Paper 120

©Civil-Comp Press, 2012
Proceedings of the Eleventh International Conference
on Computational Structures Technology,
B.H.V. Topping, (Editor),
Civil-Comp Press, Stirlingshire, Scotland

Network Analysis of Masonry: Indicator Computations for Detecting Soil Defect Impact

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Abstract

Masonry structures definitely suffer their intrinsically poor tensile strength capacities. As a consequence, thinking about an efficient manner to prevent or reducing the impact of soil defects on un-reinforced masonry buildings remains an important challenge for most engineers: it is obvious that some smart modifications introduced during the concept or design steps would be likely to strongly improve the future behaviour of the structural system. After a short introduction to related challenges, the paper discusses the importance of developing a calculation tool likely to detect and objectively quantify the impact of a given soil defect on a given building. Then, the recourse to a control-profile method is proposed: it allows an objective value to be associated with a configuration composed of a given building morphology submitted to a set of loads and perturbed by a given soil defect. The first step consists of a quick calculation of the building using a simplified FE approach (with and without the soil defect). The second step relies on an arbitrary distributed network allowing scanning the general stress states obtained by the end of the first step: inside each control-profile of the network, an equivalent force pattern computed that would later be used for calculating a conventional fictive reinforcement pattern associated to the influence zone concerned. The succession of fictitious reinforcement patterns gives birth to both the succession of codes (DNA-codes) corresponding to the configuration with and without the soil defects. In the third step, the comparison of these code successions allows the estimate if an impact on the building of the soil defect and, once the case occurs, quantifying this impact through a global indicator computed on the basis of each zonal contribution to the fictitious reinforcement. Finally, the paper illustrates the process for the case of the former Choiseul Seminary, an ancient un-reinforced masonry building located in a karstic region of southern Belgium.

Keywords: masonry, finite element method, computer-aided detection, soil defect impact, control-profile, distributed network, soil-structure interaction.

1 Introduction

Masonry constitutes a smart building system: it allows erecting complicated and robust structures based on limited size blocks assembled using a mortar. These fundamental points lead the unreinforced masonry (URM) technique to be widely used on most of the continents everywhere around the world. Nevertheless, URM structures definitely suffer an intrinsic weakness concerning their tensile strength capacities. Therefore, the structural engineers have to carefully consider the potential interactions between their building project and its environment.

As some soil defects may not be precisely documented at the design step, the recourse to geotechnical investigations will directly avoid only part of pathologies to the buildings. For by-passing this partial knowledge, engineers active in the design of new constructions will have to prescribe a morphology that would be as less sensible as possible to soil defects once engineers engaged in the retrofitting of existing constructions will have to understand the origin of observed disorders. In this framework, disposing of a practical tool that would allow **detecting** and, once the case occurs**, quantifying the impact** of a given soil defect on a given masonry system would reveal definitely useful.

The present paper is articulated around four principal parts. The first part presents **the challenges** associated with the satisfaction of masonry building owners and insurance companies: any soil defect (from natural or anthropic origin) is likely to alter the boundary conditions of a structure, providing vertical settlements or horizontal movements that are likely to induce parasite forces or moments inside the masonry system. As URM are highly sensitive to this kind of phenomena, the associated disorders may be significant. The second part discusses **the interest of an efficient tool** likely to detect and objectively quantify the impact of a given soil defect on the structure of a given masonry building. The third part details a method transposed from the works carried out by Maunder [1] and Maunder & Harvey [2] in the study of arch systems: **the method** relies on a finished number of control-profiles (distributed network) in order to express a codification of the stress state inside the general continuum. By comparing the codes associated to an altered and a not altered system, it is possible to outline (and quantify) the eventual impact of a feared soil defect on a given structure. A **practical implementation** coupling MATLAB with SIMULIA **and** a **numerical application** treating a simplified case are presented in the last part for illustrating the proposed method.

2 Masonry Systems on Sensitive Soils: Challenges

A construction project definitely remains an interaction couple gathering a structure and a welcoming soil. This last member of the couple is often associated to non- or less-predictable phenomena. On one hand, soils are made by and live in the nature. This matter of fact implies a great variation in the space and in the time for their properties. Considering such a double variability, it is simple to understand why geotechnical investigations are required and in what manner their predictions are far to be exhaustive. On the other hand, external causes are likely to modify the state of an initially sane soil. Such causes may be of anthropic (overload, excavation, tunneling, seepage) or natural (compressible layers, karsts) origin. Whatever the case, soil defects will generally induce ground deformations that modify the bearing capacity in some places at the boundaries of the URM system. Facing a global or local lack of bearing capacity, parasite solicitations may be generated inside the structure and potentially affect it. As an assembly of limited size units, the intrinsic nature of URM is associated with limitations concerning the response to both the normal and the tangential effects. For the first aspect, although an important strength may be assumed towards compressive actions, it is far to be the case with tensile ones: masonry is hardly likely to exhibit a reasonable level of tensile strength. For the second aspect, it is important to remember that a rather poor behavior is observed when masonry is submitted to shearing solicitations. If parasite actions mobilize some of the intrinsic weaknesses of the masonry structure, disorders are likely to appear in the system. It has been shown that, depending on the relative capacities of blocks and mortars, the consequences could reveal of several levels: from deformations if the masonry exhibits adaptation capacities up to mixed crack propagation processes affecting the mortar or the mortar and the blocks. The global problematic is illustrated on Figure 1.

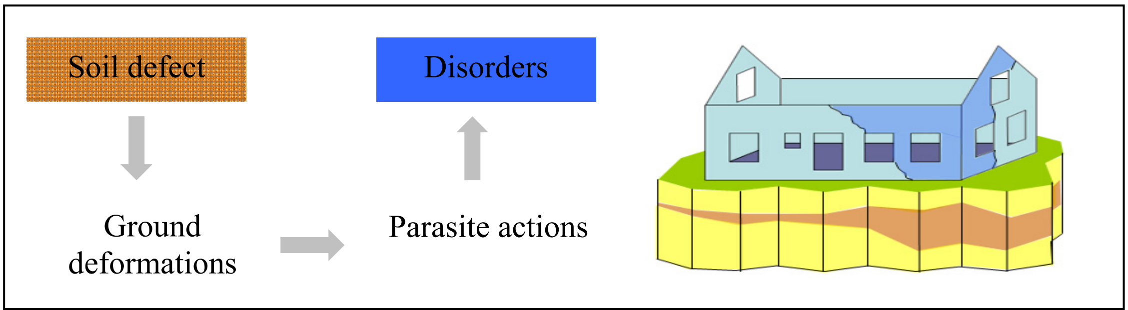

Figure 1: disorders affecting URM structures as consequence of a natural soil defect

Aware of the interaction risks, still potentially reinforced by contemporary land planning programs that impose to contemporary builders to match their project with the sites that are not devoted to non-erection usages (nature preservation, agriculture) whatever the effective quality of the ground and the surroundings activities, insurance companies bring a more and more special attention to the requests the owner will address to structural experts involved in the conception of the project. In such a risk management framework, structural engineers have to work one step further than designing a given reinforcement as a response to a given soil defect: a "probably reasonable" soil defect should be expected although it may not become precisely localized (e.g. in karstic zones) and the proposed solution should potentially fit for all cases.

In practice, masonry structures usually present an important level of static redundancy. As soil defects manifest themselves as modifications of bearing conditions at the boundaries of the system, load redistributions are likely to occur inside the URM system that will adapt itself to the modifications brought to its supports. A convenient approach that would capture such a fundamental phenomenon should then consider both the under- and upper- ground aspects of the problem simultaneously inside a same model and numerical simulation appears as a key approach. Nevertheless, the upper- and under-ground aspects concern modeling field that remain clearly separated, explored by researcher presenting different backgrounds. On one hand, specific modeling philosophies for precisely replicating the behavior of URM through macro-, micro-, or meso-modeling are available although they are computationally expensive. On the other hand, a sharp soil simulation with advanced models remains a challenge namely due to the double variability in space and in time. Facing the hardly achieved compatibility between both theses advanced modeling strategies, the structural engineer confronted to soil-structure interaction problems will usually opt for simplified FE analysis where only useful aspects of URM and soils are replicated.

3 A Tool for Impact Detection and Quantification

The establishment of an efficient FE model gathering the URM system and the soil system may rely on various strategies, namely the simplified approach proposed by Van Parys et al. (2006). Once the model has been developed, its exploitation for studying the potential influence of a soil defect on the URM system could usually take place. A typical scheme of study is presented on Figure 2. The not altered architectural configuration (d) is obtained by gathering the external solicitations on the URM structure (a), the URM structure proposed by the architect for complying with functional aspects (b) and the shape and nature of the soil collected through geotechnical investigations (c). After the FE analysis (e), the general stress state inside the URM system (f) is obtained under the shape of stress fields covering the entirety of the studied model. The altered architectural configuration (h) is obtained by gathering the not altered configuration (c) with the soil defect (g). A similar FE analysis (e) will provide the corresponding general stress state inside the URM system (i).

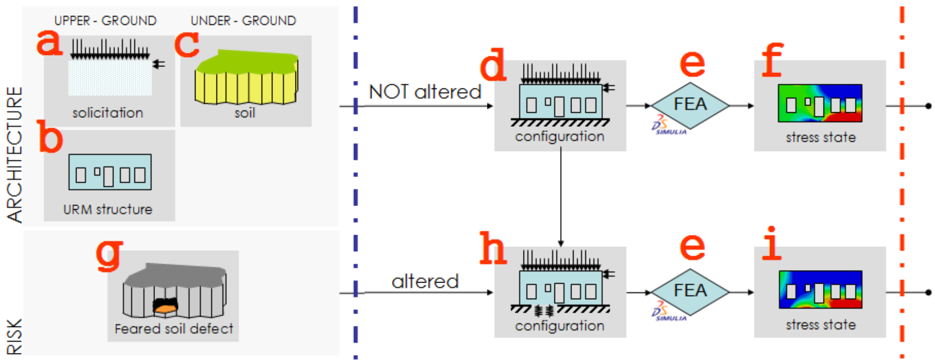

Figure 2: problem data and base for manual impact detection

An eventual influence of the soil defect on the URM system may now be outlined by comparing both the general stress states (f and i). Based on his experience, the structural engineer has to detect if the feared soil defect induces a significant impact on the masonry system. In the case where the defect reveals to have an impact, an appropriate modification of the URM system may be proposed and designed by the engineer before verifying it constitutes a convenient response towards the observed problem. In practice, carrying out an iterative study process in such a manual framework appears rather time expensive, the key problem concerning mainly the interpretation stage.

Developing a method that would manage an automatic and objective comparison of stress states in order to detect and, once the case occurs, quantify the impact of any feared soil defect on a given masonry structure would open the way to the efficient solving of two main families of problems associated with risk management.

The first family concerns a **direct approach, taking place in a "design" framework**. The problematic soil is precisely mastered: on the basis of a conventional (CPT, DP, PMT) or non conventional approach (geophysical tests) the geotechnical specialists have been likely to propose a cute cartography of the local underground including sharp information about a potential soil defect. Then, the impact detection tool will make possible to realize a comparison between several constructive solutions that may be proposed by structural designers (depending on the problem and the morphology of the building, one or the other will reveal more advantageous). Such a tool could also help to outline morphological modifications that would still enforce the advantage of one solution relatively to the other one, opening the way to morphological optimization. The second family concerns a **reverse approach, taking place in a "retrofitting" framework**. The soil data is totally unknown and only the disorders and crack patterns that may be observed on given buildings are available. In this framework, a specific use of the detection tool in a computer aided decision framework could orientate geotechnical surveys in order to understand the cause of pathologies noticed in the building and, later, to prescribe a structural intervention likely to make the building safe again.

4 Evolutive C-Profile Method for Network Analysis

By comparing the general stress states obtained inside a masonry structure before and after it has been submitted to a soil defect, it becomes possible to estimate the impact of the soil-defect on the studied structure. The control-profile method aims at representing the information associated with a given stress state under the shape of a conventional and standardized code. The standardized aspect intervenes in relationship with the fact that the proposed code is dependent of an arbitrary spatial discretization (a limited number of control-profiles) proposed by the user when he begins to study a model. Once each stress state will have been associated with a suite of codes, the impact detection will be simple to achieve through a basic member to member comparison or through any advanced image processing method.

Once detected, the impact becomes easily quantifiable by computing the “distances” between not altered and altered configurations taking the codes as references.

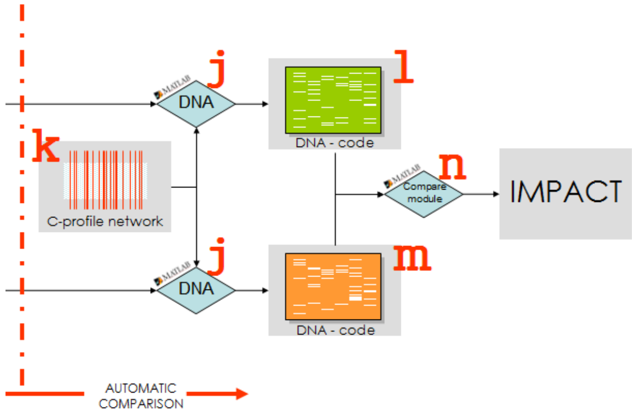

Figure 3: automatic impact detection (and quantification)

The automatic impact detection proposed by the authors is based on a Distributed Network Analysis module (j) that will analyze any given stress state (f or i) through an arbitrary control-profile network (k) in order to provide a corresponding code (respectively l or m). Each code transcripts the general stress state into a standardized manner through a matrix of digits. This representation is conventional: it is definitely depending on the chosen control-profile network but may be used as a comparison reference as this network remains unchanged from one item to the other. A compare module (n) manages the comparison action and outlines a binary response (YES = impact, NO = no impact) according to a given tolerance as well as a value estimating the importance of the impact once the case occurs.

5 Basic Implementation of the C-Profile Method

This paragraph details in what manner most of the concepts that have been presented previously may become simply and practically implemented. The FE models are developed using 3D simulation inside SIMULIA software. The simultaneous replication of behavior for masonry materials (upper-ground parts) and soil materials (under-ground parts) is important as the static redundancy is likely to provide load redistribution inside the system along the process. For replicating **the behavior of masonries**, a macro-modeling approach is proposed: the material is modeled considering a fictive medium that is assumed to be equivalent to the effective assembly of mortar and masonry units. For the purpose of our study, the equivalent constitutive material exhibits an elastic and isotropic behavior that constitutes a strong assumption. Nevertheless, such an approach has widely shown its suitability for studying similar cases: it is recognized to provide convenient stress repartitions inside the model in conjunction with underestimated global deformations. In opposition to usual practices illustrated by Van Parys et al. [3] with such an approach, no limitation of stresses is imposed inside the model. On one hand, the effective compressive capacities exhibited by the studied masonries are assumed to be sufficient for avoiding compression-associated failure modes to become critical. On the other hand, the limited value associated with the masonries tensile strength are taken into account later, through the Distributed Network Analysis module: by outlining a quantity of steel reinforcement required for avoiding cracking and then ensuring the model to remain continuous, this allows the approach to remain fully coherent. For replicating **the behavior of soils**, the definition of equivalent springs is proposed. A spring is linked to each boundary node of the masonry foundation that is supposed to interact with the soil. The section, the length and the rigidity of each spring may be computed on the basis of information collected by geotechnical specialists. Such an approach is possible for replicating as well good as bad quality soils. Specific studies aiming at computing such parameters in a rigorous manner have been initiated by Cuvelier [5], providing encouraging results for karstic defects.

Following this approach allows providing general stress state configurations that could be used either for manual impact detection and quantification. The basic implementation of an automatic tool has been proposed inside the MATLAB environment under the shape of stand-alone routines articulated around specific viewing facilities, likely to interact with SIMULIA what is practically important as the user may define his control-profiles in his FE software.

The **Distributed Network Analysis-module** manages the first part of the automatic mission. It aims to compute a code for transcripting the general stress state inside the masonry system. It is articulated as a loop scanning each control-profile defined in SIMULIA. Each profile is discretized into *n* slices and, for each slice, the module extracts the principal stress data out of the SIMULIA output files. Then, various valuable analysis patterns could be proposed. A basic implementation could focus on the arbitrary computation of a fictive steel reinforcement likely to balance the value of normal tensile stress acting orthogonally to the profile. This give birth to a theoretical value of local steel reinforcement *LS* associated to each slice *i* and computed by an integration along the slice of the stress signal σ previously filtered. This is summarized in Equation 1 where the local wall thickness is denoted *t* and the filtering function is denoted $\xi(\sigma)$.

$$LS\,(i) = t\,(i)\,.\int_{z_{min}(i)}^{z_{max}(i)} \xi\,(\sigma)\,.\,\sigma\,(z)\,.\,dz \qquad \text{with} \quad i = 1 \ldots n$$

$$\text{where} \quad \xi\,(\sigma) = 0 \quad \text{if} \quad \sigma\,(z) \leq 0 \quad \text{and} \quad \xi\,(\sigma) = [\,f_{steel.tension}]^{-1} \quad \text{if} \quad \sigma\,(z) > 0 \qquad (1)$$

The **compare module** manages the second part of the automatic mission. Once DNA-codes have been computed for each-profile in both the not altered and the altered configurations, they may be used as an input for the comparison module. Once again, the comparison may be performed according to various patterns. It is namely possible to rely on advanced considerations in image processing for efficiently comparing rich codes. Nevertheless, a basic implementation could simply establish a map of local differences between not altered and altered configurations, uniquely registering values higher than a user-defined tolerance. Zones of burned tolerance appearing on a map reveal an impact. Then, a smart integration of the outlined local differences allows computing a global steel reinforcement GS value, quantifying the impact of the soil defect through a single number.

6 Numerical Application

As a proposed association of SIMULIA with simple modules developed inside MATLAB has been described and has allowed the problem of automatic detection (and quantification) of a soil defect impact to become contoured, under the assumption of given control-profile network and given tolerance, this paragraph illustrates the direct application of this simplified implementation on a real case study. It concerns an old masonry building located in Tournai (southern Belgium), in an area that is characterized by karstic activity. The concerned building is the first diocesan seminary built in Belgium during the reign of Louis XIV and called Choiseul seminary.

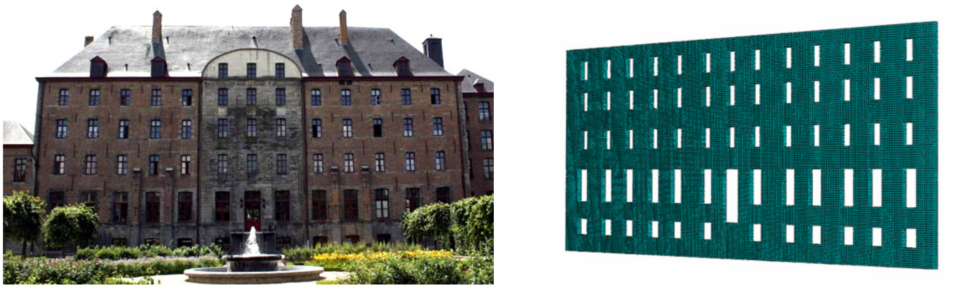

Figure 4: Choiseul seminary - north elevation wall: picture (left) and model (right)

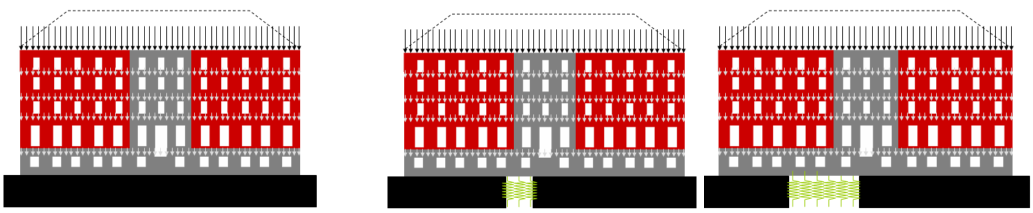

Figure 5: presentation of the not altered (left) and altered (right) configurations

The proposed study concerns the north elevation of the seminary. It is a brick and block masonry wall with five rows of windows. The superstructure is a plain masonry wall composed of clay bricks and limestone blocks assembled with a lime mortar. The external solicitation configuration is provided by the roof at the top of the wall and the floor at each level of the building. In the not altered configuration, the soil configuration concerns a good quality sandy soil providing a convenient load bearing capacity. The feared soil defect intervenes in relationship with the karstic activity: it concerns the occurrence of a localized soil collapse under the studied wall and providing a local loss of load bearing capacity. The extent of the zone concerned by the karstic phenomenon may be approximated by specialists. Two cases are treated here. The aim of the study consists in detecting if the occurrence of such a defect will bring any impact inside the masonry system.

For achieving this aim, both the not altered and the altered configurations have been modeled using SIMULIA. Based on a simplified topographical survey, the **morphology** of the model may be established inside the software. The proposed model of the north elevation is presented in Figure 4 (right). The physical (mass density) and mechanical (Young modulus and Poisson ratio) **properties** required for qualifying the equivalent masonry materials have been computed separately for brick and block masonries on the basis of experimental data obtained on similar materials from the same area. The interactions between the model and the external world may be taken into account through the **boundary conditions**. The effect of the ceiling tie bars and principal shear walls is replicated by imposing, at the corresponding places of the mesh, a zero value for the displacement orthogonal to the plan of the studied elevation wall. Due to its effective properties, the soil in the not altered configuration is considered as sufficiently stiff for replicating its effect by imposing zero values for the vertical displacement at the bottom of foundation walls. In the altered configuration, the feared soil defect is taken into account by using springs whose rigidities have been set to zero for replicating the effect of an already formed cavity (soil collapse occurred). Due to its major structural role, the studied elevation wall has to support the vertical reactions **forces** provided by the roof and each of the four floors. The associated values may be computed and applied as line loads on the model. The model discretization uses a structured three-dimensional **mesh** with eight-node elements. Such a modeling approach has been followed for studying the not altered and both the altered configurations (limited and significant size soil defect) illustrated on Figure 5. It allows a sharp stress calculation. The stress field repartitions inside both the not altered and the altered model are illustrated on Figure 6 for the case of limited size soil defect. They constitute a basis that should be used by engineers for manually detecting an eventual impact of the soil defect on the masonry structure.

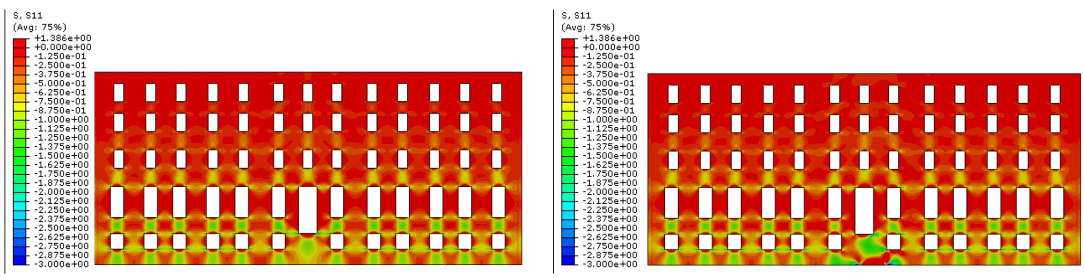

Figure 6: stress state in the not altered (left) and the altered (right) configurations

They also represent the start data for the Distributed Network Analysis module that aims to automatically detect and quantify the impact. In the framework of the proposed case study, a dense control-profile network has been used. It was not very computationally expensive due to the limited size of the model and the simplified level of calculations implemented in the DNA-module (see Figure 7 - left). For the analysis of bigger models, it could be interesting to rely on a looser network densified in zones of potential interest and released elsewhere as presented on Figure 7 (right). This operation is easily performed by a pertinent user choice inside SIMULIA.

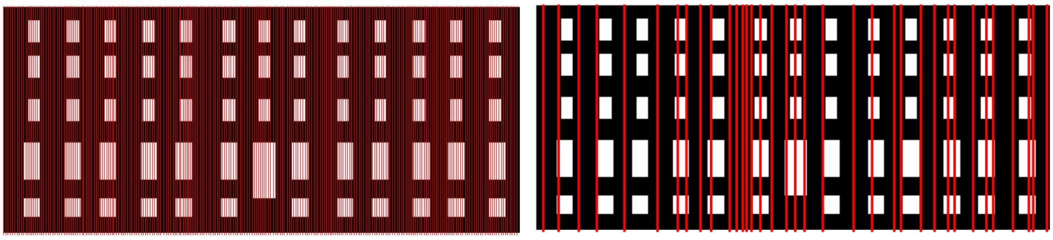

Figure 7: dense (left) or loose (right) control-profile networks

In each profile, the treatment of internal solicitations performed inside the DNA-module allows to express the corresponding DNA-code that summarizes the information under the shape of a column-vector that will advantageously be used for further comparisons. The corresponding data are presented in Figure 8 for a limited size soil defect and in Figure 9 for a significant size soil defect.

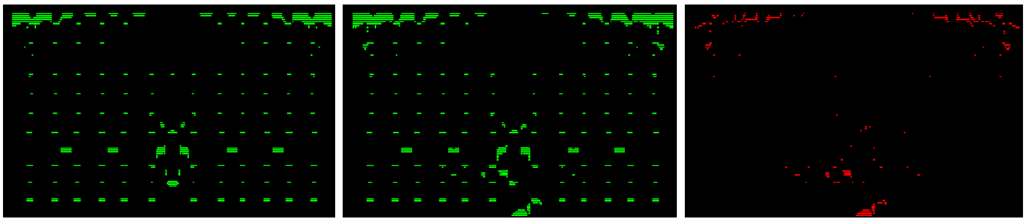

Figure 8: DNA-code not altered (left), altered configurations (centre), impact (right)

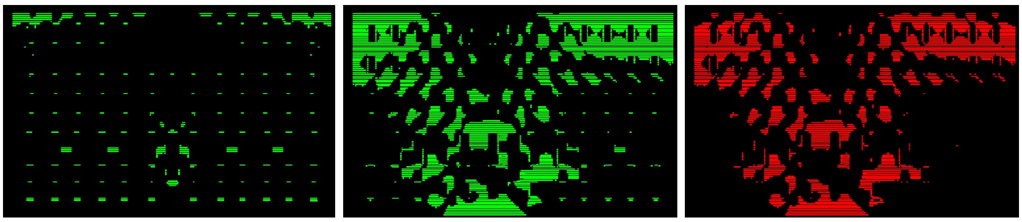

Figure 9: DNA-code not altered (left), altered configurations (centre), impact (right)

7 Conclusion

The potential impact detection of a soil defect inside a masonry system is not an easy operation although it is going to become more and more crucial due to constraints imposed by land planners and insurance companies. Important challenges remain and are still enforced by the difficulty of concealing both the masonry and soil simulation disciplines.

The interest in automatic and objective impact detection and for a quantification of it appears as great. The recourse to an external coding proposed by the authors allows the problem to be brought to another plane. The proposed implementation is simple although it shows interesting ways of evolution towards various particular cases. Advanced implementation works are in progress, taking into account both the tensile and compressive effects. A smart integration of this information allows re-computing an equivalent value of normal force and bending moment for specific zones of each profile. Then, relying on the usual design codes (Eurocode), a yield calculation approach may be carried out where the masonry is assumed to show disorders under a given level of strain. A more realistic estimation of LS and, later, GS in relationship with effective values of M and N may be achieved. Such an improved approach places the method directly on its way towards comparative design and risk estimation through discrete optimization and could lead to the establishment of very practical para-karstic guidelines similarly to the work proposed by Plumier & Doneux [4] concerning para-seismic guidelines.

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