area.



3.1.4. Thesis I/d

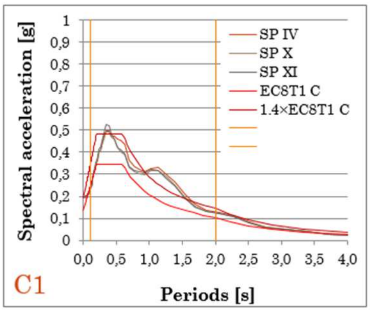
I performed seismic site response analysis for 15 different averaged soil profiles. Based on the response analyses, I was able to differentiate between regions of the city.

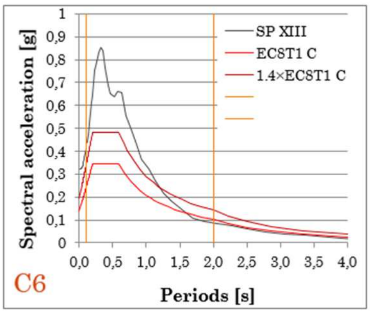


3.1.5. Thesis I/e

Even though the soil in the city area is classified as soil type C according to EC8, I determined that the hazard is not uniform.

Soil profile	Acceleration 0.00 m [g]		Amplification factor	Data from transfer function				V_{s30} [m/s]	Soil category
	Median	Log Stdev	m	f_1 [Hz]	T_1 [s]	f_2 [Hz]	T_2 [s]	Med	
I.	0.192	0.447	1.601	0.652	1.533	2.262	0.442	299.8	C
II.	0.214	0.374	1.782	0.767	1.304	-	-	278.9	C
III.	0.234	0.413	1.949	0.915	1.093	-	-	298.4	C
IV.	0.199	0.363	1.660	0.727	1.376	-	-	285.3	C
V.	0.206	0.440	1.715	0.717	1.395	-	-	322.8	C
VI.	0.197	0.462	1.642	0.644	1.554	1.976	0.506	305.8	C
VII.	0.216	0.492	1.797	0.843	1.186	-	-	307.9	C
VIII.	0.212	0.437	1.768	0.757	1.321	-	-	330.8	C
IX.	0.210	0.419	1.754	0.788	1.269	2.356	0.424	295.8	C
X.	0.191	0.405	1.595	0.727	1.376	2.003	0.499	297.6	C
XI.	0.197	0.378	1.639	0.727	1.376	2.030	0.493	301.0	C
XII.	0.211	0.457	1.761	0.799	1.252	-	-	297.8	C
XIII.	0.322	0.452	2.680	1.231	0.812	-	-	313.6	C
XIV.	0.296	0.416	2.471	1.019	0.981	3.129	0.320	414.3	B
XV.	0.243	0.535	2.029	0.832	1.202	4.758	0.210	448.3	B



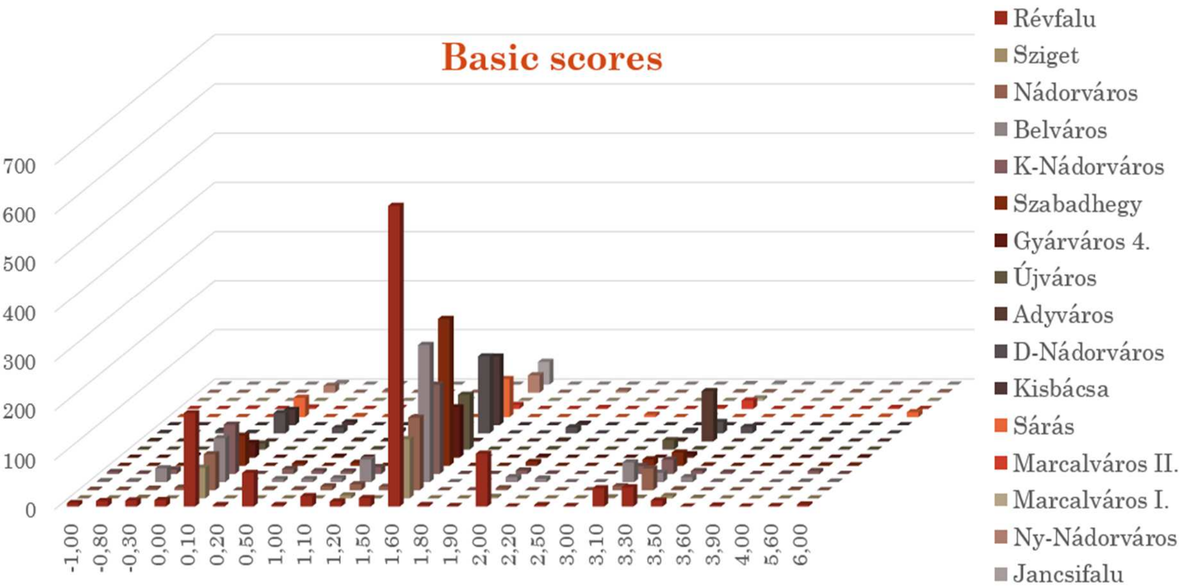


3.2. Thesis II (Chapter 7)

I performed building vulnerability assessment for the designated area.

3.2.1. Thesis II/a

I defined a simplified methodology for rapid evaluation of dynamic analysis of buildings and created a checklist. Based on the checklist I led the evaluation of more than 5000 buildings in area of Győr.



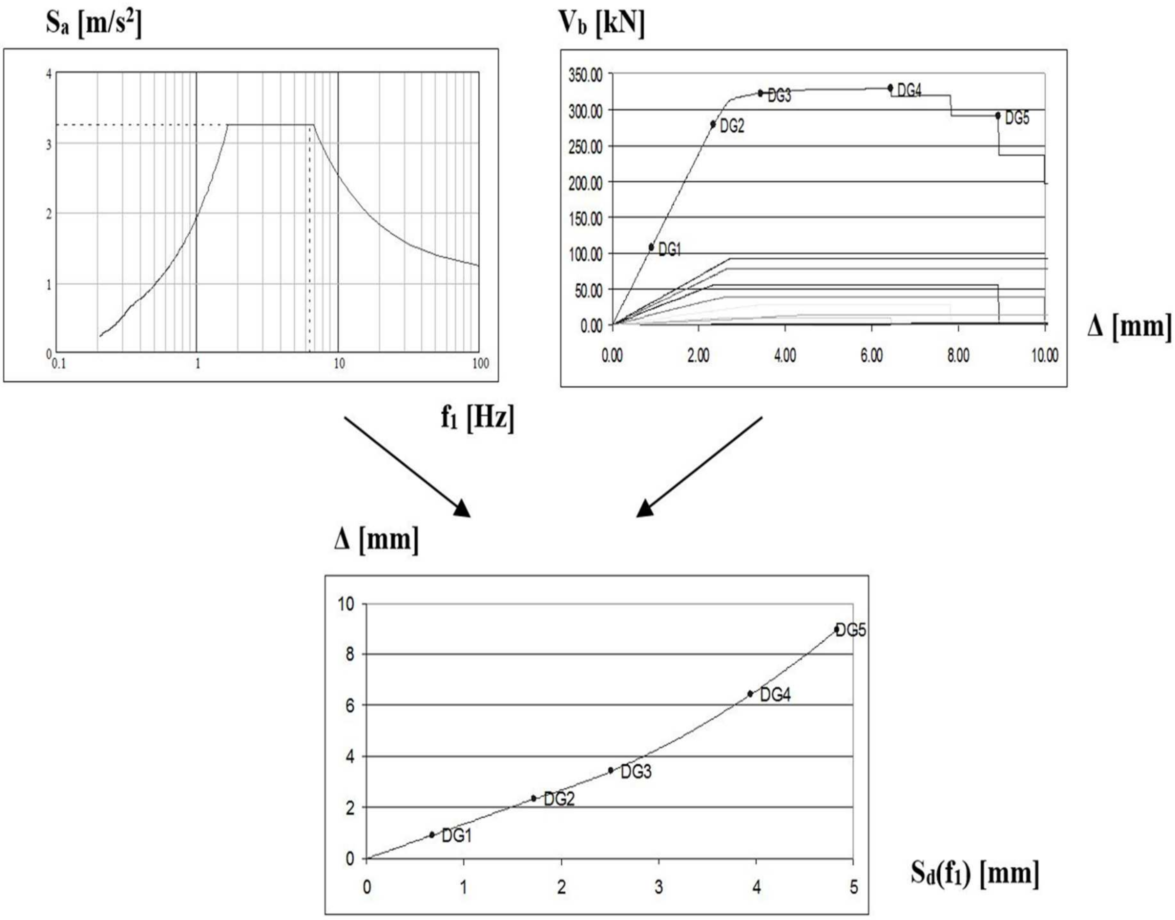
3.2.2. **Thesis II/b**

I determined the vulnerability of the building stock based on score assignment.

TOWN PARTS					TOTAL
Function of the area	Belváros	Nádorváros	Újváros	Révfalu	
economic, commercial, industrial	2.51%	30.23%	8.34%	1.49%	
special (cultural, educational, ecclesiastic)	69.79%	14.72%	5.94%	9.57%	
rural residential	-	7.69%	50.25%	36.97%	
garden city residential	-	29.74%	15.11%	34.49%	
urban residential	4.89%	12.46%	0.40%	0.14%	
Total area [ha]	**90.49**	**256.37**	**117.39**	**263.81**	**728**
Number of residents	**10,358**	**20,130**	**4,397**	**6,640**	**41,525**
Soil profile	**C1**	**C1/C2/C5**	**C2/C5**	**C1/C3**	
Basic Structural Hazard Score	2.7	4.2	4.2	4.2	

3.2.3. **Thesis II/c**

I determined the vulnerability of masonry and reinforced concrete buildings typical to Győr by several pushover methods.



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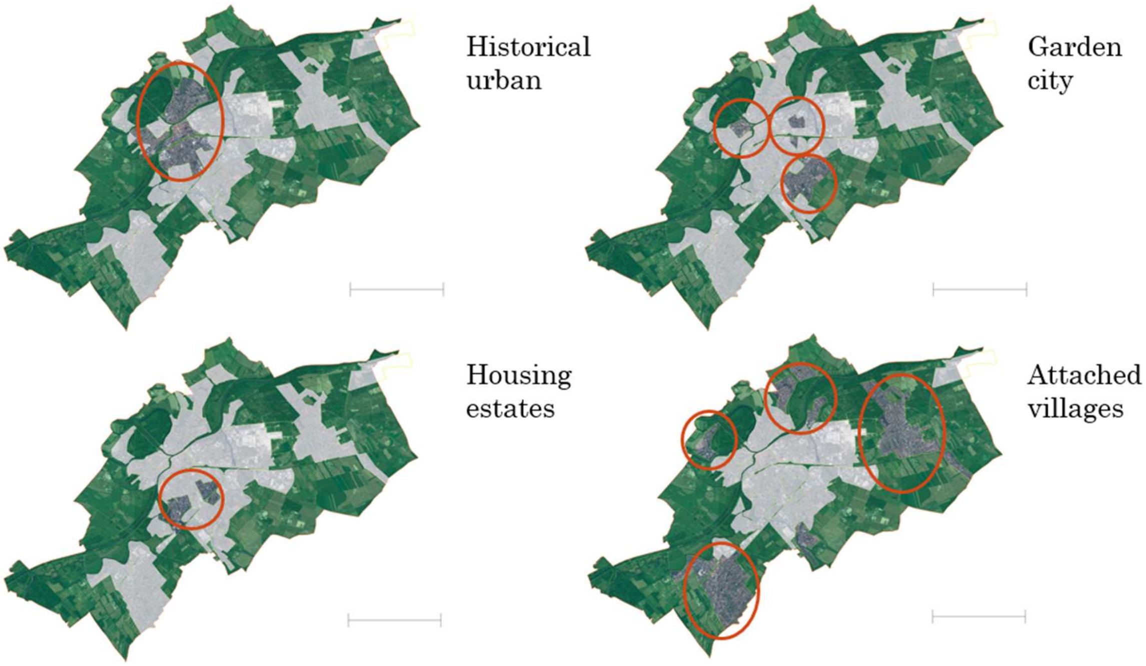
3.2.4. Thesis II/d

I delineated the zones for the designated area with different seismic vulnerability.

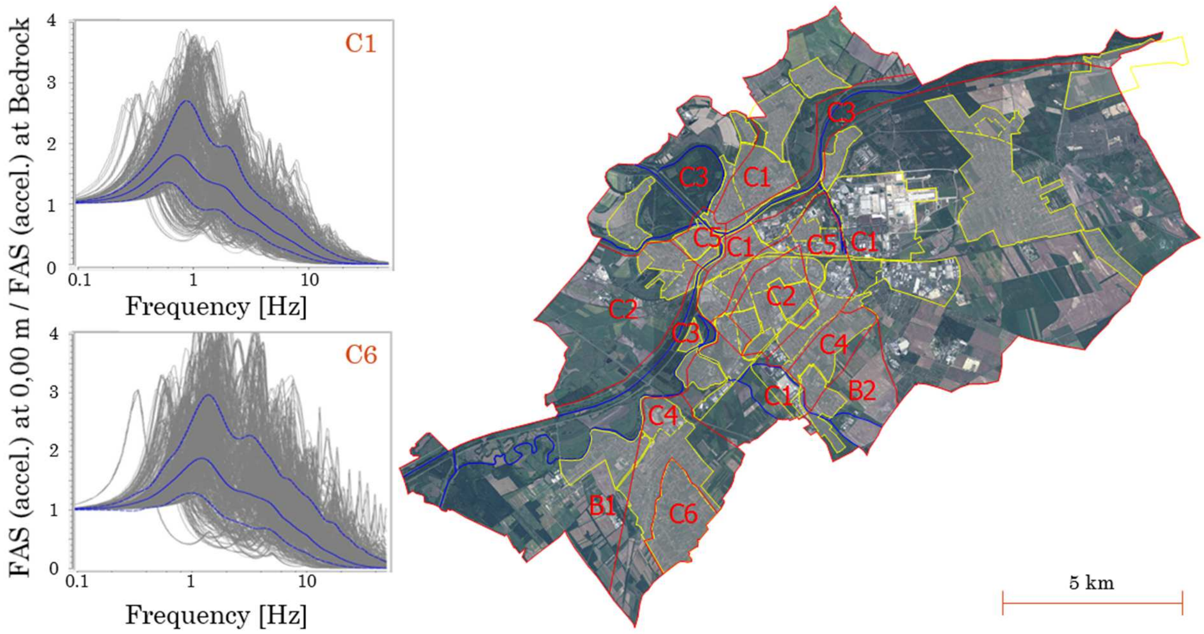


3.3. Thesis III (Chapter 8)

I designed the method for seismic risk analysis using a rapid assessment method based on available data with limited resources. I demonstrated the feasibility of performing the analysis using only public domain software.

3.3.1. Thesis III/a

I delineated the zones for the designated area with different seismic hazard..



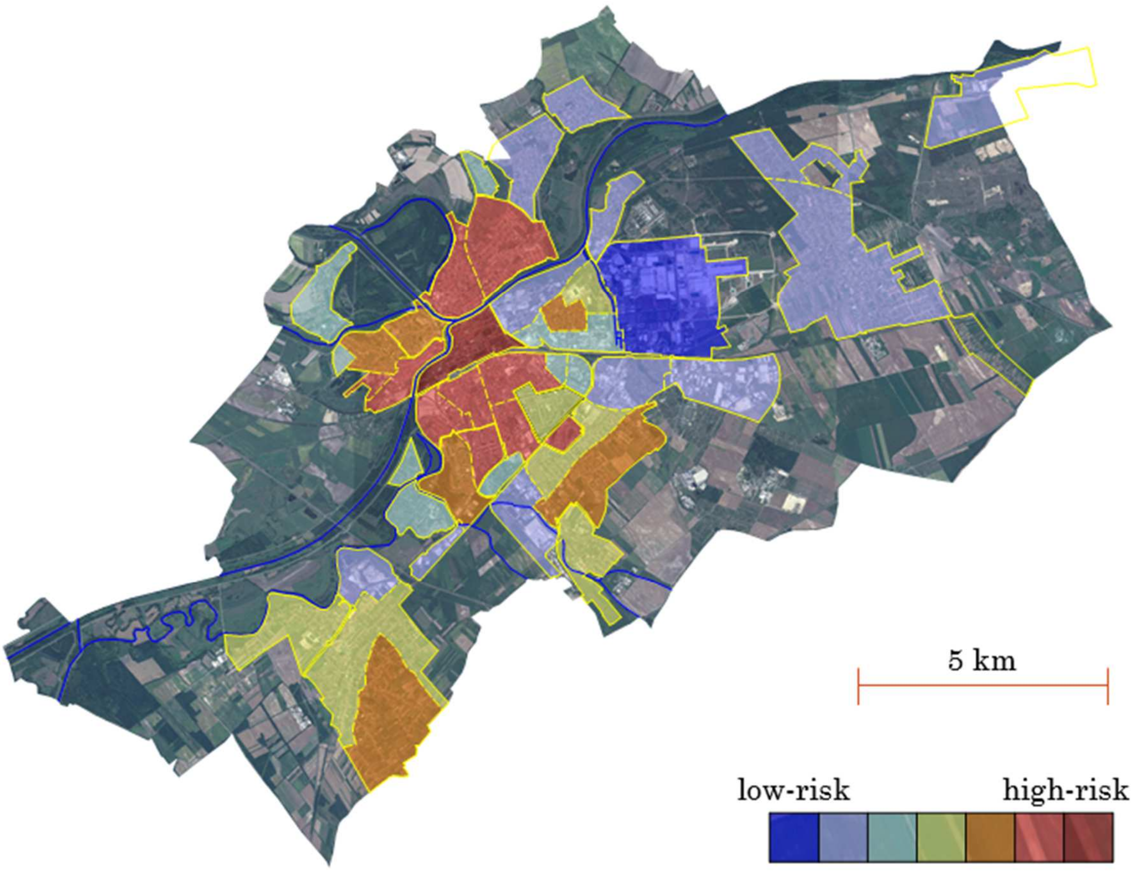
3.3.2. Thesis III/b

I determined the districts with different vulnerability level of the buildings.

TOWN PARTS					TOTAL
Function of the area	**Belváros**	**Nádorváros**	**Újváros**	**Révfalu**	
economic, commercial, industrial	2.51%	30.23%	8.34%	1.49%	
special (cultural, educational, ecclesiastic)	69.79%	14.72%	5.94%	9.57%	
rural residential	-	7.69%	50.25%	36.97%	
garden city residential	-	29.74%	15.11%	34.49%	
urban residential	4.89%	12.46%	0.40%	0.14%	
Total area [ha]	**90.49**	**256.37**	**117.39**	**263.81**	**728**
Number of residents	**10,358**	**20,130**	**4,397**	**6,640**	**41,525**
Soil profile	C1	C1/C2/C5	C2/C5	C1/C3	
Basic Structural Hazard Score	2.7	4.2	4.2	4.2	
Modifier of soil	-0.4	-0.6	-0.6	-0.5	
Structural Hazard Scores Scenario I.	**2.3**	**3.6**	**3.6**	**3.7**	
Structural Hazard Scores Scenario II.	**0.7**	**2.0**	**2.0**	**2.1**	

3.3.3. Thesis III/c

I applied the risk assessment methodology over discrete areas making it ideal for GIS implementation. The method is directly applicable to other towns in Hungary.



Conclusion

The research gives a good overview about seismic hazard of the city, the vulnerability of the building stock and the seismic risk concerning the designated area. The area is considered a moderate earthquake risk with past events estimated up to M=6.5. It is a typical situation for many cities in Hungary and throughout Europe where the seismic hazard is not great, but cannot be ignored.

In order to make the best use of limited resources, this methodology used existing soil data, rapid visual building assessment, a limited number of field tests and free, but sophisticated software. Estimates of seismic risk were computed using seismic hazard results and building vulnerability functions. As one would expect, since the hazards and vulnerabilities were not uniformly distributed around Győr, there were zones of higher and lower risk.

The results can be directly applied into development plans, emergency planning, insurance calculation, etc. The method developed for Hungarian context can be directly used to evaluate the earthquake risk of other cities. The research can be even carried on to determine the earthquake risk of the whole city of Győr.

The results of site response analysis reveals the fact, that in areas with diverse soil conditions, especially in case of alluvium further analysis is needed for creating elastic response spectrum for design purposes.

Future work related to this research is recommended in several directions:

- Seismic risk of the whole city could be performed based on the methodology.
- Societal and economical aspects could be incorporated to be able to estimate the cost of the different events.
- The seismic risk analysis of infrastructures could be evaluated, because damages of this structures can have an effect on the buildings.

Based on detailed building analysis, further simplifications could be implemented concerning visual screening, which does not worsen the results, in order to reduce the man-hours needed for field survey.

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