Estimation of the Hydroconsolidation Susceptibility of the Anthropogenic Fill of the Historical Center of Thessaloniki, Greece

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ABSTRACT: *The collapse of soil structure due to wetting is called hydroconsolidation and occurs only once under constant loading, in cases of perturbation of the soil's moisture content. It is encountered usually in non-sedimentary soils such as anthropogenic fills and residual materials. This paper presents an interpretation of hydroconsolidation settlements of a building in the historical center of Thessaloniki after a rise of the water table. The interpretation is based on the results of laboratory evaluation of hydroconsolidation properties, in conjunction with in situ measurements of settlements.*

KEYWORDS: hydroconsolidation, anthropogenic historical fill, collapse settlement, oedometer simulation, Thessaloniki's Metro

SITE LOCATION: IJGCH-database.kmz (requires Google Earth)

INTRODUCTION

The volumetric change behavior of a saturated soil is generally controlled by effective stress. However this behavior under unsaturated conditions cannot be estimated on the basis of effective stress alone but it is controlled by the changes of the soil moisture that result in changes of soil's matric suction (Khalili et al, 2004). The phenomenon of soil collapse can be manifested gradually and not necessarily as an immediate settlement, depending on the initial moisture content and the moisture variation range. If the soil is loaded under saturated conditions then it will consolidate without collapsing. If however its moisture content under constant loading is initially low (partially saturated) and is subsequently increased, then for low stress levels the soil will swell, whereas for higher stress levels it will sustain volume decrease due to structure collapse. Figure 1 shows the phenomenon of gradual collapse with increased wetting which is called hydroconsolidation; it occurs once and results in a new more stable soil structure (Knight, 1961).

Hydroconsolidation usually occurs in cases of wetting in soils of unstable granular structure due to technical interventions, in residual soils and in non cohesive man-made historical and urban non-engineered fills. The magnitude of settlements due to soil collapse depends on the soil's void ratio as well as the applied load. For low foundation stress levels from 100-300 kPa, research shows observed volume changes up to 10% and settlement as much as 15% of the thickness of the susceptible layers (Tromp, 1985). Hydroconsolidation is estimated via oedometer test with simulation of the loading procedure followed by sample inundation as in Figure 2 (Jennings & Knight, 1975).

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The scope of this paper is the estimation of hydroconsolidation susceptibility of Thessaloniki's historical fill formations through laboratory simulation for the interpretation of settlement measurements at a building of the historical centre of the city.

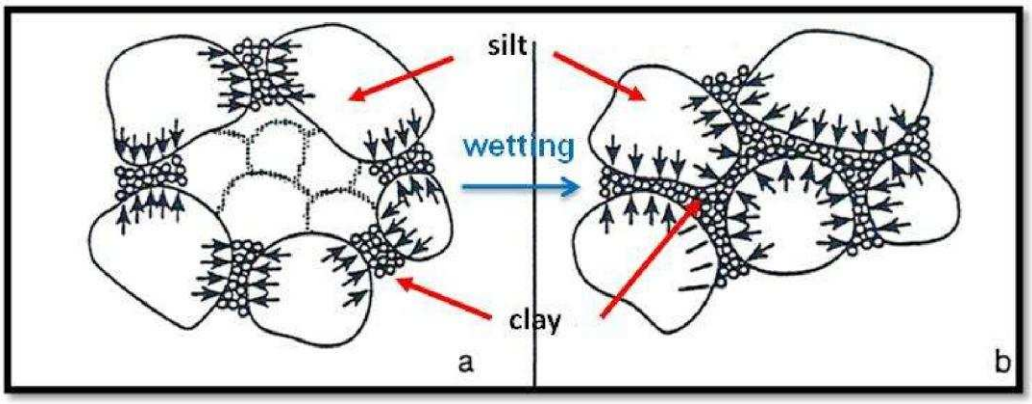


Figure 1.Collapse of a soil structure under load due to wetting (Knight, 1961).

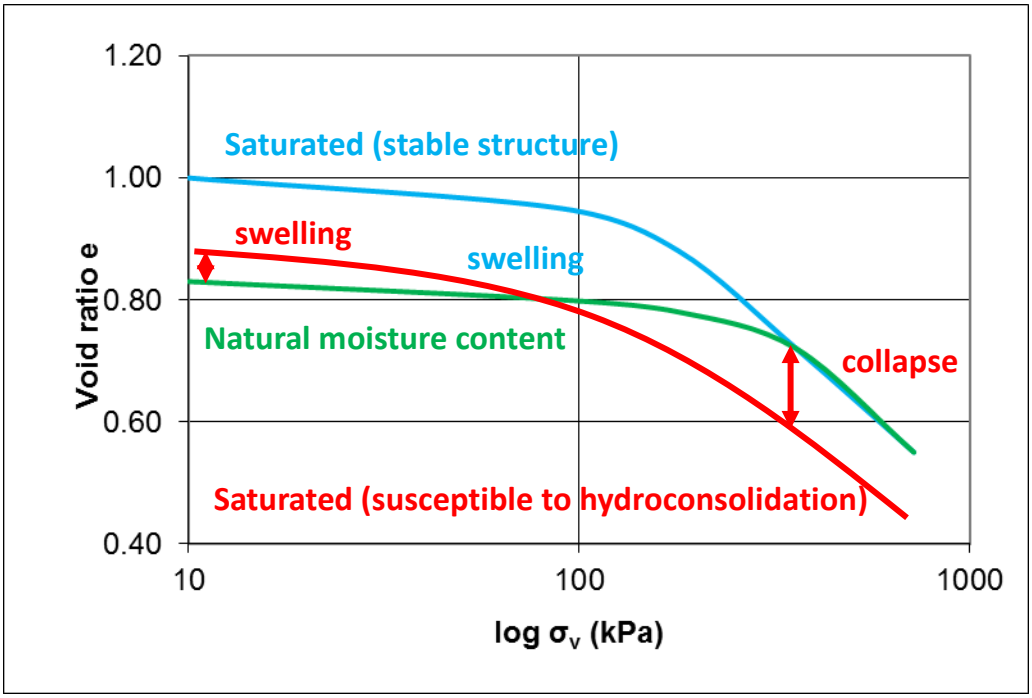


Figure 2.Soil swelling and collapse behavior after wetting under constant load (modified from Jennings & Knight, 1975).

SETTING

Location

The area of investigation is adjacent to the construction site of the "Agia Sofia" station of Thessaloniki's Metro. During the construction of the station's north diaphragm walls displacements were observed on an adjacent block of flats at the corner of Agia Sofia and Egnatia streets (building E73). The displacements resulted in the deflection of the building towards SW. Systematic measurements of the displacements on the foundation ground were carried out to investigate the phenomenon as well as measurements of the groundwater level in piezometers of the construction area as shown in Figure 3.

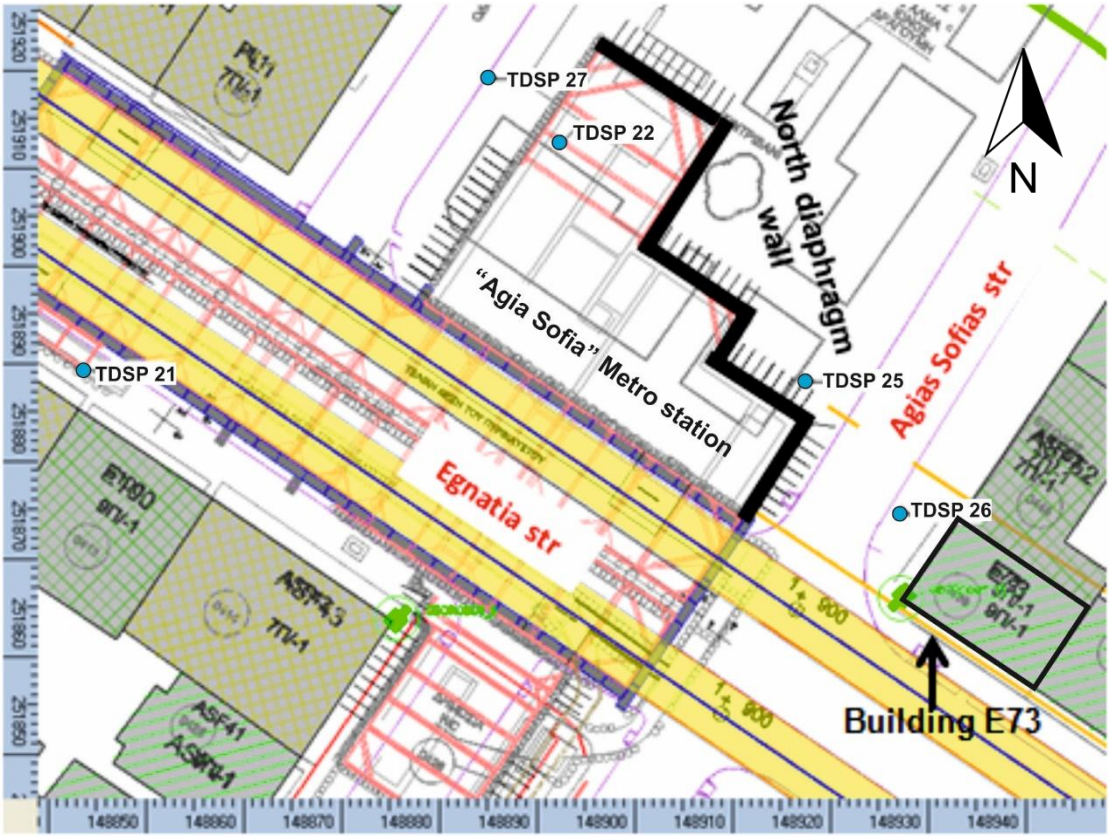


Figure 3.Planar view of the construction of diaphragm walls and piezometers (TDSP 21-27) in "Agia Sofia" Metro Station, along with building E73.

Geological and geotechnical conditions

The general stratigraphy of the area comprises of the red clays formation which underlies the recent Quaternary deposits and the historical fill, which is the foundation layer of the majority of the buildings in the historical centre of the city. This layer is an extremely heterogeneous formation of substantial thickness that has been formed by anthropogenic activity and consists generally of soil, building materials as well as backfill. The layer's thickness varies locally from 2-13 m without a specific pattern. The layer's characteristics pose serious problems in the assessment of its mechanical properties in terms of construction design parameters. It is classified as SM-CL according to USCS, has a relatively high void ratio (0.65-1.1) and moisture content ranging 15%-25%. The Neogene red clays formation is the main geological formation overlying the gneisses and green-schists of the bedrock. As shown in Figure 4, the clays follow a terraced pattern parallel to the former (natural) coastline of the city, which is due to the NW-SE faults of the bedrock (Chatzigogos et al, 2006).

The data used in the analysis were obtained by exploration boreholes that were drilled for Thessaloniki's Metro in the study area. Based on these data the historical fill has a local thickness of 9-10 m whereas the Quaternary deposits that are encountered only at the western part of the study area overlying the red clays have a thickness of 3 m. This stratigraphy forms a perched water table in the historical fill as shown in Figures 5 and 6, with an underground flow direction NE-SW that follows the morphology of the red clays. The underground flow is oriented by a backfilled underground flow network formed on the red clays that were in the past, before urbanization, the surface level formation. Figure 5 shows a map of the isodepth curves of the red clays formation which is the natural boundary of the historical fill. The groundwater level presents insignificant seasonal changes due to the existing structure that prohibits surface water percolation. As a result an unsaturated zone of significant thickness is created above the groundwater table and the geo-materials of this zone have not sustained any wetting during the past.

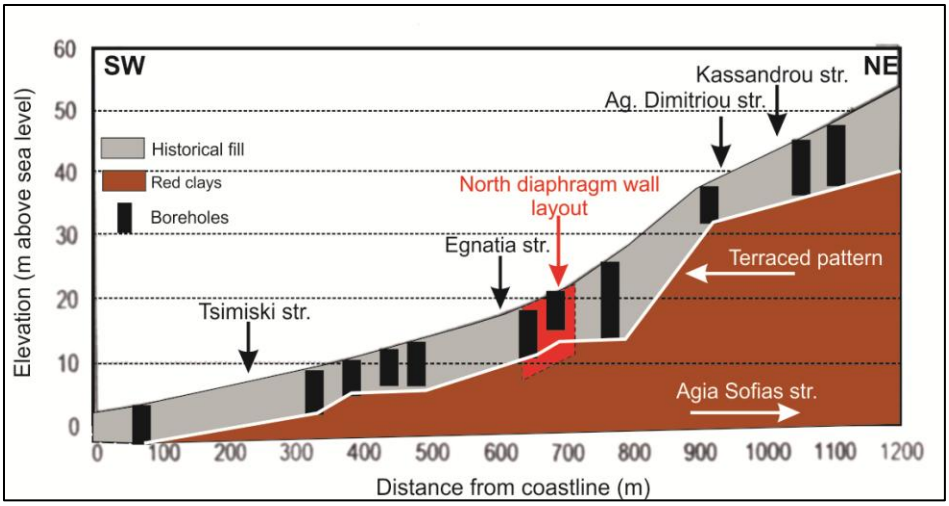


Figure 4. Cross section along Agias Sofias street indicating the terraced pattern of the soil strata underneath the historical fill (modified from Chatzigogos et al, 2006).

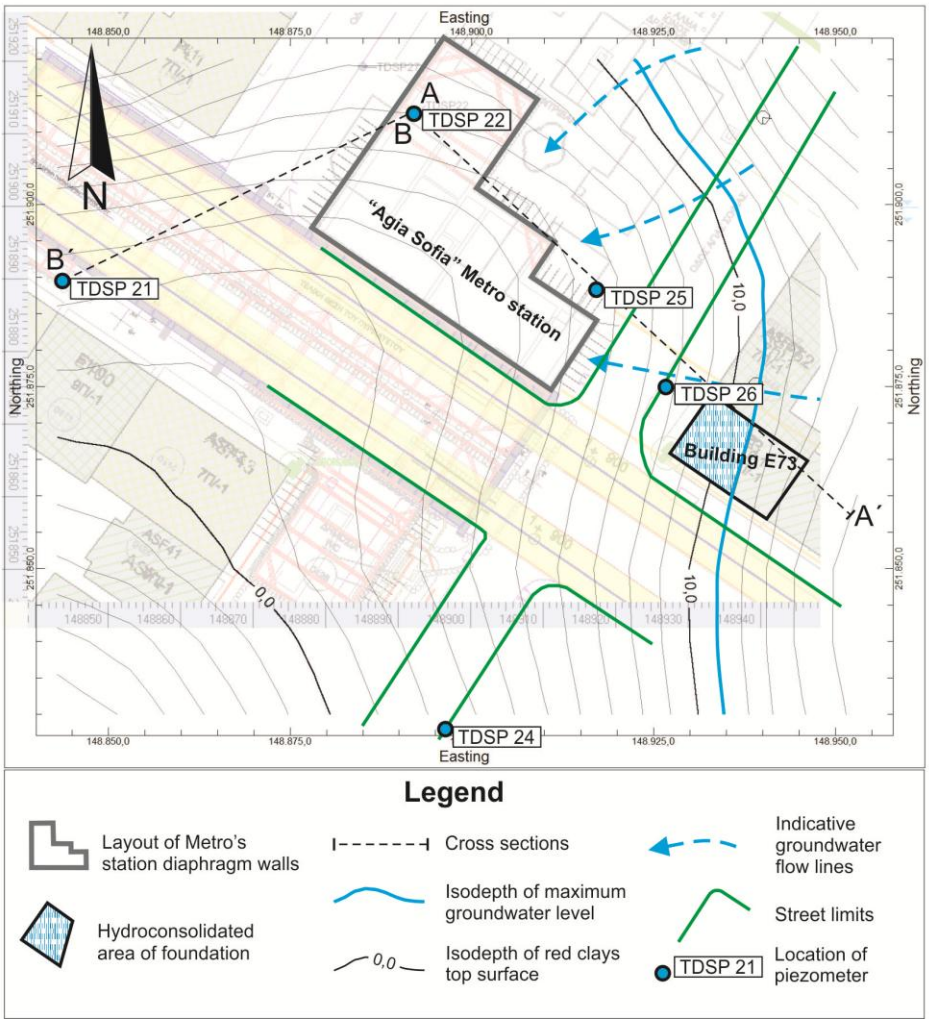


Figure 5. Map of the investigation area with the isodepths of the red clays.

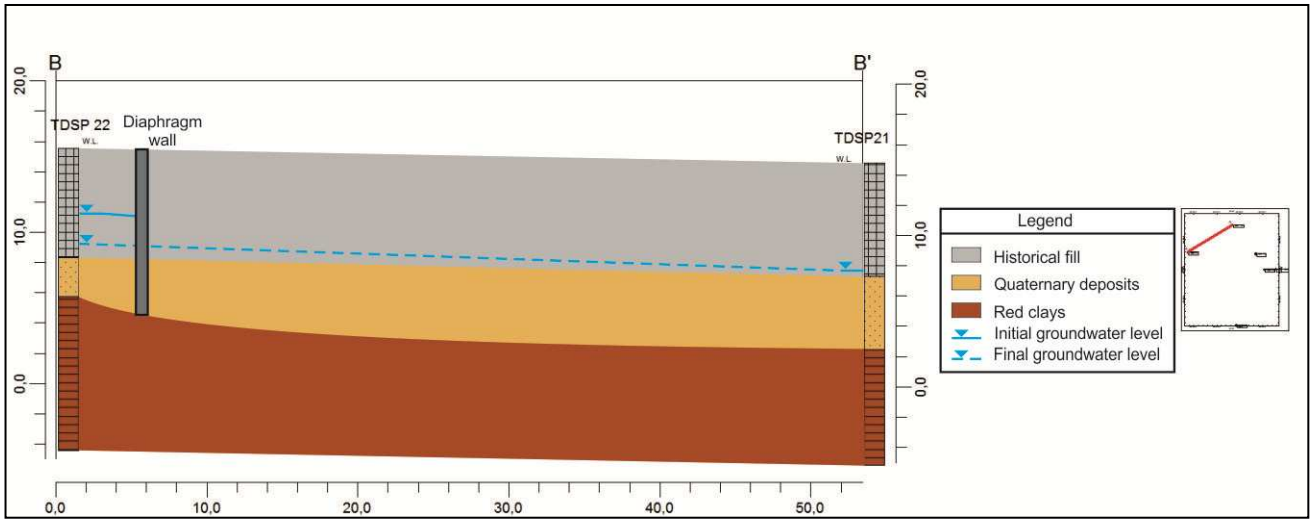


Figure 6.Geological cross section in NE-SW direction along boreholes TDSP22-TDSP21.

Background

The works in the station begun with the construction of the northern side diaphragm walls. This created a cutoff barrier to the underground flow of the perched water table resulting to a significant local rise in piezometers TDSP22, TDSP25, TDSP26 and TDSP27 shown in Figure 7, as water flow is bypassing around the diaphragm walls. After the bypass to the SW the water level drops back to the normal level and that is why no rise is detected in piezometers TDSP21 and TDSP24 that are located S-SW of the diaphragm walls. The total rise reached 1.5 m and displacements - settlements were simultaneously observed on the aforementioned building (E73) at the corner of Egnatia and Agia Sofia streets. These displacements resulted in a deflection (inclination) of the building towards Egnatia str. (the free face of the building). The displacement reached 30 mm in a time period of 3 years starting from September 2008 (Figure 8). An additional issue that required interpretation was that the displacements did not affect equally the entire area of the building foundation but only its W-SW section and they were observed during a rise and not a drop of the groundwater level.

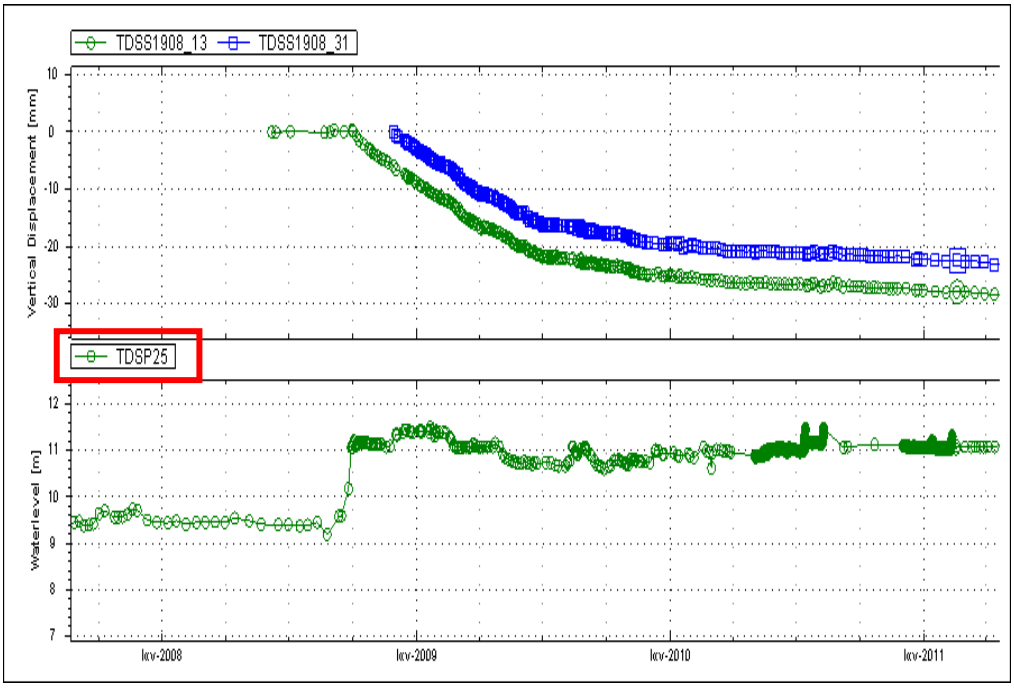


Figure 7.Settlement in building E73 following the rise of the water table (borehole TDSP25).

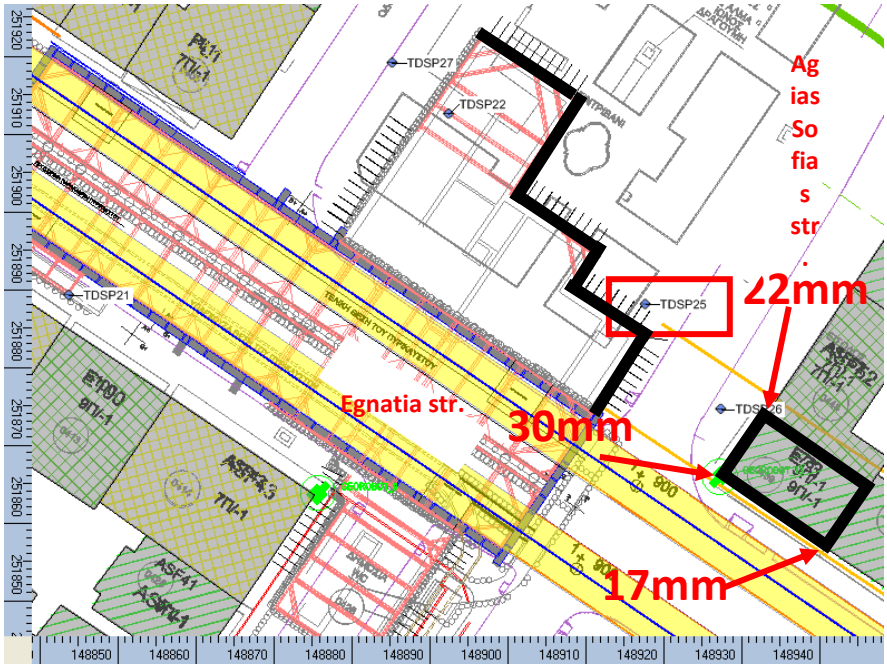


Figure 8.In situ measurements of vertical displacements .

METHODOLOGY

The displacements observed during the rise of the groundwater level in the historical layer are clearly due to the layer's hydroconsolidation given that they were manifested with no load change whatsoever. For the investigation of the problem a laboratory test program was carried out to simulate the hydroconsolidation susceptibility of the historical fill using representative samples from nearby boreholes.

A series of soil consolidation tests was carried out to determine the soil volume change during wetting under constant load. The specific loads were initially applied on samples with their natural moisture content and the samples were subsequently inundated until saturation (Brandon et al, 1990). Thus it was possible to calculate the change in void ratio (or strain) ε_w due to wetting only. The complete series of tests produced the axial strain ε_w - axial load σ_v curve for various loads, which illustrates the susceptibility of the tested material to hydroconsolidation. The respective change of ε_w for sedimentary soils unsusceptible to hydroconsolidation results in swelling following soil wetting.

Following the test program the expected settlements due to hydroconsolidation were calculated using Settle 3D software. The calculations were based on data of the hydroconsolidation characteristics from the laboratory tests combined with the geological model of the area. Finally the calculated settlements were compared to the in situ measured displacements.

RESULTS

The test program was carried out for samples from the historical layer and Table 1 presents the results for ε_w values due to wetting of the samples under constant load. Figure 9 shows the change of void ratio due to hydroconsolidation of sample 4 for constant load (200 kPa) during wetting. The results of Table 1 produced the characteristic hydroconsolidation curve of the studied layer as seen in Figure 10, which describes the volume change behavior of the layer after wetting under constant load. There is swelling of the layer for stress <95 kPa and volume decrease for stress >95 kPa. As an example, the volume change calculated due to wetting under constant stress of 400 kPa is ε_w=4.1%.

Table 1. Laboratory tests results of hydroconsolidation properties.

Sample	Depth (m)	γ (kN/m^3)	γ_d (kN/m^3)	w (%)	e	S (%)	σ_v (kPa)	ε_w (%)
1	2.5	16.7	13.4	24.60	1.01	65.76	100	0.10
2	4.3	15.8	12.6	24.98	1.14	59.16	100	0.15
3	6.4	19.0	15.3	24.10	0.76	85.62	100	0.20
4	2.6	16.3	12.9	26.10	1.09	70.47	200	2.49
5	6.7	19.0	16.1	18.01	0.67	72.58	200	1.81
6	2.2	18.3	15.4	18.80	0.75	67.68	300	2.14
7	2.9	17.7	14.2	24.06	0.89	72.99	400	4.11
8	6.2	17.0	13.6	24.72	0.98	68.11	400	4.48

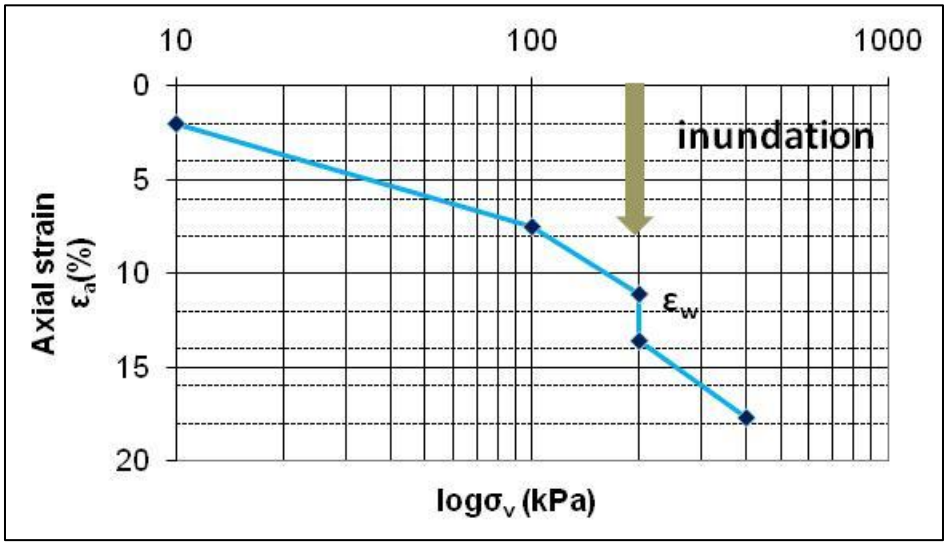


Figure 9.Axial strain due to wetting under constant load of 200 kPa.

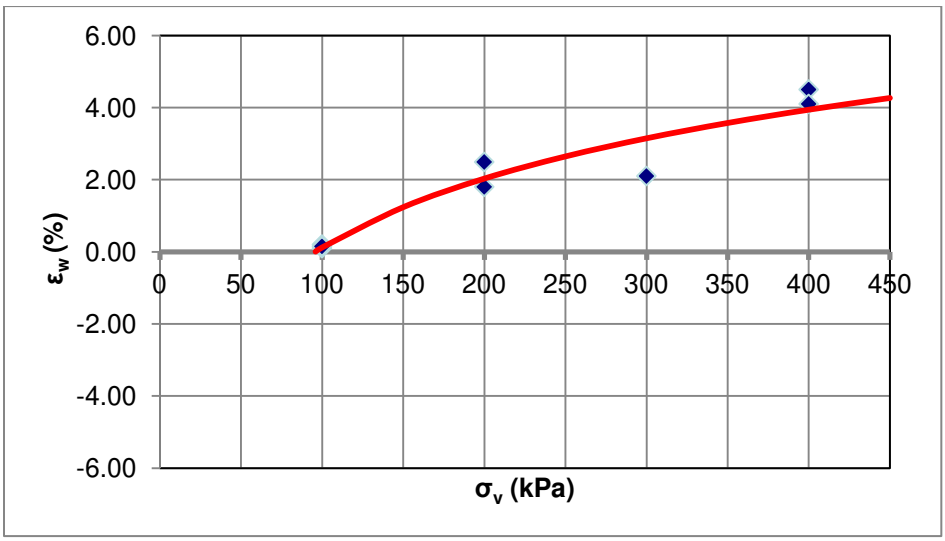


Figure 10.Axial strain due to wetting of Thessaloniki's historical fill at different stresses

The in situ measured displacements shown in Figure 11 correspond to a maximum deformation of approximately 2.25% due to hydroconsolidation for a groundwater level rise of 1.5 m. The maximum displacement measured at the SW corner of the building for a time period of more than 5 years is 34 mm and still increases. Despite the fact that all measuring points show different magnitude of displacement they all produce displacements of relatively high rate for the initial 9 months and then the rate decreases dramatically. The same mechanism is displayed in the displacement-time curves after inundation in the laboratory tests in Figure 12. An initial deformation at high rate takes place representing the collapse of the structure after wetting and then the soil is consolidated at a much slower rate.

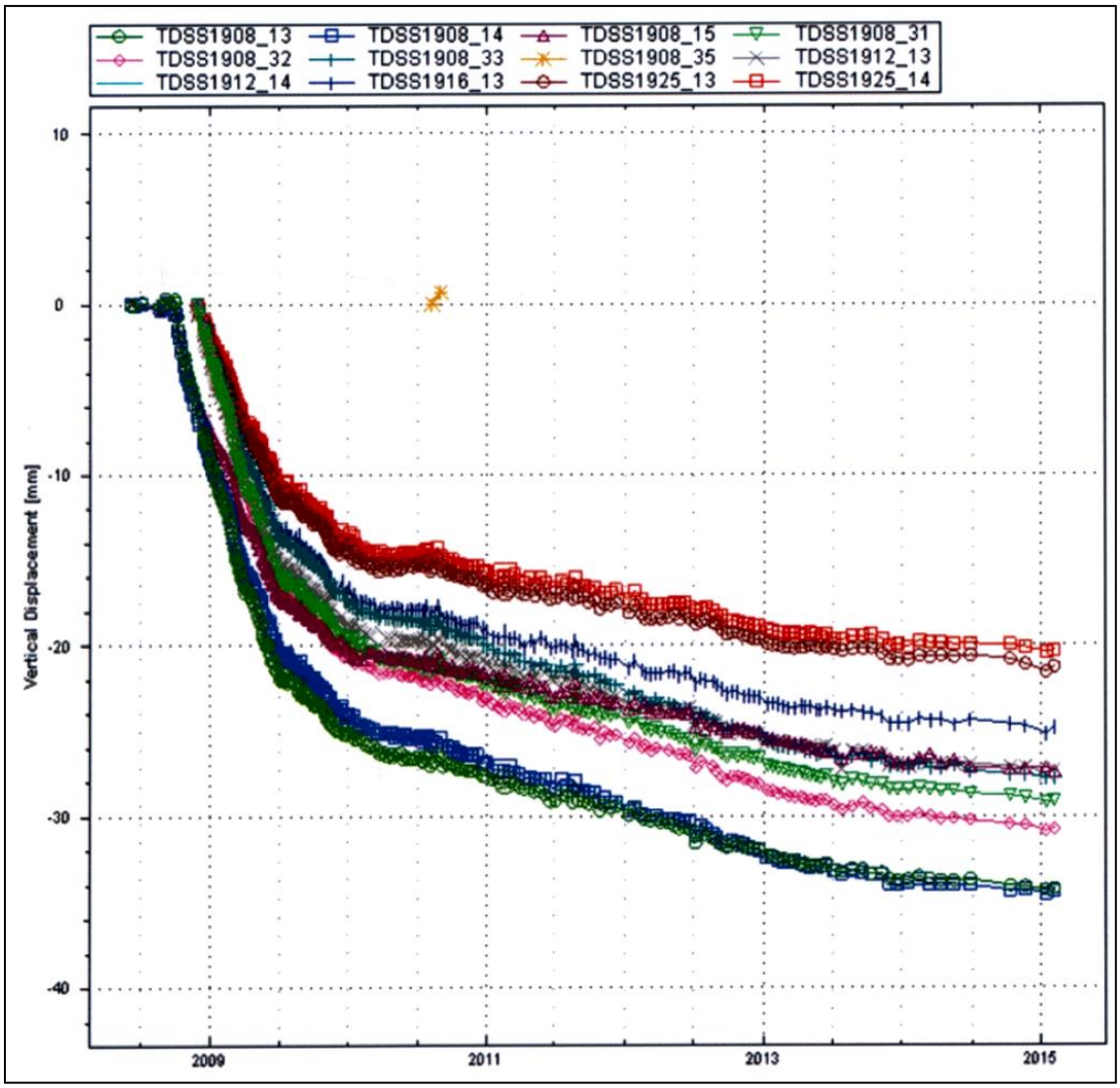


Figure 11. In situ measurements of vertical displacements in the perimeter of building E73.

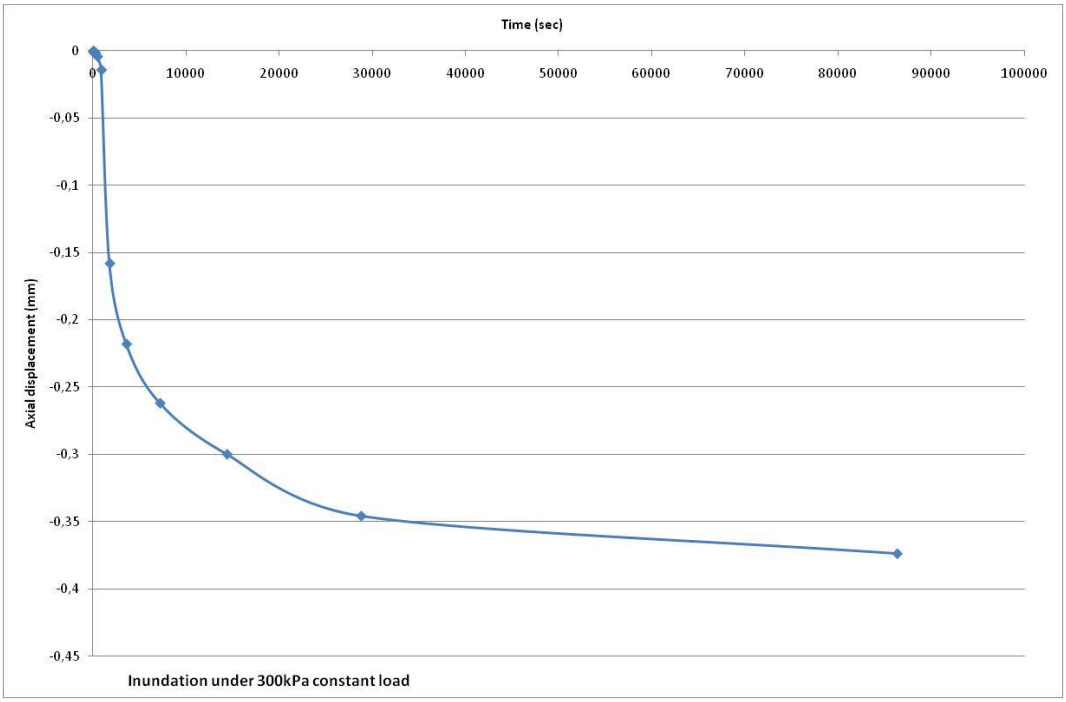


Figure 12. Laboratory displacement-time curves after inundation.

In comparison to the in situ measurements, the anticipated settlements were calculated introducing the layer parameters from the geological model, the groundwater lever rise and the hydroconsolidation characteristics of the layer estimated from the laboratory tests in Settle 3D and the results are shown in Figure 13. As seen from the results there is an uneven distribution of settlements with increased values for the Agia Sofia str. side of the building with a maximum value of 3,75 cm on the SW corner (Figure 13). The Egnatia str. side shows decreasing values of displacements towards E. The calculations correspond to the in situ measurements which also show a gradual decrease of the displacements on the building from SW to NE.

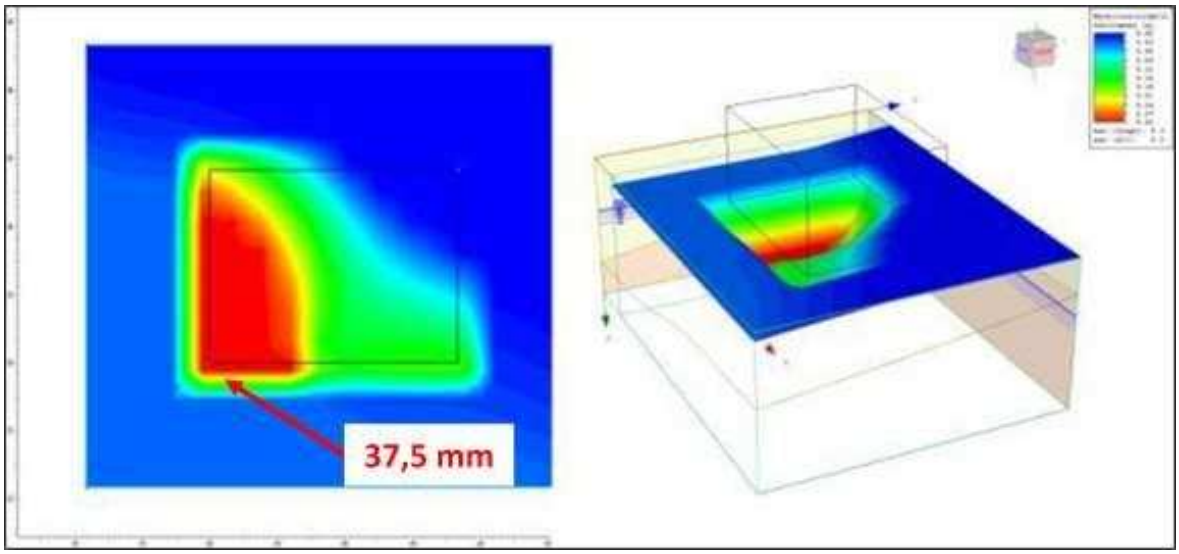


Figure 13. 2D and 3D analysis of hydroconsolidation settlement in building E73.

The differential distribution of settlements is due to the fact that the thickness of the susceptible historical layer (which experienced a maximum groundwater level rise of 1.5 m) is uneven because of its SW dip. Therefore the layer is located

higher towards the NE in respect to the groundwater level and consequently the hydroconsolidated part of the layer becomes less at this direction. Figure 14 shows a characteristic cross section of NW-SE direction that depicts the hydroconsolidated area below the building.

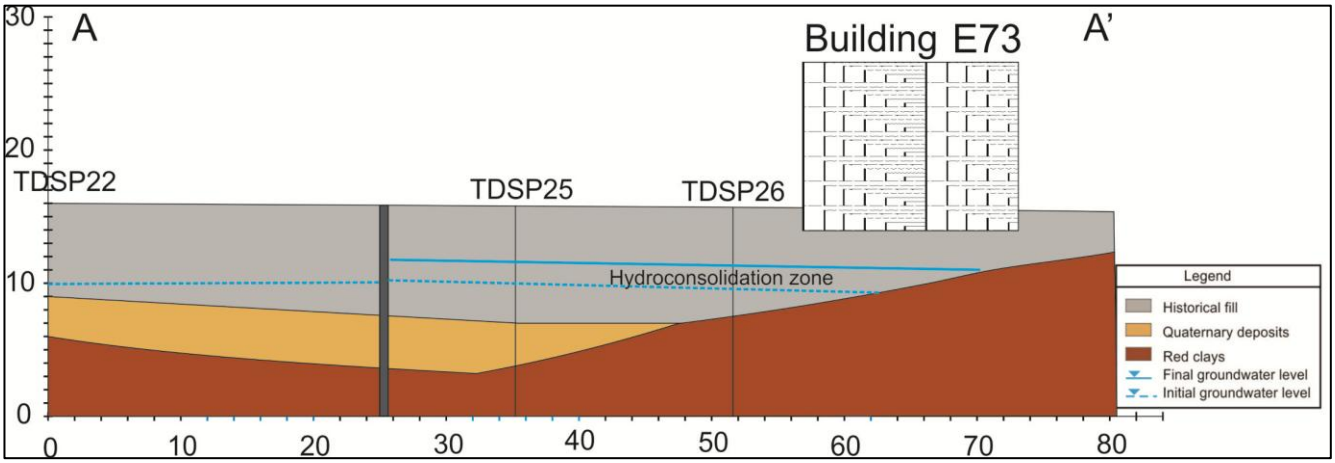


Figure 14. A-A' geological cross-section pointing the hydroconsolidation region.

CONCLUSIONS

Based on the results of this study, the historical layer of Thessaloniki's fill is susceptible to hydroconsolidation. This is due to the layer's formation and the origin of the materials as well as due to the absence of significant changes to its water content in the past. The magnitude of settlements due to hydroconsolidation depends on the thickness of the layer affected by the rise of the groundwater level and the existing stress field. The technical interventions during the construction of Thessaloniki's Metro led to the rise of the groundwater table causing hydroconsolidation and consequent deformations on the foundation ground of a nearby building.

The magnitude of the in situ measured deformations for an estimated local vertical stress of 230 kPa reached a value of 2.25%. The respective laboratory value for similar load was estimated approximately 2.5%. It should be noted that the laboratory test limits the sample deformation in one direction only, thus overestimating the total amount of deformation which in situ occured in three dimensions. In addition to that, a scale effect may be possible since the studied layer is very heterogeneous and contains sizeable objects and materials that cannot be included in laboratory samples (stones, ceramics, etc). Instead of a uniform deformation, the observed differential settlements of the studied layer are mainly due to the layer's geometry (dip to SW) that has a variable thickness and decreases to NE.

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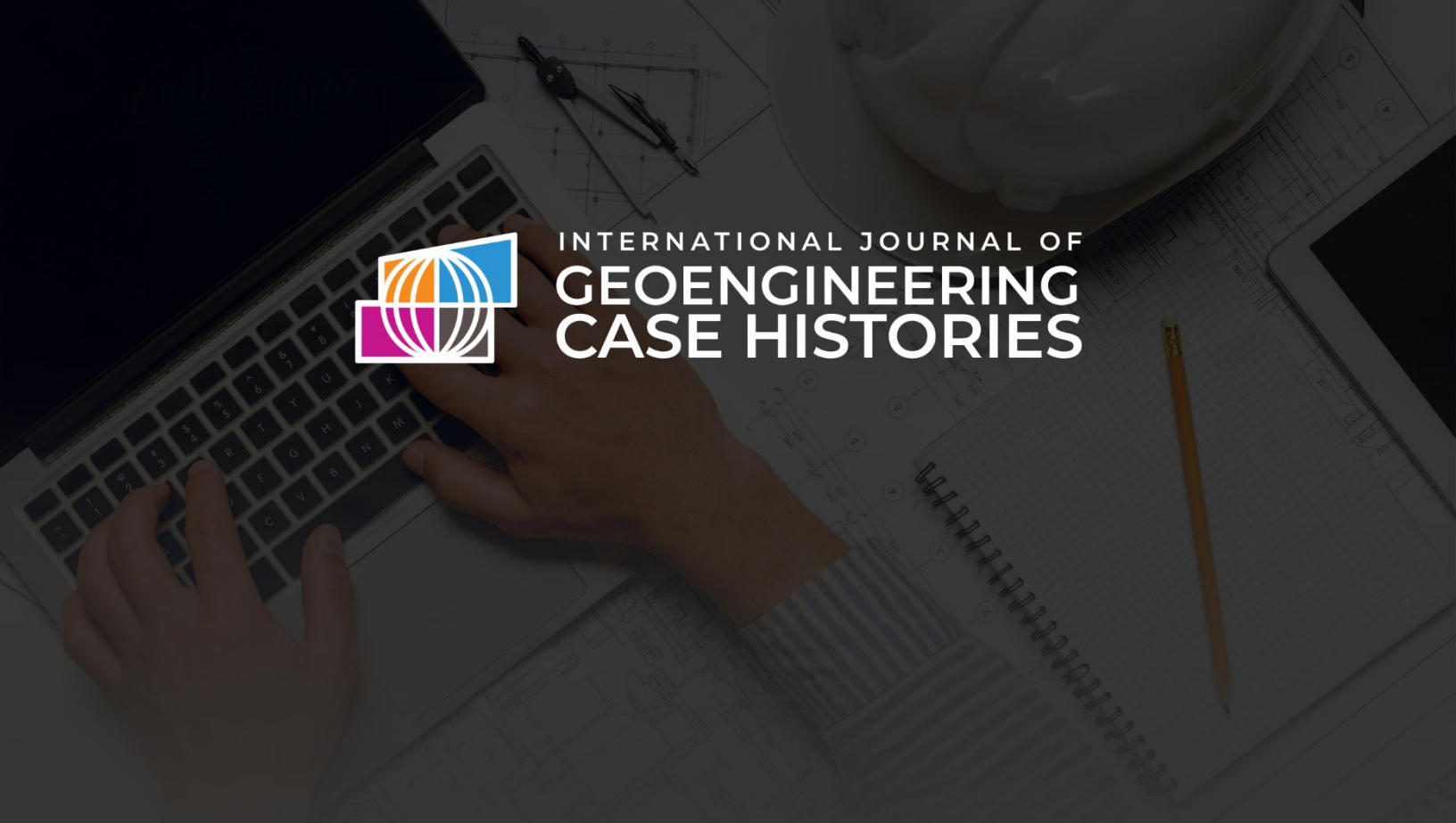
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