ENGINEERING GEOLOGICAL CHARACTERIZATION
AND NUMERICAL MODELLING OF STONE MASONRY ARCHES

New scientific results

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1. **BACKGROUND AND MOTIVATION**

Stone masonry arches are one of the most ancient forms of the engineering structures. Although in these days new stone masonry arches are seldom built, the maintenance and restoration of the old ones represent a special challenge at the present time as well. In historic times masonry arches and vaults were widely used all over the world in large range of structures, even so their modelling and analysis brings up many questions even today. In Hungary there are no methods commonly used for controlling and investigating stone masonry arches and arch bridges thus the calculation of load-bearing capacity of such structures causes difficulties in many cases. Due to the age of these kind of structures the condition of most of them increasingly deteriorates. Moreover, the traffic and related load has increased significantly, thus these old structures have to fulfil new expectations. As a consequence, their stability control and verification of their load-bearing capacity became necessary in many cases.

One of the most frequently investigated stone structures are the stone masonry bridges. Only in the United Kingdom there are approximately 40000 (McKibbins et al., 2006), and in Hungary the number of these bridges is also more than 1500 (Gálos & Vásárhelyi, 2005). Thus my research primarily focuses on the analysis of the load-bearing capacity of stone masonry arch bridges thus as a first step investigations were made in case of several arch bridges from the in situ diagnostics through the laboratory investigations to the different stability analyses. My research pointed out that in case of investigations of existing arches it is difficult to determine adequate input parameters for the numerical modelling from the measurable data even for the simplest methods for instance trust line analysis and rigid block method. The scope of effect of these input parameters is unclear as well. In addition, the analysis of the structural behaviour also brings up further questions.

2. **OBJECTIVES OF THE DISSERTATION**

Based on the above mentioned findings my dissertation concerned with two major topics: analyses of load-bearing capacity of stone masonry arch bridges and the effect of their input parameters, and the usage of more difficult numerical modelling for investigating the structural behaviour. Analysis of spatial behaviours, fatigue, skew or multiring arches, analysis of the soil-structure interaction, effects of lateral loading do not belong to the scope of the research. The objectives of the dissertation are the followings:

- comparison of the results of different load-bearing capacity analyses (MEXE method, thrust line analysis, rigid block method)
- evaluation of the effect of the input parameters on the load-bearing capacity calculation by means of sensitivity analysis
- comparison of the results of laboratory experiments and numerical models to investigate if a hybrid finite element program is capable of analysing the structural behaviour
- investigation of the applicability of a hybrid finite element program for the analysis of carbon fiber reinforced polymer (CFRP) strengthened masonry vaults

3. SUMMARY OF THE RELATED LITERATURE

Since the cultural significance of stone masonry arch bridges is high and their structural behaviour is unique, several papers, studies and researches are concerned with some aspects of masonry structures. Modern equilibrium analyses of masonry arches were based on Heyman (1966) work. His articles have been published since the 1960s and 1970s, and with his work he laid down the basis of the plastic analyses of masonry arches. Heyman (1995) summarizes most of his findings. There are a great many researchers of this topic, the works of Harvey (1988), Page (1988), Gilbert & Melbourne (1994), Vermeltfoort (2001), Fanning & Boothby (2001) Cavicchi & Gambarotta (2006), Milani et al. (2008), Gibbons & Fanning (2010) ought to be mentioned in the first place. The most comprehensive work about the assessment of masonry arch bridges from the in situ diagnostics to the different calculations is presented by McKibbins et al. (2006). CFRP strengthening in case of masonry arches is a relatively new topic. The papers of Foraboschi (2004), Oliveira et al. (2010), Oliveira et al. (2011), Basílio et al. (2014), Maruccio et al. (2014) give an outline of this research area.


In the home literature there are no previous papers regarding the laboratory experiments and numerical modelling of masonry arches.
4. **Methodology**

4.1. **Load-bearing capacity analyses of masonry arch bridges**

In order to get familiar with the practical difficulties and the whole process of load-bearing capacity calculations of masonry bridges, investigations were made in case of seven arch bridges (Benta-brook bridge in Sóskút, Mill-bridge in Sóskút, Bükkös-brook bridge in Szentendre, Derék-brook bridge in Patak, Lókos-bridge in Romhány, Bér-brook bridge in Héhalom, Rédei-Nagy-brook bridge in Gyöngyöspatai) from the in situ diagnostics through the laboratory investigations to the different stability analyses. Comparison was made between the results of an approximate calculation with the MEXE method (MEXE, 1963), the thrust line analysis and the rigid block method. For the calculations the ARCHIE-M software (Obvis, 2016) and the LimitState Ring program (LimitState Ltd, 2011) developed by the University of Sheffield were used. By means of the results of the load-bearing capacity calculations the applicability of the MEXE method in case of multispans bridges with stocky piers was analysed. The investigation based on the work of Melbourne et al. (1997) and Magyar Útügyi Társaság (2006). Finally, sensitivity analyses were carried out with the rigid block method to investigate the scope of effect of the input parameters to the load-bearing capacity. Figure 1 demonstrates the different steps of the research.

![Flowchart of the research of load-bearing capacity analyses of masonry arch bridges](image-url)
In situ tests included the identification of lithotypes. Weathering forms were classified according to Fitzner et al. (1995), Török (2002) and ICOMOS (2008). For the assessment of the condition of the stone materials N-type Schmidt hammer was use. Laboratory tests and measurements were made in the material testing laboratory of the Department of Construction Materials and Engineering Geology. The investigations were made with calibrated instruments. Determination of bulk density was made according to the MSZ EN 1936:2007 standard. Rock strength tests were performed on oven-dry and water-saturated cylindrical specimens with a length-to-diameter ratio of 2:1 at ambient temperature. Tensile strength tests were carried out according to the MSZ 18285/2-79 Hungarian standard, uniaxial compressive strength tests were performed according to the MSZ EN 1926:2007 standard. Elastic modulus and Poisson ration were measured according to the suggestions of the ISRM (2014).

There are no unified method for taking into account the different damages of masonry structures. Few damages can be considered in different extent and in different ways depending on the different calculation methods. Present results take into account the effect of mortar loss, the decreasing of the effective width of the vault due to lengthwise cracks of the arch. Displacements of the abutments, foundation settlements, occasional backing, fallen blocks, stiffener effect of the spandrel wall, partial collapses are not considered.

4.2. Laboratory and numerical modelling of masonry arches

In foreign researches it is an accepted procedure to verify the applicability and the accuracy of new methods and software by means of laboratory experiments. Such validations are presented in Melbourne & Gilbert (1995), Vermeltfoort (2001), Milani et al. (2008). Following the international examples present research validate a hybrid finite element program (Rocscience RS2) by means of laboratory experiments of small scale arches. The aim of the validation was to decide if the mentioned numerical method is capable of analysing the structural behaviour, estimating the load-bearing capacity accurately enough. Figure 2 summarizes the different part of the research.

Construction materials used for the experiments were tested as it was shown above in Chapter 4.1. Bending and compressive strength tests of the mortar were performed according to the MSZ EN 1015-11:2000 standard. Bonding strength tests were measured by following the instructions of the e-ÚT 07.03.21:2000 [ÚT2-3406] Hungarian standard. The tests were performed on an arch (Figure 3) and on two barrel vaults with the same geometry with and without reinforcement (Figure 4). On the strengthened arch carbon fiber reinforced polymer (CFRP) plates were used to increase the load-bearing capacity thus it was also observed if a calibrated numerical model can calculate the strengthening effect. During the laboratory experiment the arches were loaded to collapse then
the results were compared to the results of the numerical modelling. The most parts of the laboratory experiments represent the results of the work together with Richárd Varró. The results of the experiments are also presented in Varró et al. (2013), Varró et al. (2014). Further information can be found in Varró (2012) and Varró (2015).

The constructed small scale vaults are semi-circular arches built from sandstone blocks with a size of 3 x 3 x 4 cm. The normal size masonry arch has a segmental shape. It was built from standard sized brick. The joints of all three arches were filled with traditional lime mortar. For the strengthening of one of the small scale vaults SIKA CarboDur M-514 type CFRP strips were used with a width of 50 mm. The strips were pasted up to the full length of the extrados and intrados with a special mortar, the Sika dur-30 which is a 2-component, moisture-tolerant, high-strength, structural epoxy paste adhesive for bonding external reinforcement.

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**LABORATORY MATERIAL TESTING**
1. Testing the material of the blocks
   - specimen forming
   - saturation or drying
   - measuring mass and geometric data
   - set up of testing system and sensors
   - compressive strength test
   - tensile strength test
   - assessment of the measurements
2. Testing the mortar
   - mixing mortars with different recipes
   - preparing specimens
   - measuring mass and geometric data
   - bending-, and compressive strength test
   - bonding strength test
   - assessment of the measurements
   - choosing recipe for mortar
3. Testing the CFRP strips
   - bonding strength test of the special mortar on different materials
   - assessment of the measurements

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**LABORATORY EXPERIMENTS**
- preliminary investigations
- building the centre and the foundations
- preparing blocks and mortar
- construction of the arches, strengthening with CFRP strips
- set up of testing system and sensors
- loading the arches till collapse
- observing failure load and mechanism

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**NUMERICAL MODELLING**
- set up required parameters for the modelling
- 2D hybrid finite element modelling (Rocsience RS2 program)
- creating different modell set-ups concerning the geometrical idealization looking for the best fitting one

**Failure load**
**Failure mechanism**
- using the validated numerical modell for analysing the CFRP strengthened vault
- verification of the results with the new laboratory experiment

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**EVALUATION**
- comparison of the results of the laboratory experiments and the numerical models
- comparison of the different numerical modell set-ups
- revalidating the CFRP strengthened model
- conclusions

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**Fig. 2.** Flowchart of the research of laboratory and numerical modelling of masonry arches
Fig. 3. Small scale vault with geometrical data (left), vault strengthened with CFRP strips (right)

Fig. 4. Normal size masonry arch with geometrical data

The numerical modelling was carried out with the Rocscience RS2 (Rocscience, 2014) two-dimensional hybrid finite element program. Plane strain analysis was used with homogeneous, isotropic, linear elastic, six nodded triangle finite elements. The connections between the blocks were taken into account as joints. A joint represents an interface along which movement could take place. A joint was assigned strength and stiffness properties in accordance with the Mohr-Coulomb failure criterion. Residual values of strength parameters can be adjusted thus the behaviour of a yielded joint can be observed. Figure 5 shows the mechanical model of the joints. Normal and shear stiffness were carried out by using the findings of Senthivel & Lourenço (2009).

\[ j_{kn} \]– normal stiffness, \[ j_{ks} \]– shear stiffness, \[ j_{ten} \]– tensile strength, \[ j_{fric} \]– friction angle, \[ j_{coh} \]– cohesion

Fig. 5. Behaviour of the joints (Sarhosis et al., 2015)
5. **NEW SCIENTIFIC RESULTS**

5.1. Theses regarding load-bearing capacity analyses of masonry arch bridges

1. Thesis [5, 6]

I have demonstrated by the comparison of the results of numerical modelling (with thrust line analysis and rigid block method) and approximate calculation (MEXE method) of five multi-span masonry arch bridges with stocky piers that in case of the investigated multi-span bridges (rigid abutments, 0.11-0.87 pier height/thickness ratio, 3.6-9.2 m long span, 2.11-3.83 span/rise ratio) the MEXE method is applicable for calculating the permissible axle loads. In case of the investigated bridges the load-bearing capacity calculated with the MEXE method is 55-70 % of the results of the calculation with the rigid-block method.

The investigation based on the work of Melbourne et al. (1997) and Magyar Útügyi Társaság (2006) according to which the vaults of multi-span arch bridges work independently if their piers considered to be stocky. Since the approximate calculation of MEXE method is only applicable for single span bridges, the statement of the 1. Thesis extends the boundary conditions and the applicability of the method. The verification was carried out with the thrust line analysis and the rigid block method to which Figure 6 and 7 provide examples. Table 1 summarizes the results of the different calculation methods, the permissible axle loads are presented in the ratio of the rigid block method. Bridges with grey coloured background are single span bridges. In case of the Lókos-bridge (“e”) the MEXE method overestimates the permissible axle load which is a known defect of the calculation. It can occur in case of bridges with short span and thin layer of surface fill. In the other cases the approximation was as accurate as it was expected.

![Fig. 6. Thrust line analysis in case of the Bér-brook bridge (39.06 t)](image)

![Fig. 7. Failure mechanism by the rigid block method in case of the Bér-brook bridge (49.0 t)](image)
Table 1. Permissible axle loads of different bridges in the ratio of the rigid block method

<table>
<thead>
<tr>
<th></th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>d</th>
<th>e</th>
<th>f</th>
<th>g</th>
</tr>
</thead>
<tbody>
<tr>
<td>MEXE method</td>
<td>0.55</td>
<td>0.74</td>
<td>0.89</td>
<td>0.70</td>
<td>2.08</td>
<td>0.57</td>
<td>0.67</td>
</tr>
<tr>
<td>Thrust line a.</td>
<td>0.64</td>
<td>0.41</td>
<td>0.75</td>
<td>1.15</td>
<td>0.96</td>
<td>0.81</td>
<td>0.82</td>
</tr>
<tr>
<td>Rigid block m.</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
</tbody>
</table>


I have demonstrated by the sensitivity analyses of seven stone masonry arch bridges (2 single span, 2 double span, 3 triple span) carried out with rigid block method that the friction coefficient has the largest effect on the load-bearing capacity. The other five tested parameters (compressive strength of blocks, unit weight of blocks, unit weight of backfill, angle of friction of backfill, angle of dispersion of surface fill) effected less the load-bearing capacity of the investigated bridges (rigid abutments, 0.11-0.87 pier height/thickness ratio, 3.6-9.2 m long span, 2.11-3.83 span/rise ratio).


I have demonstrated by the sensitivity analyses of seven stone masonry arch bridges (rigid abutments, 0.11-0.87 pier height/thickness ratio, 3.6-9.2 m long span, 2.11-3.83 span/rise ratio) carried out with rigid block method that load-bearing capacity of the investigated bridges is more sensitive to the unit weight of the backfill than to the compressive strength of the blocks. The average variation of the load-bearing capacity of the investigated bridges due to ±10% alteration of compressive strength is ±1.88%, due to ±10% alteration of unit weight of backfill is ±4.80%.

Figure 8 and 9 give examples of the results of sensitivity analyses. According to these results in case of arch bridges the friction coefficient and the soil physical properties have the largest effect on the load-bearing capacity. It confirms also that the backfill has a multiple role in forming the forces and behaviour of the structure. The results show that the emergent failure mechanism could affect significantly the rate of the influence of the parameters. Therefore it is suggested to pay attention to the accuracy of the parameters depending on the failure mechanism. In case of sliding only failure mechanism (Figure 8) the accuracy of the value of friction coefficient is especially determining. In case of the investigated bridges minor alteration of this coefficient causes significant difference in the failure load (10% alteration could cause 28% difference on the average).
5.2. Theses regarding laboratory and numerical modelling of masonry arches

4. Thesis [7, 9, 11, 14]

I have demonstrated by numerical modelling supported by laboratory experiments that a hybrid finite element method (Rocscience RS2) is capable of analysing the structural behaviour of segmental masonry arches and vaults, and it can estimate the load-bearing capacity of the analysed structures accurately (83-97 % of the results of the laboratory experiments). To achieve the mentioned accuracy it is necessary to use the accurate geometry for setting up the model instead of idealized geometry that is to say it is necessary to take into consideration the real form of the blocks and the real width of the mortar. The numerical model made with idealized geometry overestimated the load-bearing capacity of the tested arch, and the failure mechanism also differed from the laboratory results. In case of the numerical model with the accurate geometry the calculated result gave a conservative approximation (83 % of the result of the laboratory experiment) and the failure mechanism of the model was equivalent to the observed results of the laboratory experiment.
Table 2 summarizes the calculated failure loads as results of the numerical modelling and the measured failure loads as results of the laboratory experiments in case of the brick arch and the small scale sandstone vault. The results show good correspondence in both cases, the method was suitable for calculating the load-bearing capacity with adequate accuracy. The numerical model of the brick arch can be seen in Figure 10. Figure 15 shows the numerical model of the sandstone vault. In the figures mentioned above the emergent displacements at the moment of collapse are illustrated with a range of colours, and the cracked parts of the cross sections are highlighted with red colour. Beyond the values of the failure loads, the numerical models gave a good correspondence of the failure mechanism as well. The emergent failure mechanisms of the brick arch can be seen in Figure 11 and in case of the sandstone arch Figure 12 presents the results. In both cases the arches were lost their stability after the four hinges failure mechanism occurred.

<table>
<thead>
<tr>
<th></th>
<th>Numerical models</th>
<th>Laboratory experiments</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Calculated failure load</td>
<td>Calculated/Measured failure load</td>
</tr>
<tr>
<td>arch</td>
<td>0.25 kN (2 x 0.125 kN)</td>
<td>97 %</td>
</tr>
<tr>
<td>vault</td>
<td>0.16 kN (2 x 0.08 kN)</td>
<td>83 %</td>
</tr>
</tbody>
</table>

Fig. 10. Failure load of the brick arch and the emergent displacements at the moment of collapse

In case of masonry arches built from stone materials it is frequent that the masonry consists of irregular blocks with different shape and different sizes. On the other hand, in case of numerical models idealized geometry is used in most cases with regular uniform shaped and sized blocks. The effect of these differences was analysed in case of the sandstone vault which was built from irregular blocks. In such cases there are different approaches to create the numerical model considering the geometry of the blocks. The model can be built from idealized blocks with the same size and shape (Figure 13). One other option is to using the real geometry of the blocks (Figure 14).
or using the real geometry of the blocks and the mortar thickness (Figure 15) as well. Due to the small scale of the sandstone vault the influence of the real thickness of mortar has higher significance in this experiment.

**Fig. 11.** Emergent failure mechanisms of the arch: laboratory model (above), numerical model (below)

**Fig. 12.** Emergent failure mechanism of the vault: laboratory model (above), numerical model (below)
Table 3 demonstrates the differences between the calculated failure load in case of the three different model set-ups and the result of the laboratory experiment. According to the results the idealized model set-up significantly overestimates the real failure load. The model with real block geometry and mortar gave the best approximation of the measured laboratory results. Figure 13-15 show that depending on the model set-up the geometry effected the failure mechanism as well. Emergent displacements at the moment of collapse are illustrated with a range of colours, and the cracked parts of the cross sections are highlighted with red colour.

**Table 3.** Comparison of the failure loads of the different model set-ups with the result of the laboratory experiment

<table>
<thead>
<tr>
<th>Model set-up</th>
<th>Calculated failure load</th>
<th>Calculated/Measured failure load</th>
<th>Measured failure load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Idealized model</td>
<td>0.8 kN (2 x 0.4 kN)</td>
<td>414 %</td>
<td>0.193 kN (2 x 0.097 kN)</td>
</tr>
<tr>
<td>Model with real block geometry</td>
<td>0.28 kN (2 x 0.14 kN)</td>
<td>145 %</td>
<td></td>
</tr>
<tr>
<td>Model with real block geometry and mortar</td>
<td>0.16 kN (2 x 0.08 kN)</td>
<td>83 %</td>
<td></td>
</tr>
</tbody>
</table>

**Fig. 13.** Failure load and displacements at the moment of collapse in case of the idealized model

**Fig. 14.** Failure load and displacements at the moment of collapse in case of the model with real block geometry
I demonstrated by laboratory experiment of a masonry vault strengthened with carbon fiber reinforced polymer (CFRP) strips on the full length of the intrados and extrados that the effect of the strengthening can be calculated with the calibrated numerical model (using Rocscience RS2) and the altered failure mechanism can be predicted.

By means of the experiment validated numerical model of the small scale vault it was tested if the calculation works properly in further investigations. Thus the strengthening effect of the CFRP strips was analysed with the validated model and the results of the calculation were compared to the laboratory experiment. The failure load of the strengthened laboratory vault was (2 x 11.25 kN) 24.5 kN. According to the previous findings the model was made with the real block geometry and mortar width. The accuracy of the calculation was proved to be adequate again, the approximated failure load was 91% of the measured value in the laboratory (Table 4).

<table>
<thead>
<tr>
<th>Table 4. Comparison of the failure load from the numerical model and from the laboratory experiment of the CFRP strengthened vault</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Numerical model</strong></td>
</tr>
<tr>
<td>Calculated failure load</td>
</tr>
<tr>
<td>22.4 kN (2 x 11.2 kN)</td>
</tr>
</tbody>
</table>
Figure 16 shows the emergent displacements of the vault at the moment of collapse. Till the failure occurred all of the joints of the structure cracked through. Still the arch did not collapse since simultaneously the rotations and the formation of the four hinges mechanism were hindered with the CFRP strips. The altered failure occurred due to the debonding of the strips and the sliding of the blocks near to the exerted loads (Figure 17). The numerical model simulated the real behaviour of the arch suitably.

![Image of vault with applied forces and displacements](image)

**Fig. 16.** Failure load and displacements at the moment of collapse in case of the CFRP strengthened vault

![Image of laboratory and numerical models of strengthened vault](image)

**Fig. 17.** Emergent failure mechanism of the strengthened vault: laboratory model (above), numerical model (below)
Typical failure mechanism of masonry arches is the four-hinge mechanism. Since CFRP strips hinder the formation of rotation, hinges mechanism are blocked. Therefore the failure mode of strengthened arches will be completely different. In such cases crushing of the blocks, sliding, debonding of the strips, or rupture of the CFRP strips can occur (Foraboschi, 2004). The altered failure mode in this case started with the debonding of the strips which lead to sliding between blocks.

6. APPLICATIONS OF THE RESULTS, OUTLOOK AND FUTURE WORK

The presented new scientific results help the investigation of the bearing capacity of masonry arch bridges and the analysis of the structural behaviour of arches and vaults. With my results I extended the potential use of a simple and common approximate calculation (MEXE method) for multi-span bridges with stocky piers. By this I enabled an easier way to examine many other bridge in practice.

From the results of the sensitivity analysis I concluded that the accuracy of the various input parameters should be taken into account depending on the failure mechanism. The results of my research draw attention to those parameters (e.g. friction between blocks), of which inaccuracy influences significantly the load-bearing capacity. Therefore these results could be a guideline for the engineers in case of practical investigations. An interesting result is that the load-bearing capacity is more sensitive to the uncertainty of the unit weight of the backfill than to the compressive strength of the blocks. This statement highlights the importance of the investigation of the backfill for these calculations. Since the friction coefficient between the blocks cannot be measured, but it is an important parameter in terms of the calculation, the setting up of these values opens the door to further researches with the laboratory examination of different stone materials and different mortars.

I proved with my results of the laboratory and numerical modelling of masonry arches that a hybrid finite element method (Rocscience RS2) is able to calculate the failure load of the arches with adequate accuracy and it is suitable to predict the fracture mechanisms in case of unreinforced and reinforced arches by CFRP strips as well. The most important lesson of the numerical models was that there may be significant differences between idealized modelling and modelling with actual geometry. The modelling with idealized geometry overestimated the load-bearing capacity of the arch significantly and it never gave back the failure mechanism. Therefore as far as possible the geometric imperfections should be taken into account in case of the modelling of arches built by blocks with irregular shape and different size. The results should be definitely validated for real-size arches in the future. The numerical models demonstrated by the presented experiments are
suitable for further studies, because these validated models are useable to analyse additional effects (filling, horizontal forces, etc.).

All things considered it can be said that the investigation of stone masonry arches is a complex, multidisciplinary research topic that provides more and more questions to be answered and problems to be solved for engineers. With the development of the material sciences, measurement technologies and numerical methods the interest of this theme shall intensify in the future. At present, the accuracy of the available mechanical models is far superior to the measurement accuracy of the individual material properties. Therefore in theory we can perform high precision calculations, but in practice we can only calculate the carrying capacity of existing structures with high estimation. Thus, in the future more effort should be put into the development of diagnostic methods and into the closer cooperation of these connecting scientific areas.

7. REFERENCES


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8. **MAIN PUBLICATIONS ON THE SUBJECT OF THE DISSERTATION**


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