"Tunnels and the Future"
2-5 November 2015

A structural approach to building damage risk management during the construction of the bored tunnel for Mashhad Urban Railway Line No. 2

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LONG ABSTRACT

Ground deformations due to the tunnelling process may pose a threat for buildings and infrastructure objects. The amount of damage that may be induced depends on a combination of the settlement profile along the geometrical and structural characteristics of the building. It is good practice to conduct a Settlement Risk Assessment (SRA) prior to the start of a tunnelling project. Determination of settlements and ground displacement due to tunnelling and building response to these displacements is relatively complex and time consuming. Within project planning however, it is often required to obtain a quick overview of the possible risks related to settlement induced damage. In this article the set-up of a system is proposed that can give a swift insight into the range of possible settlements and related risks. The proposed SRA-system combines finite element modelling (FEM) and a geographical information system (GIS) and facilitates mapping of buildings along the route in different building- and damage classes. Combination of all information in the GIS, applying logical relations result in risk categories for each building and infrastructural object. Through monitoring actual deformations that occur, the SRA database can be updated. If required, precautions to prevent damage can be taken. The proposed system in this article was succesfully applied for the Mashhad Urban Railway Line 2 project. The proposed GIS-based SRA-system is a state of the art tool that can play a major role in processing large amount of data to a number of simple, logical set of rules, in order to predict and control the building damage during the project.

Keywords: Settlement Risk Assessment, GIS, Tunnelling, Building Damage, Monitoring

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ABSTRACT

Ground deformations due to the tunnelling process may pose a threat for buildings and infrastructure objects. The amount of damage that may be induced depends on a combination of the settlement profile along the geometrical and structural characteristics of the building. It is good practice to conduct a Settlement Risk Assessment (SRA) prior to the start of a tunnelling project. Determination of settlements and ground displacement due to tunnelling and building response to these displacements is relatively complex and time consuming. Within project planning however, it is often required to obtain a quick overview of the possible risks related to settlement induced damage. In this article the set-up of a system is proposed that can give a swift insight into the range of possible settlements and related risks. The proposed SRA-system combines finite element modelling (FEM) and a geographical information system (GIS) and facilitates mapping of buildings along the route in different building- and damage classes. Combination of all information in the GIS, applying logical relations result in risk categories for each building and infrastructural object. Through monitoring actual deformations that occur, the SRA database can be updated. If required, precautions to prevent damage can be taken. The proposed system in this article was succesfully applied for the Mashhad Urban Railway Line 2 project. The proposed GIS-based SRA-system is a state of the art tool that can play a major role in processing large amount of data to a number of simple, logical set of rules, in order to predict and control the building damage during the project.

KEYWORDS: SETTLEMENT RISK ASSESSMENT, GIS, TUNNELLING, TROUGH, BUILDING DAMAGE, MONITORING

1. INTRODUCTION

Mashhad is the second largest city of Iran and is located in the north-eastern part of the country. The city has a population of 2.5 million citizens, and welcomes approximately 20 million visitors each year. To improve passenger transport in the city of Mashhad, the second urban railway line is planned to be constructed with a Tunnel Boring Machine (TBM). The trajectory of this line has a length of approximately 13 km, and runs generally from northeast to southwest (See Fig. 1). The TBM bored tunnel has an external diameter of 9.10 m.

Ground deformations due to the tunnelling process may pose a threat for buildings and infrastructure. Depending on the state and nature of the buildings and infrastructural objects and the amount of settlement that will occur, damage may be induced to these buildings and infrastructure. It is, therefore, good practice to conduct a Settlement Risk Assessment (SRA) prior to the start of the boring and construction activities. During the constructional phase of the project, based on the SRA a swift overview can be obtained of possible risks. Through monitoring actual deformations that occur, the SRA can be updated. If required, precautions to prevent damage can be taken. Nowadays GIS-based applications are state of the art tools playing a major role in processing large amount of data to a number of simple, logical set of rules, in order to predict and control the building damage during the project.

Figure 1: Map with the trajectory of Mashhad Urban Railway Line 2 (MURL2), Line 1 that is already constructed, and Line 3 and 4 both planned to be built in the near future.

2. SYSTEMATIC APPROACH

In order to conduct a SRA, different steps should be taken. Fig. 2 shows the respected flow diagram with the steps of the method proposed. Firstly, an inventarisation of (technical) information of all buildings along the route within the settlement risk zones is made, which is followed by the categorisation of buildings in damage classes. Subsequently the settlement along the route is calculated, for which a geotechnical profile is required, in order to determine the settlement zones (as in the next paragraph). Based on this damage category the risk class of the buildings and the amount of settlement at the location of a building is established. For buildings belonging to the high-risk class, counter measures should be defined. A standard monitoring programme is applied for all buildings under the influence of the bored tunnel.

3. TECHNICAL INFORMATION

3. 1. Geology

The city of Mashhad is located in the valley of the Kashaf River near Turkmenistan, between two mountain ranges of Binalood and Hezarmasjed as part of the Kopeh Dagh mountain range. Large strike-slip faults run through these two mountain ranges roughly trending NW-SE [4]. South of the city of Mashhad, the Mashhad Metamorphic Complex is found, which consists of Permian and Triassic metamorphic rock granitic intrusion, and ophiolite units [6]. The city of Mashhad is mainly built on Quaternary alluvial deposits. The tunnel will be bored through mainly these deposits [1].

3. 2. Geotechnical profile

In order to characterize the subsoil geotechnically along the tunnel route, which is essential to perform the settlement calculations, based on the available geotechnical data from boreholes supplied by the client three main geotechnical units were distinguished. The three main units are silty clays (I), clayey sands (II), and clayey gravels (III).

Unit I makes up the main part of the trajectory covering the section of the route between the start at the eastern entrance shaft of the TBM and station G2 (See Fig. 1 for the location of the stations). Unit II is predominantly encountered between station G2 and K2. Unit III is found along the remaining section between station K2 and the western TBM entrance shaft. Hence, the tunnel will predominately be bored through a layer of sand.

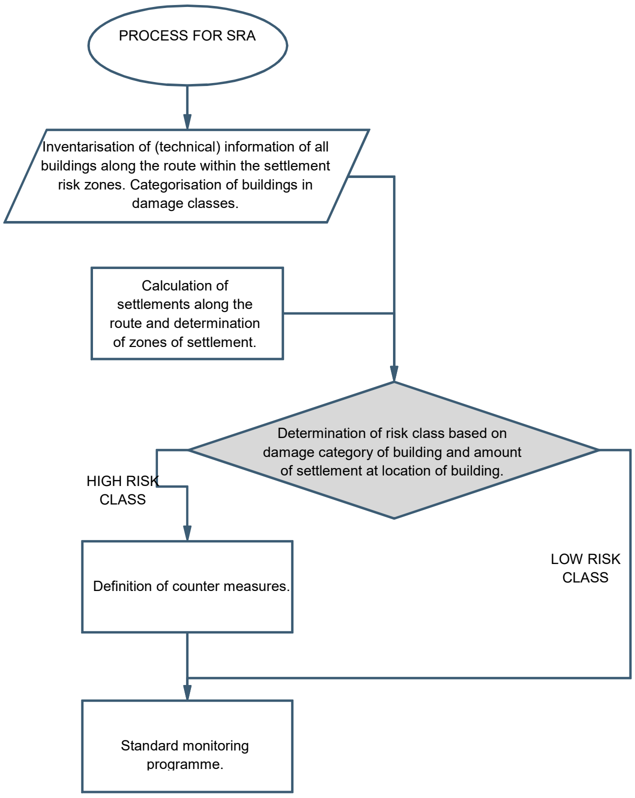


Figure 2: Flow diagram of the systematic approach how to conduct a Settlement Risk Assessment (SRA).

3. 3. Buildings and it foundations

All buildings along the route within the settlement risk zone have been categorized into a number of classes. To categorize each building into a building class, technical information of each building is required; i.e. type of foundation, number of stories, age and structural state. The combination of these specifications results in a building class. Distinction has been made into five building classes A to E, ranging from a low vulnerability to settlement induced damage in class A, to a high vulnerability to settlement induced damage in class E (Table 1).

Table 1: Building classes A to E in relation to a description of the vulnerability to settlement induced damage.

Building class	Vulnerability to settlement induced damage	Description
A	Low vulnerability	Low rise buildings (max. 1 storey) with a high structural integrity and low importance
B	Slight vulnerability	Low rise buildings (max. 1 storey) with a low structural integrity or a high importance
C	Moderate vulnerability	Medium rise buildings (max. 3 stories) with a high structural integrity and low importance
D	High vulnerability	Buildings (max. 3 stories) with a low structural integrity and high importance or Buildings > 4 stories with a high structural integrity and low importance
E	Extreme vulnerability	Buildings > 4 storeys with a low structural integrity and high importance High rise buildings (> 10 storeys) or Very important buildings (etc. hospitals)

4. CALCULATING AND PRESENTING SETTLEMENTS

4. 1. Finite Element Modelling

To predict settlements as a result of the boring process with a shielded TBM, finite element modelling (FEM) is used. Numerical calculations take into account the various construction phases and the influences on the surrounding buildings and structures. Within FEM, a hardening soil model is used for the settlement calculations, which is based on hardening plasticity.

To determine representative calculation results, the calculated settlements for the various grout cases were further assessed. These grout cases represent the boundary conditions as a result of the accuracy and soundness of the grout-injection process.

Grouting is applied to maintain the natural soil stresses and minimizing the displacements after excavation. It also protects the concrete segments being in direct contact with aggressive soil, and it improves the water-tightness.

Grout Case 1 (GC1) represents the ideal case were the pressure of the injected grout in the tail void compensates for the existing effective vertical soil pressure before excavation. It therefore represents the lower boundary for the settlements. On the contrary, Grout Case 4 (GC4) represents the worst case with regards to occurring settlements. This case is a result of a very poor injection procedure of grout, and represents the upper (worst case).

4. 2. Peck's surface settlement profile

To interpolate the settlement troughs calculated with the FEM (for GC1 and GC4), the vertical displacement along a cross-section, were curve fitted with empirically calculated troughs at regular intervals.

The most commonly used empirical method is the one first proposed by Peck [5], who stated that the surface settlement profile could be represented by a Gaussian distribution curve.

In Fig. 3, relevant points along the Gaussian settlement trough are indicated: at distance i from the tunnel axis, the maximum angle of inclination of the settlement trough is located, which is the location the horizontal movements are greatest and the horizontal strain is zero. At this position, the hogging and the sagging zone also alternate. At a distance of approximately $\sqrt{3} \cdot i$, the point of maximum bending is located; i.e. the horizontal strain is maximal. These are important points for the assessment of the reaction of the building on the settlement. Although the building's reaction also is dependent of its geometry, the building's location with regard to this settlement trough yields the angle of rotation of a building's foundation [3].

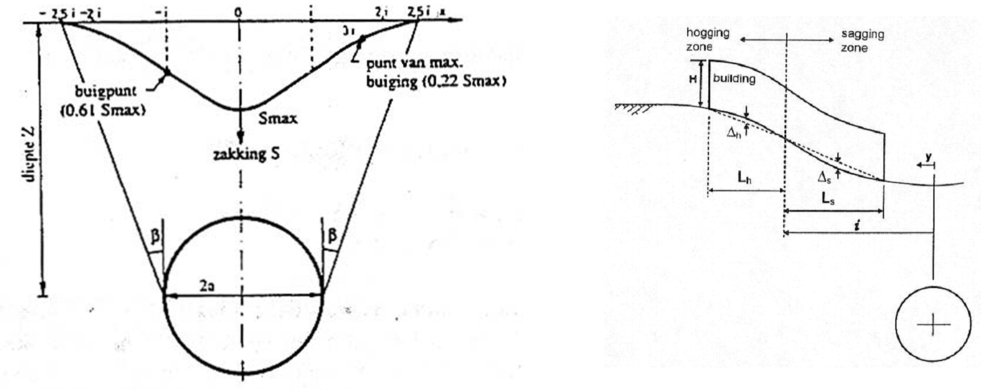


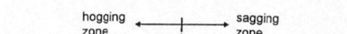
Figure 3: Gaussian settlement trough according to [5].

4. 3. Geographical Information System

The calculated settlement results were curve fitted for a large number of representative cross sections. Between the calculated cross-sections, settlements were linearly interpolated along the route. Hence, settlement contours could be approximated for the whole trajectory using a geographical information system (GIS).

In the GIS a grid with data points has initially been created, which has a regular spacing of 10 m in axial direction, and 5 m in radial direction with 40 m (8 points) at both sides of the tunnel axis. Subsequently this grid has been converted to a TIN (Trangular Irregular Network) settlement contour map representing the amount settlement for 40 m at both sides of the tunnel axis; i.e. the settlement trough. Fig. 4 shows a part of this settlement trough combined with the buildings located in the proximity of the trough.

Moreover, all (technical) information has been combined into a GIS database. The database has been referenced to the locations of the buildings on the city plan and alignment.



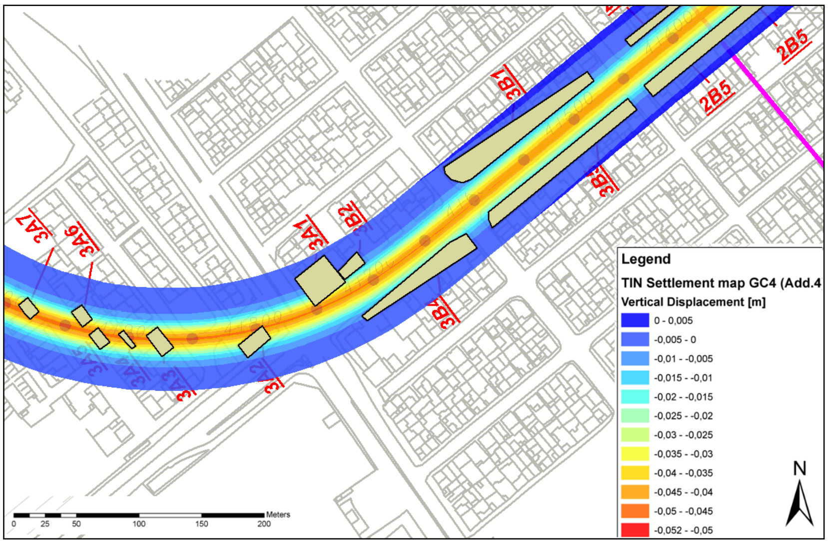


Figure 4: Contour map with vertical displacement (GC4) laid over the city of Mashhad. Yellowish polygons represent buildings with its distinctive number.

5. DETERMINATION OF DAMAGE CATEGORY AND RISK CLASS

5. 1. Damage category

In order to determine the possible damage to each building, the settlements should be related to building deformations. From this relationship, the strains and rotations that occur at each building can be calculated. Subsequently, the damage to each building can be estimated and categorized into damage categories.

For the classification of the damage, the generally accepted classification of Boscardin and Cording [2] is adopted. The damage classification is described in Table 2 below.

To determine the likely amount of settlement damage to each building, the geometry and position of the building are required along with the (differential) settlements at the location of the relevant building. To determine the possible damage to the building according to Table 2, the horizontal strains and relative rotations of the building due to the settlements should be determined.

Table 2: Damage categories for the damage classification after [2].

Damage category		Desciption of typical damage	Approx. crack width	Δ	Limiting tensile strain ε_{lim}(%)	β= δ/L
0	Negligible	Hairline cracks	< 0.1 mm	< 3 cm	0-0,05	< 1/300
1	Very slight	Very slight damage includes fine cracks that can be easily treated during normal decoration, perhaps an isolated slight fracture in building, and cracks in external brickwork visible on close inspection	1 mm	3-4 cm	0,05-0,075	1/300 to 1 /240
2	Slight	Slight damage includes cracks that can be easily filled and redecoration would probably be required; several slight fractures may appear showing on the inside of the building; cracks that are visible externally and some repointing may be required; doors and windows may stick	3 mm	4-5 cm	0,075-0,15	1/240 to 1/175
3	Moderate	Moderate damage includes cracks that require some opening up and can be patched by mason; recurrent cracks that can be masked by suitable linings; repointing of external brickwork and possibly a small amount of brickwork replacement may be required; doors and windows stick; service pipes may fracture; weather-tightness is often impaired	5 to 15 mm or a number of cracks > 3mm	5-8 cm	0,15-0,3	1/175 to 1/120
4	Severe	Severe damage includes large cracks requiring extensive repair work involving breaking out and replacing sections of walls (especially over doors and windows); distorted windows and door frames, noticeably sloping floors; leaning or bulging walls; some loss of bearing in beams; disrupted service pipes	15 to 25 mm but also depends on number of cracks	8-13 cm	>0,3	1/120 to 1/70
5	Very severe	Very severe damage often requires a major repair job involving partial or complete rebuilding; beams lose bearing; walls lean and require shoring; windows are broken with distortion; there is danger of structural instability	Usually > 5 mm but also depends on number of cracks	> 13 cm	>0,3	> 1/70

Once the horizontal strain and angular distortion have been calculated, the damage category can be determined from the Fig. 5 below.

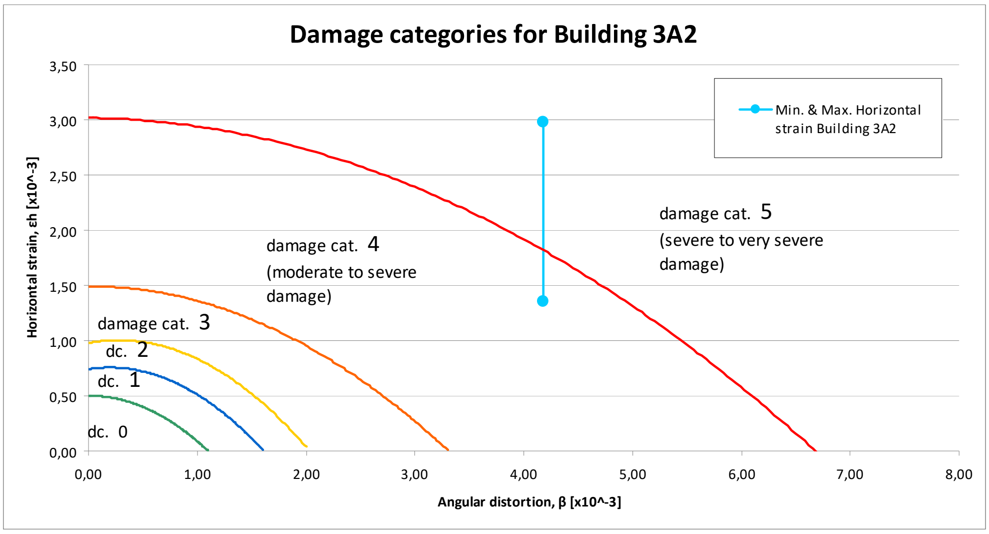


Figure 5: Relationship of the damage category as a product of the angular distortion and horizontal extension strain for building 3A2 as example: its minimal and maximal horizontal strain for GC4 (blue vertical line) intersects the damage categories 4 and 5 respectively. (Modified after [2])

For a building positioned within the settlement trough, the settlements at the outer boundaries of the building can be obtained from the GIS system. Combined with the inclination of the settlement trough at the location of the relevant building, the relative angular distortion can be determined. Plotting the data in the graph of Fig. 5 subsequently yields the damage category; e.g., building 3A2 with its minimal and maximal horizontal strain for GC4 intersecting the damage categories 4 and 5.

This process described above has been performed for each building identified and inventoried. The results of the categorization into damage categories, which have been determined both for GC4 and GC1 representing respectively the worst case and the best case scenario with respect to the settlements, yet still both cases assume an optimal situation of excavation of the TBM.

5. 2. Risk class

The final step in the SRA comprises the combination of the probable damage due to settlements (damage category) with the vulnerability to the damage (building class) of each building, which results in the risk class. A subdivision will be made in five risk classes, described in Table 3 below.

Table 3: Definition of risk classes

Risk class	Description
I	Negligible risk, standard observation of building during construction
II	Low risk, standard observation of building during construction
III	Medium risk, take mitigative measures
IV	High risk, mitigative measures required to prevent damage
V	Very high risk, damage unavoidable

Applying Boolean algebra on the variables of both the damage category and the building class finally results in a risk class, which ranges from a negligible risk that requires a standard observation during construction, to a very high risk resulting in unavoidable damage. For an important high rise building falling within building class E, for instance, the accepted damage category before taking mitigative measures will be lower than for a low rise building of relatively low importance falling within building class A. The combinations of building classes and damage categories resulting in the different risk classes for each building is given in Table 4.

Table 4: Determination of risk class from building class and damage category

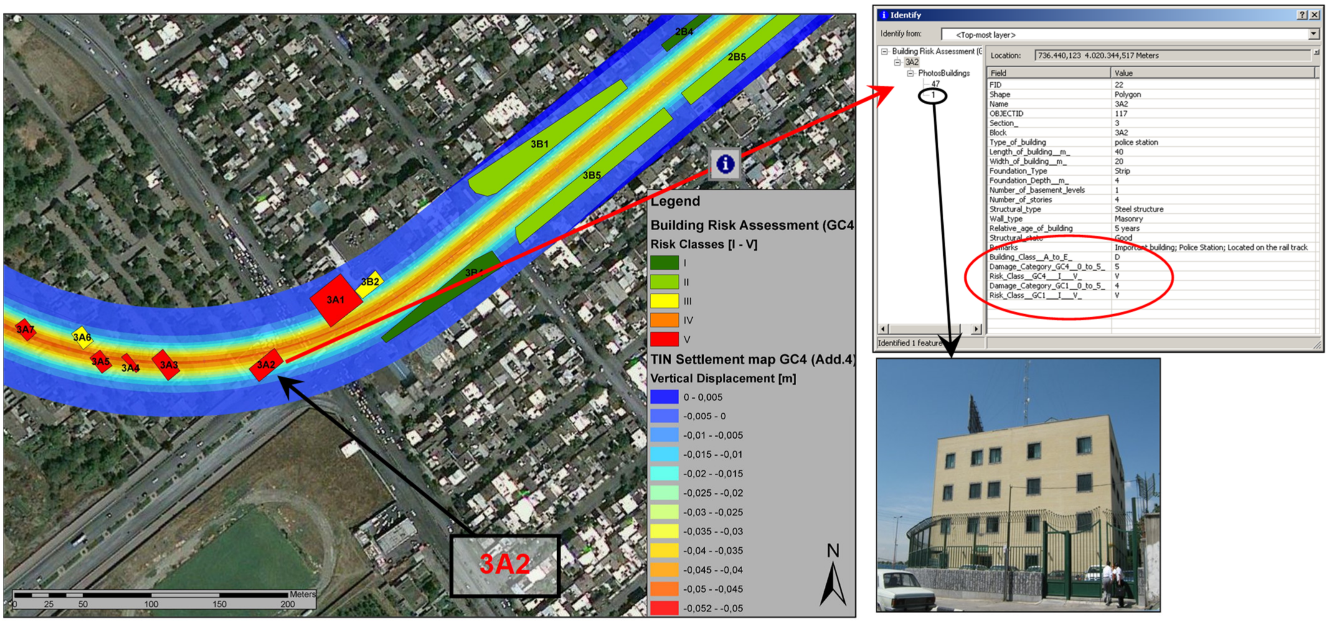
Building Class	Occurring Damage Category					
	0	1	2	3	4	5
A	I	I	II	III	IV	V
B	I	II	III	IV	IV	V
C	I	II	III	IV	V	V
D	II	II	IV	IV	V	V
E	II	III	IV	V	V	V

6. SETTLEMENT RISK ASSESSMENT

The process of the settlement risk assessment and determination of risk classes for the buildings along the route, which may be directly or indirectly influenced by ground deformations due to the tunnel boring process, has been performed for all the buildings for the settlements as calculated for GC4 and GC 1 by using the GIS system.

The complete database of all buildings, including building classes, damage categories and risk classes as well as the settlement troughs, have been incorporated in the system. Fig. 6 gives an example of the output of the GIS system. The maps include the city plan, the alignment of the tunnel, the settlement zones and the identified buildings along the route that may be influenced by ground deformations from the tunneling process, and the indication of risk classes (I – V) per building.

In Fig. 6, also an example is given for the database entry of a building: it illustrates the graphical query for building 3A2 by clicking on the relevant building on the map. The entry on the database is shown upon the screen (at the upper right of Fig. 6) with relevant information about this building. Where available, pictures of the building (at the lower right of Fig. 6) are related to the database as well.



Location: 736.440,123 4.020.344,517 Meters

Field	Value
FID	22
Shape	Polygon
Name	3A2
OBJECTID	117
Section_	3
Block	3A2
Type_of_building	police station
Length_of_building__m_	40
Width_of_building__m_	20
Foundation_Type	Strip
Foundation_Depth__m_	4
Number_of_basement_levels	1
Number_of_stories	4
Structural_type	Steel structure
Wall_type	Masonry
Relative_age_of_building	5 years
Structural_state	Good
Remarks	Important building; Police Station; Located on the rail track
Building_Class__A_to_E_	D
Damage_Category_GC4__0_to_5_	5
Risk_Class__GC4___I___V_	V
Damage_Category_GC1__0_to_5_	4
Risk_Class__GC1___I___V_	V

Figure 6: Contour map with vertical displacement (GC4) laid over a satellite image of the city of Mashhad. Coloured polygons represent buildings, which belong to an assessed risk class. At upper and lower right side respectively: database query for building 3A2 resulting in relevant information about building 3A2, and, if available, a photo of the building.

7. CONCLUSIONS & RECOMMENDATIONS

It should be stressed that a settlement risk assessment for a project as the Mashhad Urban Railway Line 2 is an ongoing process up until the completion of the actual project. As such, the SRA at the current stage is a starting point. A risk assessment is never absolute at any point and should be updated based on ongoing insights and developments by either the consultant, client or even the MURL2 organization.

The strength of the system is that it is flexible and comprehensive. Further detailing and/or updating of the system based on new insights and developments can be readily performed. Changes in building class and/or risk class can be adopted and information can be added. When starting the constructional activities and the boring process, the system can be calibrated based on the first measurements available from the monitoring program.

REFERENCES

[1] A. Aghanabati, Geology of Iran, Geological Survey of Iran, Tehran, 2004.

[2] Boscardin, M.D. & E.J. Cording, Building response to excavation-induced settlement, *ASCE Journal of Geotechnical Engineering*, 115, No. 1: pp. 1-21, 1989.

[3] Mair, R.J., Taylor, R.N. & J.B. Burland, *Prediction of ground movements and assessment of risk of building damage due to bored tunneling, Geotechnical Aspects of Underground Construction in Soft Ground*, Balkema Rotterdam: pp. 713-718, 1996.

[4] D. McKenzie, Active tectonics of the Mediterranean region, *Geophysical Journal of the Royal Astronomical Society*, 30: 109–185, 1972.

[5] R.B. Peck, Deep excavation and tunneling in soft ground, *7th International Conference on Soil Mechanics and Foundations Engineering*, Mexico City, State-of-Art: pp. 225-290, 1969.

[6] A.W. Ruttner, Southern borderland of Triassic Laurasia in north-east Iran, *Geologische Rundschau*, Vol. 82, No. 1: pp. 110-120, 1993.