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Considerations for a District-Level, Tunnel-Risk, Screening Tool

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ABSTRACT

To more rigorously address tunneling risks to above-ground structures, vulnerability evaluation of all structures along a tunnel route is required. This multi-block area along the route can be considered a district. To fully assess each structure within a tunnel's zone of influence, a multi-block or district-level model may provide new insights as to risk evaluation and mitigation strategies. However populating such a model with the existing geometry of the built environment poses a major challenge as measured drawings are not readily available for all structures along a tunnel's route. Cost-effective population of such a model could arguably involve remote sensing data in the form of laser scanning or photogrammetry. However even for unreinforced masonry structures, where external, above-ground geometries can be captured, without a prohibitively expensive building-by-building, in person survey many factors would remain unknown. To consider these uncertainties in an automatic way, a performance assessment framework is proposed. Such a framework allows a more rigorous, initial, risk quantification than is currently possible within the simple empirical models generally being used in industry when tunneling risk is initially assessed. This paper introduces (within the allowable space limits of this format) considerations for auto-population and application of a district-level, tunnel-risk screening tool.

INTRODUCTION

Challenging topography, intense urbanization and infrastructure development, combined with limited land availability and a growing awareness of environmental issues have led to increasing usage of underground spaces to control aboveground traffic and provide essential services in metropolitan areas. Tunneling, however, is not without its own risks, especially with respect to aboveground structures whether it be widespread minor damage (Burland et al. 2001) or the more notable, although less frequent, large-scale collapses such as the 2003 Shanghai (Allianz 2015) or 2004 Singapore (Magnus et al. 2005) events.

While one may argue that effective risk management ensures that insurance coverage is available (Ndekugri et al. 2013), in reality, even minor damage to historical buildings and monuments, is a topic that is not simply about economics. Such damage brings with it bad press, public backlash, and a general negativity about tunneling that is harmful for the future of the industry and the general health and functionality of urban areas. Arguably, such widespread, low-level damage is a general artifact of urban tunneling, because the concept of risk is not appropriately addressed. Most tunneling projects make construction-induced damage the responsibility of the contractor, its sub-contractors and/or their insurers. Within this arrangement is a long-standing imbalance between stakeholder expectations of no damage whatsoever and the complexity in predicting the interactions of tunneling activities with the material distribution and behavior of the subsurface and its affiliated aboveground structures.

In many sectors more reasonable sets of expectations have evolved through the adoption of performance-based assessment/design. The concept of performance-based assessment/design (PA) is primarily a mechanism for the expression of community values and subsequent decision making (National Research Council 1995), which aids in project development and management. As a successful example, PA is a common component in seismic design (FEMA 2012) that aims to balance cost with post-earthquake functionality, as part of the design methodology. In that context, the goals of PA are to (1) produce long-term cost savings, (2) enable continued operations and immediate occupancy after catastrophic events for certain classes of buildings, (3) illustrate a clear quantitative picture on how a facility will perform during a seismic events, and (4) predict the consequences of each performance level with respect to an effective mitigation plan. In other words, the objectives of PA are to achieve a pre-specified level of performance, as correlated to appropriate consequences, which may be measured in numerous ways (e.g. monetary loss or loss of life). Arguably, in the tunneling community acceptable performance levels would have to be negotiated between the various stakeholders [e.g. building owners, facility managers of key facilities (e.g. hospitals), community groups, and insurers], as well as the contractual players (i.e. designers, contractors, and the project owner).

Gathering the necessary data to generate a PA for each building along a tunnel route is not trivial. However, remote sensing (RS) technology (e.g. in the form of light detection and ranging [LIDAR]) can be a major contributing component to this. Aerial RS has been used for approximately two decades for disaster planning (especially flooding) [Laefer and Pradhan 2006], because it (1) can generate rapidly high-resolution data across large geographic areas, (2) may provide insight into failure morphologies of damaged ground and structures in post-event scenarios, and (3) furnishes baseline data for further exploration and visualization of both pre-event vulnerabilities and post-event actualities such as vulnerability zoning and consequence analysis at a city-scale (Kayen et al. 2006).

This paper proposes how PA can be integrated into the traditional risk screening processes for buildings subjected to tunneling-induced subsidence and the role that RS data can play in that process. This paper will focus on unreinforced masonry structures (URMs), which pose the greatest challenge to tunneling across Europe and other cities with historic centers. This paper's URM focus reflects both the higher level of vulnerability of these structures to ground movements and the ability of RS technologies to capture much of the geometry of critical, load-bearing elements.

This is not to say that capturing the external components gives a comprehensive picture of a URM. Wall thicknesses, interior load bearing elements, basements depths, and foundation types and layouts remain unknown and cannot become known without a prohibitively expensive building-by-building, in person survey. However, the overall height, length, width, and position of the building with respect to a particular tunneling alignment can be established. As will be described below, these are the components generally considered in initial risk assessments and are essential elements to document, as measured drawings rarely exist for this class of structures.

CLASSICAL APPROACH IN DAMAGE ASSESSMENT DUE TO TUNNELING

Preventing damage to adjacent buildings in a cost-effective fashion depends on being able to predict the damage that tunneling can cause. This requires an adequate theoretical model to establish how vulnerable a building is to damage, which in turn requires some quantitative description of the building and/or site in question (Laefer et al. 2006). Burland (1995) [based on previous works (Burland and Wroth 1974, Burland and Wroth 1977, Boscardin and Cording 1989)] proposed a 3-Step process for assessing risks

related to tunneling-induced settlement for large building stocks footing on shallow foundations (fig. 1). In that, Step 1 relied on the generation of a greenfield settlement trough to establish whether a maximum slope ($\theta_{\max} < 1/500$) or a maximum settlement ($\lambda_{\max} < 10\text{mm}$) of the ground surface was exceeded at the location of any building. Any building at such locations was to be considered in Step 2. Step 2 then considered each building as a simple deep beam whose foundations were assumed to follow a greenfield ground displacement profile.

Subsequently, the maximum tensile strains (ϵ_t) were calculated, and an appropriate category of damage was assigned to the building. The goal of this two-step process was to determine which buildings (if any) should be further considered for detailed analysis (Step 3). The hypothesis behind this assessment process is based on this assumption that a building is subjected to the same deformation as the ground upon which it is founded. Burland et al. (2001) proposed using a procedure first outlined by Potts and Addenbrooke (1997) as an alternative for detailed analysis. However, Burland et al. emphasized that Step 3 should involve detailed considerations of tunneling methods, structural continuity, foundation characteristics, building orientation, soil-structure interaction, and previous displacements. As part of this, the subsidence trough (shape and magnitude), time-dependent movement, protective measures, and damage level (from both subsidence and horizontal strains) should also be considered, as well as the three-dimensional (3D) stiffness effects of the building undergoing displacement. Arguably such assessments would require a full 3D computational model. Analysis at such a detailed level is not currently economically feasible when considering several hundreds (if not thousands) of structures along a tunneling route.

PERFORMANCE ASSESSMENT OF MASONRY STRUCTURES DUE TO TUNNELING USING REMOTE SENSING AS A SCREENING TOOL

Previous studies (e.g. Kayen et al. 2006, Laefer et al. 2006, Schon et al. 2009, Laefer et al. 2010) have shown that RS technologies offer a new opportunity to automatically detect external building geometries at a decreased cost and increased processing speed compared to traditional surveying. As shown in Figure 1, Step 1 highly depends on the building geometries and their positional relationships to the location and alignment of a proposed tunnel. Such information can be extracted either automatically or semi-automatically (depending upon the desired level of accuracy) from RS data using one of many automatic façade and feature detection approaches (e.g. Pu and Vosselman 2009, Haala and Kada 2010, Truong-Hong and Laefer 2013, Laefer, Truong-Hong et al. 2014).

The “sensitive buildings”, identified in Step 1, are to be assessed through calculating the inflection point of settlement trough relevant to the façade of building (Step 2). This can indicate sagging and hogging zone of each building to calculate critical Strain (ϵ_{cr}). For this, the rough exterior building geometry is needed. Arguably these dimensions can be fairly gross as the current approach only represents the structure as a deep beam with equivalent elastic axial and bending stiffnesses

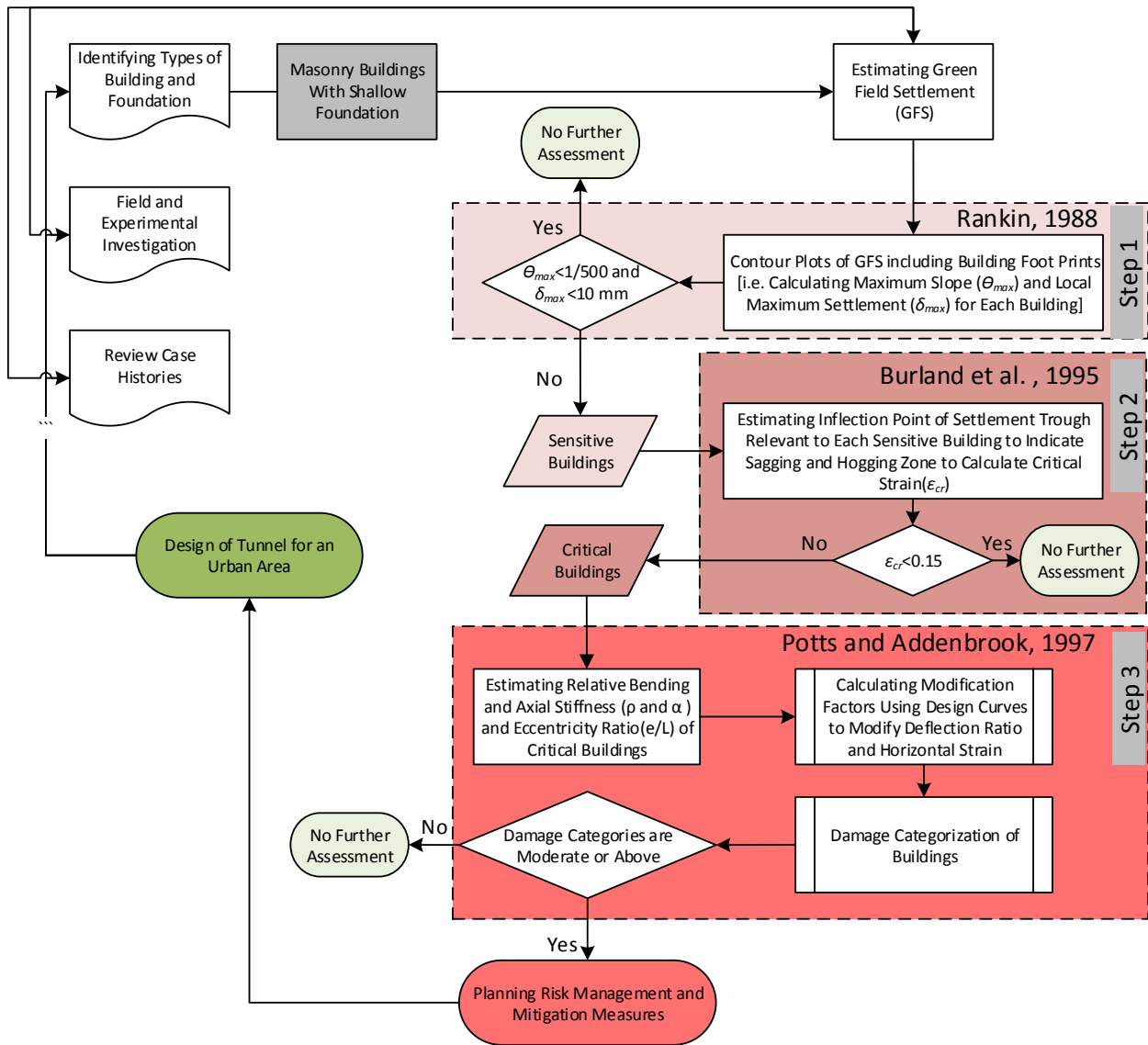


Figure 1. Typical 3-Step process for assessing risks related to tunneling-induced settlement for large building stocks

(Burland 1995). Even the more detailed analysis proposed by Potts and Addenbrooke (1997) is fundamentally based on the geometry of the structure (its width and equivalent bending and axial stiffnesses and its position relative to the tunnel's centerline).

Presently aerial RS technology is not adequate to detect small ground changes or building damage, but as RS technologies continues to improve, this will become less of an impediment. In the current context, the role of RS for damage detection and ground movement determination is introduced in Figure 2 through the term 'chronologically-based RS'. This term implies a comparison of a building's status before an event [i.e. including pre-existing damage (ED)] with the damage levels after an event (i.e. during tunnel construction and operation), which is essential for a "claim assessment" procedure. Furthermore, if the expected changes are large and obvious, a straightforward and efficient method can be used that ignores the data quality. However, even with an exhaustive effort to maximize knowledge, some uncertainty will remain. To account for this uncertainty a "knowledge factor" needs to be utilize in the damage evaluations based on RS, which is project and RS data specific.

The damage levels likely to appear in each step and process can be distinguished by introducing the concept of contractual ratios (CRs) in figure 2. In performance assessment, a contractual ratio relates to the performance of a structure and can be introduced by a pre-agreed performance criterion [e.g. maximum slope (θ_{max}), maximum settlement (λ_{max}), critical principle strains (ϵ_{cr}) and/or corresponding damage categories] as indicated in figure 2 as CRs. The exact values, which were proposed in figure 1, were suggested by Burland without considering a "building's importance factor" as previously proposed by Clarke and Laefer (2014). Thus, different performance criteria corresponding to the importance factor of buildings and predicted damage categories (figure 2) can be addressed contractually.

To complete the assessment process, a probabilistic modeling approach was suggested for "critical buildings" as a Step 4. Examples of how this can be done are available elsewhere (Clarke, Moradabadi et al. 2015, Moradabadi, Laefer et al. 2015). Potentially, this step could completely replace Step 3, and thereby overcome the simplification-based limitations introduced by the Potts and Addenbrooke's approach (Potts and Addenbrooke 1997). Notably figure 2 shows that a detailed field and experimental investigation may be needed to provide further geotechnical characterization, structural and geometrical details. Foundation specifications would be needed only for "critical buildings". Theoretically such data could be obtained in part from some type of probabilistic database for reliability analysis.

The consequence analysis result of Step 4 would indicate which building(s) or section(s) of tunnel route needs more consideration. For buildings that have unacceptable consequences, a range of possible protective measures may be proposed. A cost-benefit analysis process is always necessary to decide about the effectiveness of protective measures. This was presented in Figure 2 as the "mitigation plan (MP)". In case the mitigation plan is cost-prohibitive, updating or changing the tunnel routing may have to be considered.

CONCLUSIONS

This paper offers considerations for a new paradigm for district-level risk screening for tunneling. To better involve the concept of risk in the whole process, the methodology and terminology of the concept of performance assessment as used in the seismic community was adopted in the proposed paradigm. Additionally, the potential role of remote sensing data is demonstrated in the early steps of risk assessment for consideration of the large numbers of buildings typically impacted along a tunnel route (herein considered a district). The decision points for stakeholders are indicated explicitly as "contractual ratios"

and in the “claim assessment” process. Although this paradigm suggests a robust approach in terms of damage assessment of masonry structures due to tunneling, uncertainties will remain. Accounting for these and the development of affiliated “knowledge factors” is likely to be a major focus for the upcoming generation of tunneling-related risk research.

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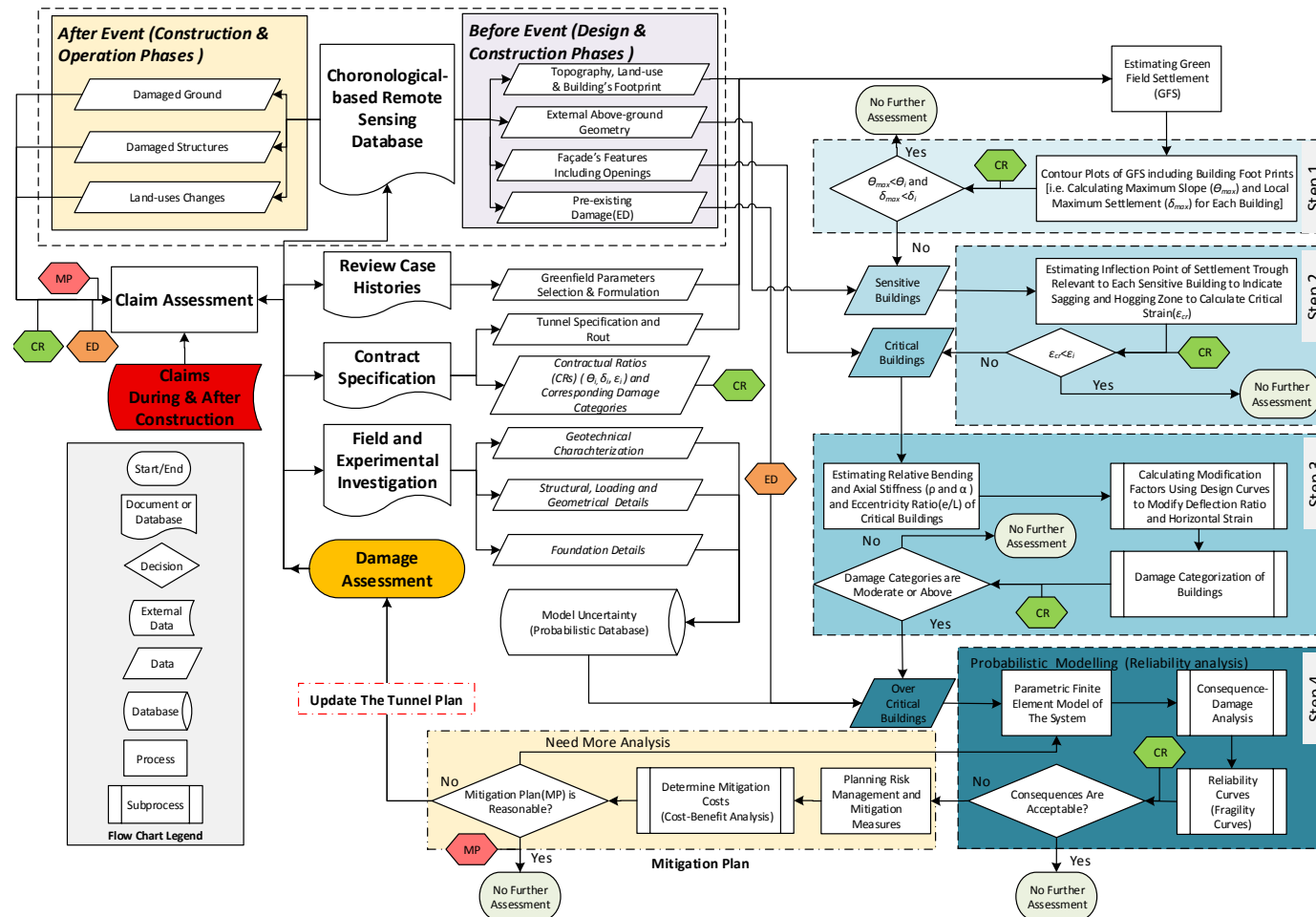


Figure 2. Performance-based process for assessing risks related to tunneling-induced settlement for large building stocks using remote sensing database (Step 4 can completely substitute for Step3)