Ground Settlement in Urban Structures Exposed to geo-environmental and Anthropic Hazards: a Case Study for Galati

Cornelia-Florentina Dobrescu\textsuperscript{a,\*}, Elena-Andreea Calarasu\textsuperscript{a}, Iolanda-Gabriela Craifaleanu\textsuperscript{a,b}

\textsuperscript{a}National Institute for Research and Development in Construction, Urban Planning and Sustainable Spatial Development - INCERC Branch, 266\textsuperscript{a} Soseaua Pantelimon, Sector 2, Bucharest 021652, Romania

\textsuperscript{b}Technical University of Civil Engineering, Bd. Lacul Tei 122-124, Sector 2, Bucharest 020369, Romania

Abstract

A case study including a detailed ground settlement analysis is made for a particular loess structure located in the city of Galati, Romania, in order to assess the interdependence of geo-environmental and anthropic settlement triggering factors in the urban system context. In the first part of the study, loess behavior and its effects on built environment are analyzed and discussed based on worldwide historic expertise and current issues. An integrative analysis of loess deposits in natural state, with reference to induced-hydraulic and stress conditions, which was performed by laboratory and in-situ investigations, is then reported. An assessment of basic geotechnical parameters, as well as small-scale modeling of loess settlements at wetting under self-weight were conducted in order to select the most representative experimental area, from the point of view of specific soil structure behavior. Field monitoring surveys were performed to obtain information for quantitative evaluation of settlement time-dependent evolution, by the simulation of excessive moisture. The processing and analysis of experimental data gathered for natural and improved ground conditions revealed that the settlement amplitude of loess deposits with high sensitivity to wetting under self-load can be significantly reduced by the selection of adequate consolidation solutions, based on realistic and undisturbed environmental conditions. The study of soil structure behavior under simultaneous settlement-triggering factors can be integrated in multi-hazard analysis as a support for efficient strategies and mitigation measures, with applicability in the urbanization process, building and foundation design and environmental protection.

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\* Corresponding author. Tel.: +4-074-865-4011; fax: +4-021-255-1852.
E-mail address: corneliadobrescu@yahoo.com
1. Introduction

Loess deposits are considered at global scale as one of the major geo-hazards to build environment due to damage in engineering structures and infrastructures caused by large ground settlements [1, 2]. The peculiar characteristics of loess are closely related to high porosity and permeability, low density and moisture, high apparent strength and stiffness in natural state condition. Collapsibility of loess has been attributed to its moisture sensitivity and to the volume changes induced by deformations in a metastable microstructure, linked to soil chemistry and mineralogy [3]. Collapse of loess structures can occur when internal stresses between soil particles or those due to external loads exceed structural strength upon saturation [4]. Additional loading and wetting can cause considerable modification of intrinsic properties [5, 6] due to stress redistribution and external factors as dynamic loads [7, 8]. Loess soils are also subjected to geomorphic dynamic processes manifested by underground soil erosion, suffusion or slope failures, associated to typical landforms such as loess caves, sinkholes, depressions or gullies [9, 10]. The problem of loess genesis represents one of the most controversial issues in geosciences literature and is addressing the origin of particles, the depositional environment and the post-depositional changes [11]. Therefore, several studies have emphasized the importance of loess geological formations in the reconstruction of paleo-climatic and paleo-environmental changes during Quaternary [12] based on stratigraphy and magnetic susceptibility data [13, 14, 15]. Geological formations of loess cover 10% of global land surface and are typically widespread on geographical areas as plateaus (Chinese Loess Plateau) or along river basins (Mississippi, Rhine, Yellow River, Danube). Loess soils are covering 20% of land surface in Eastern and Central Europe areas associated with thick layers along rivers. In Romania, loess soils are distributed on about 17% of the territory and occur to a maximum elevation of 400 m, especially in Romanian and Danube Plain, South and Central Dobrogea and Moldavian Subcarpathians. The thickness of loess deposits can reach 30-35 m in the eastern part of Romanian Plain (in areas of the Romanian counties Braila, Galati, Ialomita, Fetesti) up to a maximum of 60 m on the right bank of Danube.

In built areas, settlements induced to buildings by loess collapse can affect their long-term performance during the service life. Substantial economic losses related to the damage of structural components and infrastructure facilities were reported worldwide [16, 17]. In this regard, special regulations and technical requirements for designing and construction of settlement-resistant foundations on loess were developed and improved based on accumulated experience and a large number of observations. According to geological and environmental changes, several guidelines concerning the methods for minimizing loess collapsibility in pre-design stage, ground treatment technologies and settlement monitoring are strictly recommended in order to ensure and maintain building safety and stability. Various laboratory and in-situ tests on geotechnical parameters assessment for different loess soils in Romania and implementation of soil improvement methods have been performed [18, 19, 20]. Following previous research, the present study is focused on fusing and correlating experimental tests in order to quantify and assess the basic indicators of ground settlement with special reference to loess behavior linked to geo-environmental and anthropic factors.

2. Overview of geo-environmental and anthropic issues for Galati urban area

The selection of Galati, a city with 250,000 inhabitants in Romania, as an experimental area for the study is directly connected to high exposure and vulnerability of buildings and people to geo-environmental and anthropogenic hazards, generated by geological, geomorphologic, hydro-geological and seismic conditions overlap and impact on people and building stock. Moreover, the effects of urbanization and industrial expansion have led to serious environmental, social and economic changes and to augmentation of urban geo-hazard patterns.

From geological point of view, sedimentary geological structure of studied area consists in Upper Pliocene, Pleistocene and Holocene deposits. Quaternary soil category occurred in Galati sedimentary sequence consists of thick aeolian loess layers, formed during Pleistocene glaciations, characterized by a high sensitivity to water and large settlements under self-weight.

Exposure of Galati city to urban flooding risk during heavy rainfall periods leads, due to specific geomorphologic features, to the rise of groundwater level, attributed to city location on the first level of Danube River terraces. Deficiencies in urban sewerage systems, underground accidents or thick heterogeneous fills lead to ground water infiltration, causing severe damages to foundations and building stability, induced by ground settlements. Likewise,
the occurrence of water domes corresponding to loess wetting areas was observed after removal of natural collectors and drainage. The general stratigraphic profile of ground surface is outlined by a silty clay layer and loess and loess-like deposits, with a separation area of sandy lens, where stored groundwater sources are considered as a triggering factor in significant slope failure and erosion processes. Hydro-geological conditions of Galati city are controlled by a complex hydrographic system, where groundwater is stored in aquifers formed by alluvial gravels. The problem of groundwater level is closely related to discontinuities in soil structure.

In terms of seismic hazard, Galati city is one of the important areas affected by Vrancea subcrustal earthquakes, with several records of building damage during 1940 and 1977 strong seismic events. Even though harmonized with European standards, the current Romanian seismic design code, P100-1/2013 [21], does not include a soil factor, S, as in Eurocode 8 [22]. In terms of code, seismic hazard for the city of Galati is defined by a corner period $T_C = 1.0$ s and a peak design acceleration $a_g = 0.30$ g, associated to a mean recurrence interval, $MRI$, of 225 years. Several studies show that special investigations are required for site class S2, which includes particular soils as loess deposits, due to potential amplification effects produced during ground motion [23]. Recent studies [24] underlined the importance of considering complex effect of building foundations and soil-structure interaction on the characteristics of ground motions recorded in Galati city during strong Vrancea earthquakes.

Rapid process of urban development, oversized industrialization and associated population growth were accompanied in Galati by significant damage to existing building stock, with a specific dynamic evolution in time. Severe damage occurring during World War II or caused by 1940 Vrancea earthquake led to the necessity of modernization and rehabilitation of urban structure in Galati city. This was started in the 1950’s, following the communist model. Construction of the largest siderurgical complex in Romania in 1961, together with an abrupt population growth, have led in the following years to a rapid extension of urban system, consisting in low-rise buildings with collective dwellings, Tiglina I being one of the first district, formed by smaller urban units, called micro-districts. Past observations on building condition and on settlement development versus time have confirmed that the main source of structural damage in Tiglina I district is represented by infiltrations from water supply systems and sewage, poor surface drainage and changes in groundwater level due to urbanization or industrial activities. Large thickness of loess deposits and increase of local water-table level caused a general wetting of the soil foundation. In addition, the anisotropy and heterogeneity of loess structure created behavior discontinuities of deposits in wetting conditions, leading to non-uniform and large ground settlements at the contact with foundation and extensive structural damage, affecting more than 40% of residential buildings.

### 3. Soil characterization and methods used for settlement evaluation

Given the complex situation of studied area, given by special soil conditions, building stock vulnerability and exposure to multi-hazard factors as triggering elements, combined in-situ and laboratory testing were performed within a complex program developed over many decades. The experiments were performed to assess development of settlement amplitude with time and specific features of loess deposits at ground surface and in depths. Several criteria for selecting experimental area were considered, i.e.: (i) representative loess deposit for Galati city in terms of wetting sensitivity, (ii) loess thickness that should be considered in order to evaluate the most unfavorable situation from the point of view of geotechnical conditions, (iii) adequate locations of experimental tests, for a rapid applicability in building design for considered urban area, (iv) direct comparison between loess behavior at different sites.

Assessment of soil conditions in experimental area (Tiglina I district) has started with identification and characterization of collapsible soil structures. In order to evaluate specific criteria and values prescribed by national regulations, undisturbed samples were collected at 1 m interval, by performing shallow boreholes up to 25 m deep. Subsequently, laboratory testing for determination of basic physical and mechanical soil properties were carried out. Soil profile consists in 24 meter-thick yellow loess with more than 60% silt fraction. According to soil condition, the samples can be classified in silty loess class, with saturation degree in natural conditions (Sr) varying from 25 to 35%, with low moisture content (w) between 9% to 15% up to depth of 18 m, belonging to medium plasticity category, with plasticity indexes (PI) ranging from 10% to 18% and with high porosity (n), ranging between 46 to 53% (Fig. 1).
A continuous increase of moisture content of about 25% can be remarked within 18 m to 25 m depth interval. The porosity indicates a slow decrease, reaching 41% at maximum investigation depth. At the bottom profile, a clayey silt soil was identified, with no collapsible characteristics. By correlating values of physical parameters with the results of a supplementary specific settlement index, \( \text{im}_{300} \), corresponding to a 300 kPa load, obtained by performing oedometer tests in natural and saturated conditions, the samples were classified as collapsible soils with high wetting sensitivity (\( \text{im}_{300} \geq 2\% \)), according to the criteria specified by Romanian regulations (NP 125). Minimum and maximum values obtained for geotechnical parameters indicate a good agreement with representative loess characteristics of Galati city (Fig. 2).
Basic intrinsic parameters reveal similarities with results from past and recent studies regarding soil behavior. Taking into account the accurate correlation of measured physical and mechanical properties with respect to theoretical values prescribed for Galati city, the investigated area is considered as being representative from the point of view of ground conditions and for further use in assessment of time-dependent settlements. Existing monitoring data concerning ground settlements recorded in active area of residential buildings on a two-year period, at foundation level under loads transmitted by foundation system, were compiled in order to quantify the magnitude of soil deformations as a key indicator of loess behavior.

An overview of settlement amplitude distributions related to time-dependent evolution in analyzed area (Fig. 3), can be considered as a guideline in building design and consolidation projects due to the importance of loess behavior in selecting the geotechnical risk category. The recorded measurements emphasized that loess deposits from Tiglina I quarter should be classified in class “B” according to NP 125, characterized by settlements under self-weight due to wetting, in addition to supplementary settlements in the upper part of layer situated under foundation (Img ≥ 5cm).

After setting the representative collapsible profile, an experimental area was delimited in northeastern part of Tiglina I district, with 10 m x 10 m plan dimensions. In-situ survey carried out in the pilot area consisted in induced soaking for determining ground settlements at self-weight for different soil conditions characterized by natural loess and compacted loess using 7 m up to 10 m soil columns. Preliminary works were included 10 casing boreholes up to 25 m depth, instrumented with 250 mechanical marks for monitoring the vertical settlements. For measuring of surface settlement inside and outside the experimental area, arrays of more than 100 topographic marks were used, as well as moisture doses to monitor the wetting line advancing in both vertical and horizontal directions. The settlements occurring in experimental area were continuously monitored for one year and criteria for ceasing measurements was based on a relatively low settlement rate up to settlement amortization. After recording initial measurement using surface settlement marks, the areas were exposed during three and a half months to soaked-induced conditions, under a 0.5 meter-thick water layer. At the end of this period, water immersion process was discontinued for 4 ½ months, in order to observe time-dependent wetting front advancing and water immersion in...
the ground. During a second stage of immersion conditions of about 4 months, deformation of loess deposits also caused soil cracks. As field observations, cracking phenomenon occurred simultaneously with settlement triggering in natural loess, after second stage of artificial wetting. A progressive moistening was observed from inside to outside of experimental area, forming closed contours. Plots of settlement rate and average settlement values, recorded for natural and compacted soils under self-weight, were obtaining based on periodic monitoring measurements carried out in the investigated areas (Fig. 4).

4. Discussion and evaluation

Plotted curves indicate a rapid consumption of settlement of about 80% from the total settlement, after first soaking stage. Significant differences can be noticed between settlement amplitudes of about 800 mm and 600 mm, respectively, corresponding to compacted loess with 7 m and 10 m soil columns, and those of 980 mm recorded for natural loess. Settlement attenuation observed in case of compacted loess deposits with 10 m soil columns after first stage of water immersion (which probably would require a longer period) was considered. By analyzing subsurface measurements data, it is concluded that the settlement development of natural loess is produced in depth interval ranging from 7 m to 18 m, followed by low settlement. In natural loess, 25% of the total settlement is consumed from surface up to 7 m depth and 75% in the bottom layers. In contrast, for compacted loess layers using 7 m and 10 m soil columns a reduction of settlement of about 25% and 40%, respectively, occurred at self-weight, as compared with total settlements recorded. These relatively low percentages can be related to settlement occurrence in the bottom layers of soil profile, below the limits of compaction depth. It should be noticed that the reduced settlement rate occurs simultaneously with the increase of compaction depth. Taking into account geotechnical conditions of experimental area, compaction process on the entire thickness of loess deposit can lead to about 80% reduction of settlement amplitude at self-weight. A deeper compaction up to 20-25 m depth would minimize the consequences of large settlements of loess soils in wetting conditions under its own weight. Loess sensitivity in water immersion conditions has to be considered in relation to supplementary settlement at wetting under self-weight.
The results suggest that an integrative analysis of soil conditions in an urban area exposed to multi-type of factors dealing with loose of environmental equilibrium can be efficient in overcoming hazard barriers. Resulting similarities for small-scale conditions were considered in selecting the study area based on specific soil characteristics. Field measurements carried out in the experimental survey are considered to be the most feasible alternative to quantify the amplitude of ground settlements, by preserving real conditions of soil structure. During both laboratory and in-situ investigation, environmental and anthropic effects as flooding or water infiltration were artificially induced. Monitoring surveys have revealed the effectiveness of ground compaction using soil columns as a method of reducing loess wetting susceptibility and settlement amplitudes. Space constraints in experimental area, due to building and infrastructure density and green areas have determined the use of a relatively small area comparing to the large extent of problematic soils.

5. Conclusions

The presented research provides relevant data on loess deposit behavior via hydraulic and stress conditions, in the context of assessment of settlement amplitudes in a representative highly geo-environmental and anthropic hazards-prone area in Galati city, Romania. A combined laboratory and field testing program was used for simulating the interdependence of intrinsic physical and mechanical properties and triggering factors of soil structure collapsibility. Special consideration should be given to loess soils classified in collapsible category “B”, which can develop large settlements at wetting, even without loads induced by buildings, and irreversible damages. Based on preliminary investigations, by an appropriate compaction process, settlement of loess layers at self-loads can be significantly minimized. Moreover, further surveys should be carried out for a more detailed characterization of ground conditions, by gathering additional information needed in building and foundation design, urban planning and environmental protection in order to reduce economic losses and to ensure the safety of the urban population. The results can be integrated in multi-hazard analysis from the point of view of ground condition assessment, for supporting efficient strategies for urban development and risk mitigation measures. By simulating factors favoring large loess settlements, relevant data for assessing geotechnical risk category of existing and future building sites can be obtained. Also, in earthquake prone-areas, the role of soil class and of corresponding soil behavior has to be considered in establishing the appropriate foundation system and structure type, taking into account the amplification of soft soil response at ground surface during strong seismic events.

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