# Diagnostic of stone masonry arch bridges

Gyula Bögöly

BME Department of Construction Materials and Engineering Geology, *e-mail: bogoly@gmail.com*

**Abstract**

In Hungary there are no methods commonly used for controlling and investigating stone masonry arch bridges in bad and deteriorative condition. The old and simpler method does not give adequate results in many cases, and the new modern methods are usually very complicated or their practical adaptation is difficult. The aim of my project is to find a way to assess simply and accurately enough the condition of such stone structures which is applicable in practice. In order to see clearly the effects of each condition parameters on the stability preliminary investigations and modelling are necessary. My presentation demonstrates the basic diagnostic procedure of stone bridges through which the different stability analysis will be compared. In conclusion there will be a few words about the future of this project, and the required roles further on.

## Introduction

Stone masonry arches are one of the most ancient forms of the engineering structures. Their modelling and analysis bring up many questions even today. Although in these days new stone masonry arch bridges are not built, the maintenance and restoration of the old ones represent a special challenge at the present time as well. There are more than 1500 stone masonry arch bridges in Hungary [6]. These bridges were built mostly in the 18th and 19th century. Unfortunately these kinds of structures get low attention in Hungary and the condition of most of them increasingly deteriorates. Since the construction of these bridges the traffic and related load has increased significantly, thus these old bridges have to fulfil the new expectations (Table 1). Their stability control and the verification of their load-bearing capacity became necessary in many cases.

| 150-200 years ago | Today | Ratio |
|---|---|---|
| six horse drawn artillery (~50 kN) | the heaviest possible load according to the Hungarian standard (800 kN) | 16 |
| passing farm-wagons (~2.53 m) | passing buses (~3.75 m) | 1.5 |

*Table 1.* Change of vehicular load [by 5]

## Advancement of modelling

However the structural behaviour of masonry vaults seems to be simple at the first sight, in fact their mechanical behaviour and modelling is very complex. These inhomogeneous structures behave non-linearly under loading and their failure occurs in plastic state. These kinds of structures can be resisted only minimal tensions and this speciality influences especially the behaviour of the masonry structures. Stresses are usually low, thus the failure of the material is rare in masonry arches. Masonry vaults must satisfy three main structural criteria: strength, stiffness and stability. The structure must be strong enough to carry whatever loads are imposed, including its own weight. It must not deflect unduly, and it must not develop large unstable displacements, whether locally or overall [9].

In the history there were lot of different methods to control and design arches. In the antiquity and in the beginning of the Middle Ages rules of thumb and simple geometrical rules were used. Afterwards methods advanced a lot. For instance Coulomb made a great progress in the practical use of statics with the development of his graphic method and Gaudi, the famous Catalan architect, elaborated an empiric method to design arches and domes [10]. Nowadays these methods are not sufficient because of the increased requirements therefore more specific methods were developed such as thrust line analysis, rigid-block method, finite element and discrete element method. These methods are capable of taking into account many different influential effects, thus the failure load can be calculated with great accuracy in theory. On the other hand in practice these modern methods are not applicable so easily. In these models certain effects and attributes are taken into consideration by factual mechanical model parameters. These parameters often can be measured only with difficulty on existing structures, or it is difficult to characterize them with one factual value. The other primal trouble is the consideration of the failures. The aim of my project is to find a solution to these problems so that the condition of such stone structures can be assessed simply and accurately enough in practice. In order to see clearly the effects of each condition parameters on the stability previous investigations and modelling are necessary. In this article I will show the basic diagnostic procedure of stone bridges and give a conclusion from the executed preliminary analyses.

## Determination of model parameters

So far in the preliminary investigations I analysed four bridges (Table 2) with three different methods. Three bridges from these were made of sandstone, which is widely used in Hungary. And the other bridge was built from different types of igneous lithologies, which are typical in the bridge’s region.

| | Bükkös | Derék | Lókos | Rédey-Nagy |
|---|---|---|---|---|
| Span [m] | 6.0 | 3 * 3.6 | 2.6-2.8-2.6 | 2* 7.5 |
| Rise [m] | 1.6 | 1.4 | 0.85-0.9-0.85 | 1.96 |
| Compressive strength [MPa] | 21 | 16 | 18 | 14 |
| Weight of dimension stones [kN/m$^3$] | 22 | 22 | 22 | 16 |

*Table 2*. Parameters of the analysed bridges

The parameters, which were necessary for the models, were derived from site investigations and from laboratory tests. The site investigations included the inspections and recording of geometrical parameters, photo documentation. Lithotypes of the dimension stones were also determined and the differences between the strength of the blocks were measured in situ by using Schmidt hammer (Fig 1). It is particularly suitable technique by the diagnostic of national monument structures when sampling is not an option. Many foreign literature and research are concerned with this in situ technique because the correlation between the rebound value and the uniaxial compressive strength (UCS) is changing with the rock types [15]. The rebound value is depending on more properties, for instance: wheathering grade, dry density, porosity, grain size, moisture content and naturally the parameters of the Schmidt hammer. The moisture has a great influence to the UCS and to the rebound value which is depending on the rock types [14]. Therefore moisture content was also recorded on site. Some petrophysical properties such as compressive strengths, unit weights were identified under laboratory conditions and the friction coefficient were derived from suggestions of case studies.

*Fig. 1.* Schmidt hammer test (left), Moisture content measuring (right)

*Fig. 2.* Damages: cracked spandrel wall (left), Mortal loss on (right)

In the models of the bridges the observed damages were taken into consideration, such as mortar loss, missing blocks, cracked spandrel wall (Fig 2).

## Methods

The Hungarian standard of masonry arch bridges defines three different levels of the investigations. It begins with approximate calculations like MEXE method. On the 2$^{nd}$ level it suggests a simple 2D modelling (thrust line analysis, rigid block method), and the top level of structural analysis advises more difficult 2D and 3D modelling (rigid block method, FEM, DEM) [10]. The expected accuracy of the analysis determines which method is suggested to be used. During the preliminary investigations thrust line analysis were used with Archie-M (demo), and rigid block method with using the program developed by the University of Sheffield, named Ring. The traditional MEXE method is still widely used for assessing the carrying capacity of masonry arch bridges. For this reason approximate calculations were carried out by the MEXE method to compare the results.

MEXE METHOD

The calculation is built on empiric coherences, and it takes in account the different effects by using modifying factors. It is a strongly approximate method, but it calculates fast and simply. It was developed in England during the World War II. The aim of this method was to calculate if a cruiser-tank can cross over a bridge or not. The provisional axle load (PAL) is obtained by using the values of the thickness of the arch barrel adjacent to the keystone, the span, the average depth of fill at the quarter points of the transverse road profile, between the road surface and the arch barrel at the crown, including road surfacing. The provisional axle load is obtained then modified by the modifying factors (span/rise factor, profile factor, material factor, joint factor) and the condition factor [10].

The MEXE method cannot be used if the bridge is a multi-span bridge, the span is longer than 18 m, the skew of the bridge is bigger than 15 degree, the backfill above the extrados is bigger than 1 m, and the structure has remarkable damages. From the 4 analysed cases only 1 is acceptable at all points. The other 3 bridges are multi-span bridges. Despite the calculations were accomplished in these cases as well because in theory if the piers of multi-span bridges are short (not slender), then the arches work separately. A pier is short if the height/width ratio is smaller than 2. This condition is true in these cases. The method has more deficiencies. It underestimates significantly the carrying capacity of long span bridges, and it overestimates the carrying capacity of short span bridges.

THRUST LINE ANALYSIS

The basis of equilibrium analysis is set out by Heyman. It is based on the plastic theorems which were first developed in Hungary, but which were brought to Britain by Baker [16]. The thrust line analysis was carried out on the bridges by the Archie-M software. The program can take into account multi-span bridges, masonry strength, masonry unit weight, mortal loss, and the angle of friction of the fill unit. The program gives the line of the thrust according to a given load with a given position. Thus the load bearing capacity can be easily determined (Fig 3). The load carrying capacity of the bridge is adequate in case the line of the thrust does not leave the cross-section under the loads. With using this method the control can be carried out easily. In the case of the crossing over of the heaviest possible load according to the Hungarian standard (from now on load type “A”) the load bearing capacity of the bridges was adequate (Fig 4). While a load is crossing over the bridge, there is a chance to see which part of the structure is under strain.

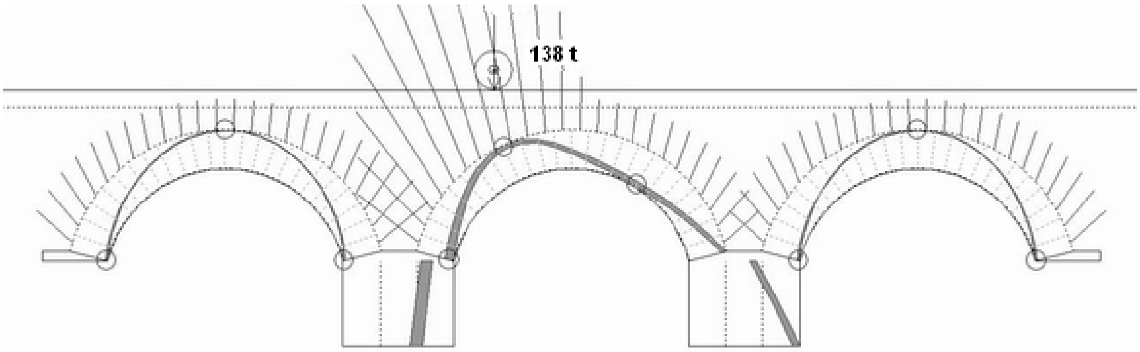


*Fig. 3.* Emerged thrust line if the failure load is at the worst position (Bridge over the Derék br.)

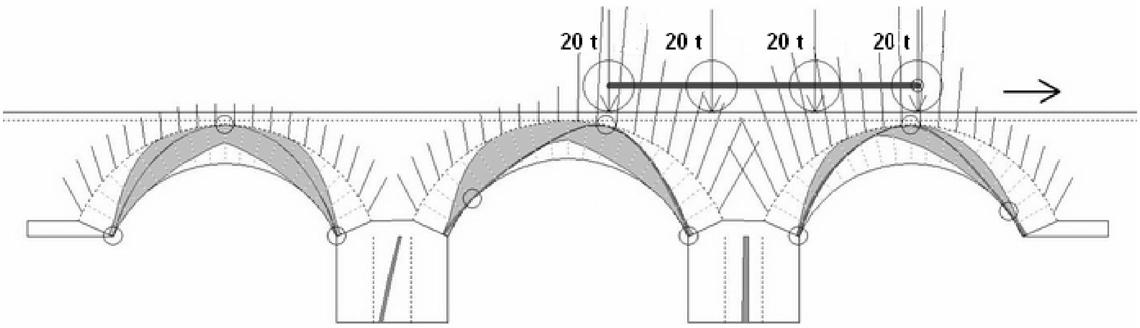


*Fig. 4.* Load type “A” is crossing over the Lókos Bridge

## RIGID BLOCK METHOD

The main principle of the method was set out by Heyman (1982) as well as Gilbert and Melbourne (1994). The method uses the upper-bound theory of plasticity in conjunction with geometrical compatibility criteria to obtain solutions to problems involving single- and multi-span arch [7].

Ring 3.0 can identify the critical failure load factor and associated failure mechanism and distribution of internal forces. This allows the safety of the bridge to be assessed. The software can take into account multi-span bridges, compressive strength of the blocks, masonry unit weight, mortal loss, the angle of friction and cohesion of the fill unit, the favourable effect of passive pressure, angle of dispersion and a few damages. The bond between the blocks is taken into account by the help of friction coefficients. The span/rise rate of masonry arch bridges influences significantly the emergent failure mechanism. The results of the models verified this as well. In case of lower rise arches (span/rise > 4.0) generally a 3 hinges mechanism emerges with sliding. In case of higher rise arches a 4 hinges mechanism is expected. And there is a third failure mechanism when there is a shear failure with sliding. On Figure 5, 6, 7 the analysis of the bridge over the Rédey-Nagy brook can be seen.

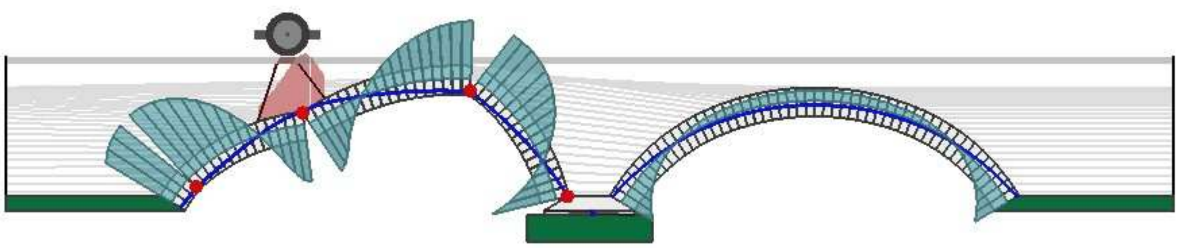

*Fig. 5.* Failure mechanism 2D and moment diagram

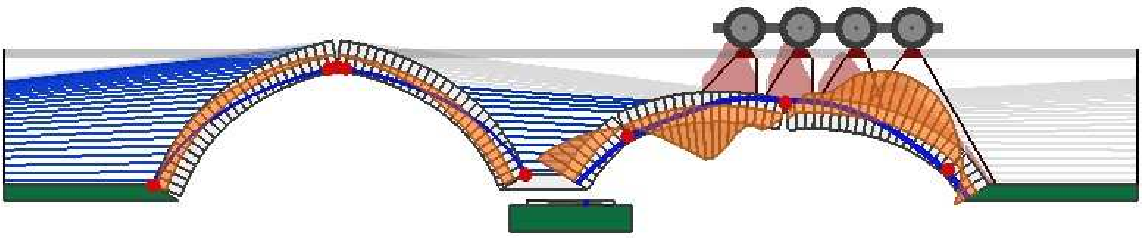

*Fig. 6.* Failure mechanism of repaired bridge by the load type “A” and shear force diagram

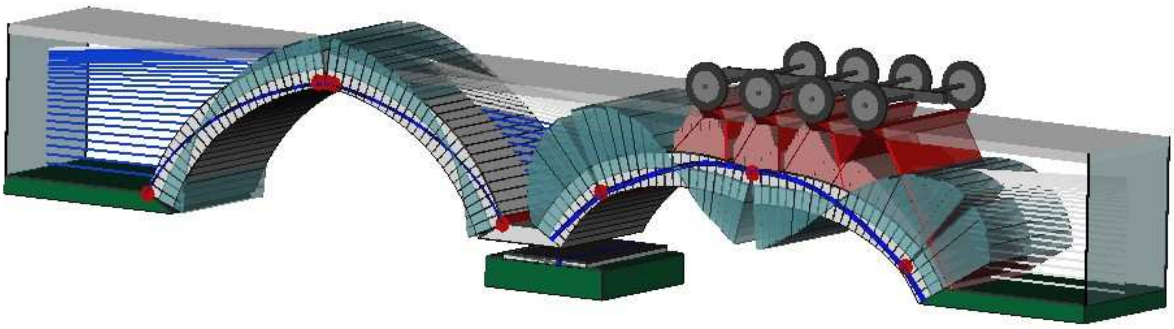

*Fig. 7.* Failure mechanism of repaired bridge 3D, and the moment diagram

## Results and conclusions

To calculate the permissible axle load the value of the failure load has to be divided by a safety factor with a value between 2 and 3 according to the Hungarian standard [10]. The results of the different types of analyses were determined accordingly (Table 3).

| Permissible axle load [t] | Bükkös | Derék | Lókos | Rédey-Nagy |
|---|---|---|---|---|
| MEXE method | 52.4 | 37.1 | 35.6 | 23.7 |
| Thrust line analysis | 62.9 | 55.3 | 20.8 | 23.0 |
| Rigid block method | 109.6 | 70.5 | 26.6 | 23.2 |

*Table 3* Results of the different analyses

In the table the results of the thrust line analysis and of the rigid block method are average values. These values due to the problematical attributes of the structures such as friction coefficients, dispersion of live load, passive pressures, inner components, damages, could change 5-20 % in either direction. If there is a new bridge and every parameter is known these models work perfectly. But in practise in case of an existing bridge it is almost impossible to measure some required parameters, for instance the friction coefficients between the blocks of the arch barrel. It is also difficult to characterize some properties such as the compressive strength or the masonry strength with one factual value, especially if the bridge consists of different types of stones with different level of weathering. Neither the loads nor the effects of the damages are simple. The diagnostic has difficulties also, because it is hard to see what is inside an old bridge. Although a backing, the surface fill depth, the properties of the backfill could change the outcome significantly.

It is noticeable that the MEXE method assesses the results quite well in case of the multi-span bridges with short pier as well. In fact it overestimates the carrying capacity of short span bridges. The difference between the levels of the investigations is conspicuous.

Although the masonry structures are ancient, we can see they bring up many questions at the present time as well. My purpose is to bring closer these methods to the practise and develop the diagnostics to get closer to an effective modelling.

These above used modern numerical design methods can be used primarily to determine the failure load with 2D modelling. With using these methods the stability control can be made quite fast and accurately enough to a simple control. To get more precise and detailed results or to get data about the structural behaviour under loading FEM and DEM methods can be used. In these methods almost every effect and circumstances can be taken into consideration but the applicability of these methods are quite difficult and the modelling takes a lot of time. Assessment of serviceability is becoming more and more important with increasing traffic volumes on masonry arch bridges. At present time there is, however, neither a suitable method for the serviceability assessment of masonry arches nor any criteria according to which such an assessment could be carried out [11]. These assessments of serviceability bring the more difficult 3D analyses into prominence. Therefore I plan to carry out 3D FEM and DEM modelling in the near future. At these preliminary analyses I wanted to compare the different methods to know what are they capable of and see clearly the differences between them. My intention is to compare the results of the numerical analyses with some factual behaviour of the structures. And I also plan to conduct experiments on a small scale laboratorial models which I hope eventually will help to reach my aim.

## Acknowledgement

This work is connected to the scientific program of the Development of quality-oriented and harmonized R+D+I strategy and functional model at BME. This project is supported by the New Széchenyi Plan (Project ID: TÁMOP-4.2.1/B-09/1/KMR-2010-0002).

### References

[1] Andai, P.: A mérnöki alkotás története, (1959), pp 364.

[2] Aydin, A., Basu, A.: The Schmidt hammer in rock material characterization, Engineering Geology 81 (2005), pp 1-14.

[3] Berkó, D.: Boltozatos kőhidak, Mélyépítés, 5 (2003) , pp 16-20.

[4] Bögöly, Gy., Görög, P., Török, Á., Building Materials and Building Technology to Preserve the Built Heritage, WTA-publications (2011), pp 95-107

[5] Gáll, I.: Régi magyar hidak, (1970), pp 3-46.

[6] Gálos, M., Vásárhelyi, B.: Közúti boltozott kőhidaink, Kő, VII. (2005), pp 21-25.

[7] Gilbert, M., Melbourne, C.: Rigid-block analysis of masonry structures, The Structural Engineer, 72 (1994), pp 356-361.

[8] Gubányi-Kléber, J., Vásárhelyi, B.: A héhalmi boltozott kőhíd vizsgálata, Mélyépítés, 1 (2004), pp 16-20

[9] Heyman, J.: The stone skeleton, Cambridge University Press (1995), pp 3-15

[10] Magyar Útügyi Társaság: Útügyi Műszaki Előírás 813/2005., (2006), pp 61-108

[11] Orbán, Z., Gutermann, M.: Assessment of masonry arch railway bridges using non-destructive in-situ testing methods, Engineering Structures, 31 (2009), pp 2287-2298

[12] Pegon, P., Pinto, V., Géradin, M.: Numerical modelling of stone-block monumental

structures, Computers and Structures, 79 (2001), pp 2165-2181.

[13] Santiago, H.: Galileo was Wrong: The Geometrical Design

of Masonry Arches, Nexus Network Journal, 8 (2006), pp 33-39

[14] Török, Á.: Geológia mérnököknek, (2007), pp 294-295

[15] Zhang, L.: Engineering properties of rocks, Elsevier Geo-Engineering Book Series, Volume 4 (2005), pp 180

[16] http://www.obvis.com/archie-theory/