Commemorate the Legacy of Ralph B. Peck
April 29 - May 4, 2013 CHICAGO
Seventh International Conference on
Case Histories in Geotechnical Engineering
and Symposium in Honor of Clyde Baker

STRUCTURAL DAMAGE OF A 5-STOREY BUILDING: DIFFERENTIAL SETTLEMENT DUE TO CONSTRUCTION OF AN ADJACENT BUILDING OR BECAUSE OF CONSTRUCTION DEFECTS ?

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ABSTRACT

The paper presents a case history of a 5-storey RC building in Athens (Greece), seriously damaged due to differential settlement. Built in 1968, the damaged structure is founded on spread footings, lying on very soft clayey soil. For more than 30 years, no damage had been observed. In 1999, construction of an adjacent 5-storey RC building begun, and shear cracks started appearing. Inclined at 45^o, the cracks implied damage due to differential settlement. The owners of the damaged building filed a law suit, claiming that the damage was due to additional loading by the under-construction adjacent building. Measurements conducted in 2011, revealed that the differential settlements were of the order of 5 cm. However, the present study also revealed that the damaged building had a number of construction defects, with the most important one being the absence of tie beams. In order to assess the relative importance of the two factors (construction of the adjacent structure vs. construction defects), numerical analyses were conducted modeling both buildings in detail, and taking account of the construction sequence. It is shown that due to the defective foundation of the damaged building, almost 70% (3.5 cm) of the differential settlement had already taken place before construction of the adjacent building. The latter, founded on a slab foundation, settled by about 3 cm, increasing the differential settlement of the damaged building by roughly 1.5 cm. No damage would have taken place, had the building been constructed according to code specifications.

INTRODUCTION–BACKGROUND

The scope of the paper lies in the analysis of an interesting case history, focusing on the interpretation of the observed damage of a 5-storey reinforced concrete (RC) building, referred to hereafter as “Building A”, and its correlation with the construction of an adjacent 4-storey RC building, referred to hereafter as “Building B”. The detailed description of the damage to “Building A”, as well as legal matters, do not fall within the scope of the paper. Moreover, since the relevant Court Appeal is still open, personal data are not revealed.

Built in 1968, Building A is a 5-storey RC structure, situated in the area of Moshato, in Athens (Greece). For more than 30 years no damage had been observed. Construction of Building B started in 1999, and is still incomplete due to the ongoing Court Appeal. As illustrated in **Fig. 1**, Building B is a 4-storey RC structure, practically in contact with Building A on the one side, and with a similar 5-storey RC building of a neighboring Hotel on the other. Its construction started on March 1999, with excavation and erection of its foundation. Early on August 1999, the construction of its RC frame had been completed. Since then, due to the ongoing Court Appeal, the structure remains incomplete.

On July 1999, i.e. just before completion of the RC frame of Building B, cracks started appearing on the infill walls of Building A. Its owners hired a Civil Engineer to investigate the causes of damage and propose remedial measures. After two autopsies (July 16 and 27), two Technical Reports were submitted, describing the observed damage in detail (cracks of transverse infill walls, and distortions of door frames). A little later (August 3, 1999), and after the construction of the RC frame of Building B had been completed, a measurement network was installed on the two buildings and the neighboring Hotel. Displacement measurements were carried out for a period of 2 months (until September 1999), based on which it was concluded that the observed damage on the infill walls of Building A was mainly due to inadequate retaining and extensive dewatering during excavation of the basement of Building B, and – most importantly – differential settlement due to the additional loads of the RC frame of Building B.

Based on the previously discussed technical reports, the owners of Building A filed a law suit against the owners of Building B, demanding a recess of its erection until adequate measures were taken to secure the structural safety of their building. The Court ruled in favor of such a construction recess, and prescribed geotechnical investigation

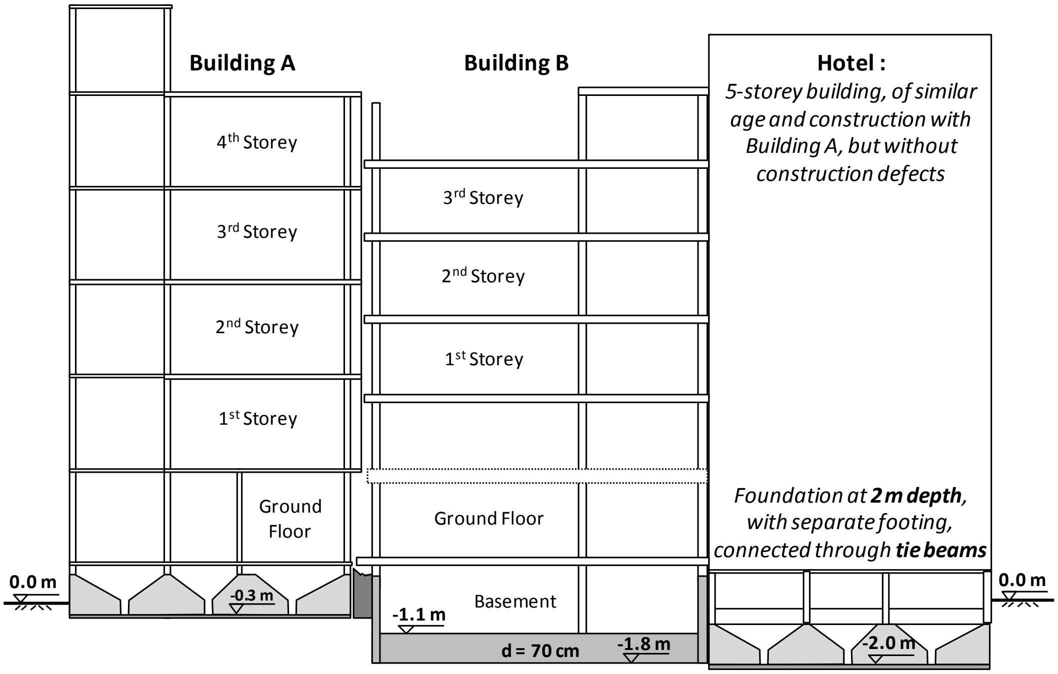

Fig. 1. Sketch showing the damaged Building A, the under-construction Building B, and the neighboring Hotel Building.

In December 1999, the owners of Building B hired a geotechnical consultancy to conduct the Court-ordered geotechnical study. New autopsies and displacement measurements were conducted (January 2000), concluding that the settlement had practically been completed. The observed damage to Building A was attributed to consolidation of the soft clayey soil underneath the foundations of Building A, due to the additional loading by the RC frame of Building B.

On May 2001, the owners of Building B requested an expert forensic investigation by the Technical Chamber of Greece (TCG). The latter concluded that during construction of Building A, its foundation was altered in two crucial points: (a) the foundation depth was decreased from 2 m to just 0.3 m, and (b) the code-prescribed tie beams were not constructed. These two crucial changes, not approved by the town planning authorities, rendered Building A extremely vulnerable to differential settlements, even under "routine cases" such as leakage of the sewer system, changes of the water table depth, any excavation (even for public utilities) adjacent to the building, or seismic shaking (even of low intensity). The weakness of the foundation system of Building A is further exacerbated by the lack of RC beams in the transverse direction of its RC frame (**Fig. 2**). The latter was found to be inadequate for seismic actions, as it had been designed for smaller seismic coefficient than the one prescribed by the seismic code of 1959 (ε = 0.04 instead of 0.08). It was therefore deemed to be an "unsafe" construction, independently of the erection of Building B. Nevertheless, construction of the latter should not be reinitiated before measures were taken to strengthen the defective foundation and RC frame of Building A.

On November 2004, the owners of Building B hired another geotechnical consultancy to undertake a geotechnical investigation. A 30 m deep borehole was conducted in front of Building B, revealing that the first 15 m consist of soft clayey silt, reaching stiff sandstone at 26 m depth. The depth of the water table was found at 1.2 m depth, i.e. 1.5 to 2 m from the ground surface. On February 2005, the owners of Building A hired another consultant to reevaluate the damage and propose corrective measures. The observed damage was once more attributed to the settlement due to the additional loads of Building B, and to inadequate retaining of the 1.5 m deep excavation for the basement of the latter.

FORENSIC INVESTIGATION

The forensic investigation presented herein was conducted during 2011 (from March until October), and is part of the ongoing Court Appeal. Three autopsies were conducted (March, July, and October 2011), and internal floor measurements were taken on July 2011. In combination with the available data and technical reports, the main findings are summarized below.

<u>Building A</u>
Built in 1968, Building A is a 5-storey RC structure, founded on separate footings without tie beams, resting on a 15 cm thick RC slab. The reinforcement of this slab is not known, but

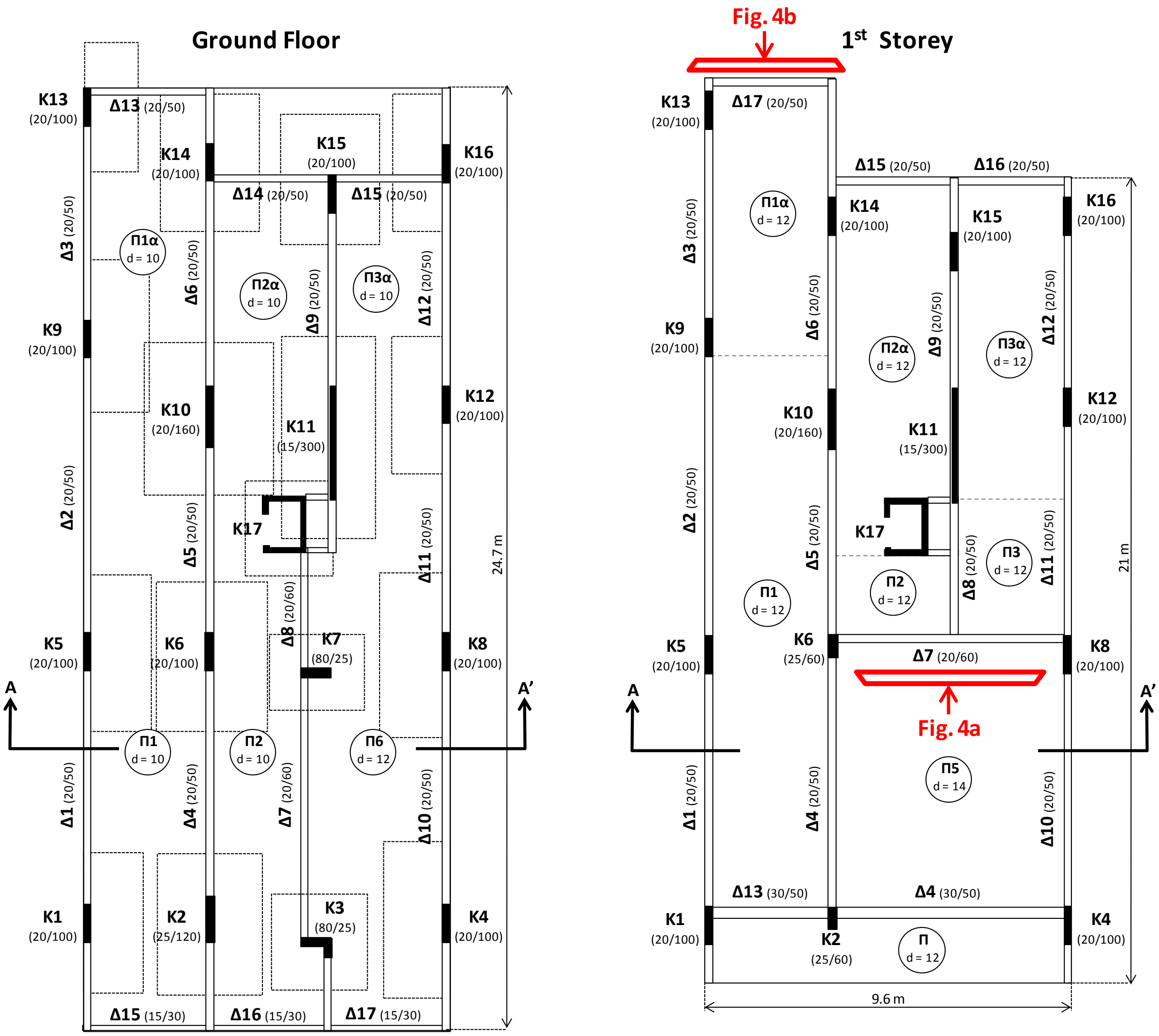

Fig. 2. Plan view of the ground and 1st floor of Building A, showing the locations of the photos of Fig.4.

according to common practice it should be very light. Therefore, it cannot be considered capable of providing any appreciable stiffness to the foundation system. As constructed, the foundation is practically on the ground surface, at a depth of barely 0.3 m. According to the building permit, the footings should be at 2.2 m depth, connected through 20 cm x 50 cm (width x height) RC tie beams. As pointed out by the TCG, and as it will be proven in the sequel, these two–unauthorized –changes rendered Building A extremely vulnerable to differential settlements.

In the transverse direction, the RC frame has four column rows, spaced at roughly 3 m. As a result, the footings (especially the ones closer to Building B) are almost in contact: the distance between two adjacent rows is no more than 30 cm (**Fig. 2**). In such cases, a grid or a slab foundation is typically preferred. As also pointed out by the study of the Technical Chamber of Greece, the RC frame was designed using a reduced seismic coefficient $\varepsilon = 0.04$, instead of 0.08 that was prescribed by the 1959 seismic code that was in effect in 1968 for poor soil conditions. As a result, the corner columns K1, K4, K13, K16 are insufficient. Moreover, with the exception of two faces of the building, in the transverse direction there are no beams connecting the columns (**Fig. 2**). As a result, no frames are formed in the transverse direction, exacerbating its inherent weakness due to the aforementioned unauthorized foundation modifications, rendering the building excessively flexible in the transverse direction and therefore extremely vulnerable to differential settlements. The importance of the absence of frames is confirmed by the absence of cracks in the front face of the building, where beams have been constructed, despite the fact that this is where the maximum differential settlement is observed.

Building B

As previously mentioned, Building B is a 4-storey RC structure, founded at 1.8 m depth through a 70 cm thick RC slab (**Fig. 1**). According to the building permits, its foundation should consist of a foundation grid. However, during construction, and after finding out that the foundation of Building A was practically at the ground surface, the Supervising Engineer decided to alter the foundation system in order to reduce the foundation depth from 2.2 m to 1.8 m. Its RC frame is designed according to modern seismic codes, and includes columns and shear walls in both directions. Its construction started in 1999, and due to the ongoing Court Appeal it has not yet been completed.

Geotechnical conditions

According to the Supervising Engineer of Building B, although no geotechnical investigation was conducted (as it is not mandatory for such buildings), three 10 m–deep boreholes from neighboring larger constructions were available and were taken into consideration. Based on those boreholes, the first 5 m should consist of soft clayey silt, followed by medium density silty sand, with the water table being at a depth of approximately 1.5 m from the ground surface. This was confirmed by the later conducted geotechnical investigation at the front of Building B [Triton, 2004], according to which the first 15 m consist of soft clayey silt to sandy silt with gravel, fine sand with silt, and high plasticity silty to sandy clay. At 15 m depth, soft clay is encountered, becoming stiffer at 20 m depth. After 22 m depth the clay contains pebbles and gravel, turning to hard sandstone at 26 m depth. Standard penetration tests (*SPT*) were also executed, according to which N_{SPT} ranges from 2 (first 2.5 m) to 36 (at 25 m depth). Note that down to 15 m depth, the average N_{SPT} is of the order of 10 (**Fig. 3**), implying that the soil is indeed quite soft. The ground water table was found at a depth of 1.2 m from the borehole level, i.e. at depth of 1.5 to 2 m from the ground surface (the borehole was conducted 0.5 m lower than the ground level). Soil testing was also conducted, based on which the compression index C_c is equal to 0.33 at 3 m depth, reducing to 0.24 at 12 m depth, and even further to 0.16 at 18 m depth.

Observed damage

The damage to Building A first appeared in July 1999, just before completion of the erection of the RC frame of Building B, and consequently about 3 months after completion of the basement excavation. Therefore, it would not be reasonable to associate the damage with inadequate retaining during excavation, since in such a case the damage should have appeared much earlier. The damage is mainly in the form of shear cracks on infill walls in the transverse direction and distortions of internal door frames. An example of the observed cracks is shown in **Fig. 4a** (see **Fig. 2** for the exact location). Inclined at approximately 45^o, the observed shear cracks are indicative of differential settlement of the first column row (closest to Building B) with respect to the second one (see also **Figs. 1** and **2**).

In addition to the cracks of the internal infill walls, which are documented in all technical reports, during the present forensic investigation similar shear cracks were detected on exterior transverse infill walls, as shown in **Fig. 4b** (see **Fig. 2** for the exact location). Inclined at approximately 45^o, these cracks are also indicative of differential settlement, but to the *opposite direction*. Therefore, they cannot possibly be related to settlement caused by the additional loading due to construction of the RC frame of Building B. It was therefore deemed necessary to measure the deformation of Building A.

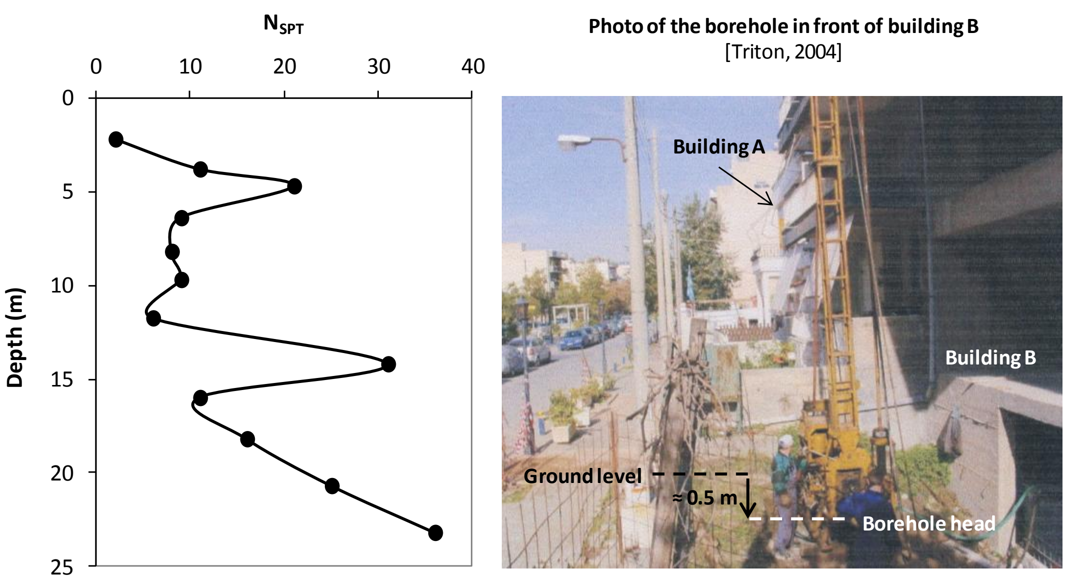

Fig. 3. Distribution of N_{SPT} with depth and photo of the borehole in front of Building B [Triton, 2004].

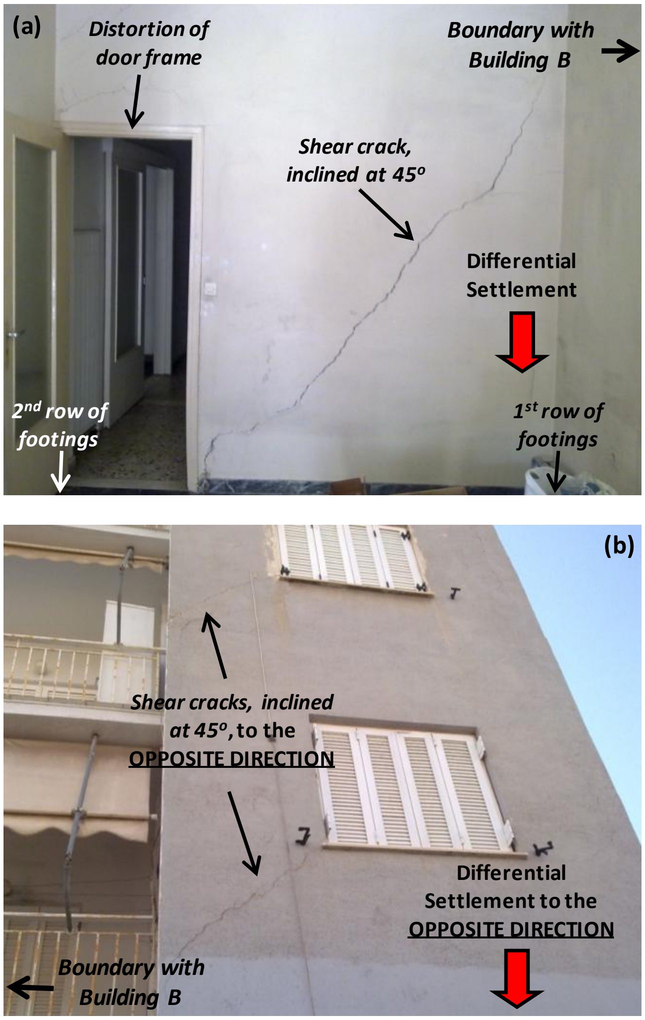

Fig. 4. Observed damage: (a) photo of internal transverse wall, showing shear cracks and door frame distortions; and (b) photo of external transverse wall showing shear cracks to the opposite direction.

On July 2011, precision leveling measurements were conducted inside Building A, on the slabs of the 1st, 2nd, and 4th floor. Based on these measurements, the maximum height difference on the first floor is about 5 cm. As sketched in **Fig. 5,** having the stairway as a reference, the maximum relative settlement of 5 cm is observed at the boundary with Building B at the front wall of the building. A smaller relative settlement of 2.4 cm is observed at the opposite side of the building. Note that this differential settlement is to the opposite direction, and cannot possibly be attributed to the settlement of Building B. Evidently, the observed cracks of **Figs. 4a** and **4b** are totally compatible with the precision leveling measurements. It should, however, be noted that the height differences measured through internal precision leveling are not necessarily exactly equal to the differential settlements, as they may be partly due to construction "flaws" of the floors.

Based on the observed cracks, in conjunction with the aforementioned precision leveling measurements, it may be concluded that Building A suffers from: (a) differential settlement of the order of 2.5 cm due to its own weight, as evidenced by the cracks of **Fig. 4b** and the measured height differences of the floors; and (b) differential settlement of the order of 2.5 cm due to the additional settlement of Building B, as evidenced by the cracks in **Fig. 4a** and the measured height differences of the floors. It is therefore reasonable to assume that the total measured differential settlement of approximately 5 cm is due to the superposition of the two above differential settlements.

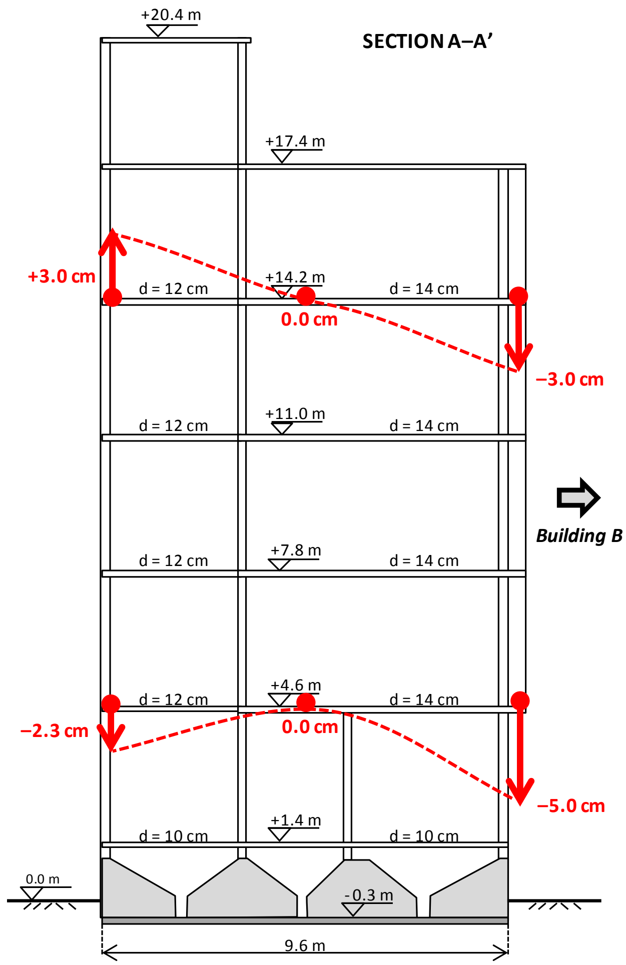

Fig. 5. Section A-A' of Building A, showing the key results of internal precision leveling measurements (July 2011).

The differential settlement due to the dead load of Building B took place many years ago (since 1968), and were probably not perceived by the owners since no noticeable damage to infill walls had taken place. Based on the generally accepted limits of angular deformation D/L = 1/300, above which damage of infill walls should be expected, for a distance $L \approx 6$ m (from the center of the building to its edge), a differential settlement D > 2 cm is required for cracks to start appearing on infill walls. Furthermore, since a good part of this differential settlement occurred during the erection of the RC frame of Building A, and thus prior to construction of its infill walls, it is totally reasonable that no damage had been observed for nearly 30 years. When the differential settlements due to construction of Building B took place, their superposition with the already existing differential settlements due to the dead load of Building A resulted to the appearance of the observed damage: $D \approx 2.5 + 2.5 \approx 5$ cm, so $D/L \approx 1/125$.

As it will be proven in the sequel, both older (due to its own weight) and more recent (due to erection of the RC frame of Building B) differential settlements would not be that large, if the foundation and the superstructure of Building A were not so flexible: i.e., if the tie beams had not been eliminated, and if the RC frame had beams in the transverse direction.

NUMERICAL ANALYSIS

To determine the causes of damage and quantify the relative contribution of the additional loading due to construction of the RC frame Building B as opposed to the construction defects of Building A, the entire construction sequence is analyzed employing the finite element (FE) method. The entire construction sequence is simulated, from the construction of Building A (in 1968), to the construction of the RC frame of Building B (in 1999). As shown in **Fig. 6**, the entire soil–foundation–structure system is analyzed, including the three neighboring buildings: Building A, Building B, and the Hotel. The latter is a 5-storey RC building of similar age, construction typology, and total height (and therefore of similar total dead load) with Building A, but having two very significant differences: (a) its separate footings are founded at 2 m depth (i.e., where the foundations of Building A should also lie), and (b) the footings are connected with RC tie beams (as the footings of Building A should also be).

In other words, the neighboring Hotel is a very similar building from all points of view, but does not have the construction defects of Building A. Since the Hotel has not suffered from any damage, it is reasonable to assume that these two differences may have played a key role. To quantify the influence of the construction defects of Building A, the adjacent Hotel is modeled as an idealized structure, identical to Building A (mirror-transposed with respect to Building B), with the only difference being its foundation. This way, Building A is simulated: (i) as constructed–with a defective foundation system, and (ii) as it should have been constructed according to the approved building permit.

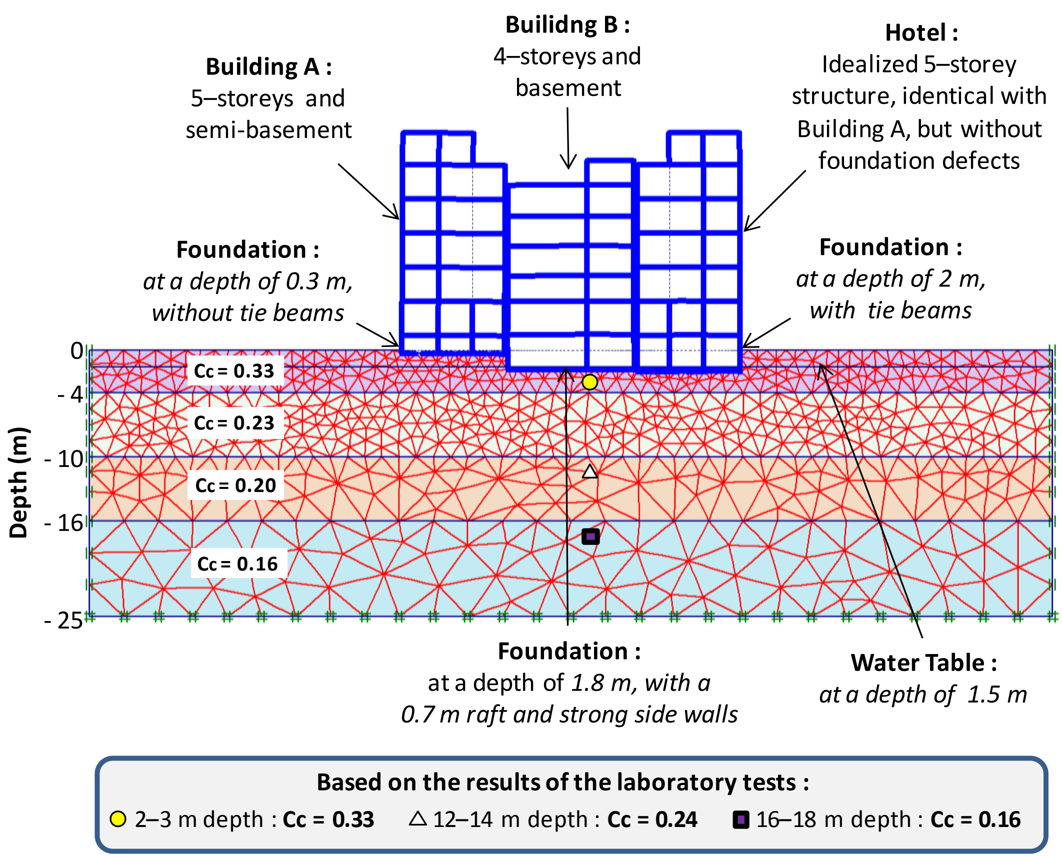

Fig. 6. Finite element modeling of the three neighboring buildings.

Finite element modeling

The soil–foundation–structure system is analyzed numerically employing the FE code PLAXIS. The analysis is performed in 2D, assuming plane-strain conditions, and considering a representative slice (in the transverse direction) of the three neighboring buildings. The soil is simulated through 15-node plane-strain triangular elements, while the foundation and the superstructure of the three buildings with beam elements. The behavior of both the foundation and the superstructure is reasonably assumed elastic (since the RC frames have no damage), considering a Young's modulus E = 25 GPa for the reinforced concrete. The nonlinear response of the soil is modeled with a Cam-clay model [Butterfield, 1979; Borja & Lee, 1990; Muir Wood, 1990] incorporated in PLAXIS ("soft soil" model). Model parameters are calibrated based on the basis of the aforementioned geotechnical investigation [Triton, 2004], taking into account the stratigraphy of the soil, the depth of water table, the *SPT* results, and of course the laboratory tests, with particular emphasis on compressibility–consolidation tests. Based on the above, the geotechnical profile of **Fig. 6** is considered representative of the soil conditions in the vicinity of the three buildings.

The numerical analysis is performed in 3 consecutive steps:

- **Step 1: Construction of the RC frame of Building A and the idealized building in place of the Hotel.** On each floor of the two buildings a distributed load of 4 kN/m^2 is applied, corresponding to the dead load of their RC slabs (having a thickness of 10 to 14 cm), the columns, and the beams. Additional loads are applied to simulate the dead load of the foundation system. The aim of this step is to estimate the absolute and differential settlements that had taken place during construction of the RC frame of Building A (and of the idealized building at the location of the neighboring Hotel), before construction of the infill walls. Obviously, these differential settlements could not have caused any damage to the infill walls of Building A.

- **Step 2: Completion of Building A and the corresponding idealized building in place of the adjacent Hotel.** Considering a lower estimate for the additional permanent loads (infill walls, floors, etc.), and assuming that only 50% of the design live loads have actually been imposed, on each floor of the two buildings a total distributed load of 8 kN/m^2 is applied. The aim of this step is to estimate the absolute and differential settlements that had taken place due to the overall weight of Building A (and the idealized building at the location of the neighboring Hotel), after construction of the infill walls. It is actually the differential settlement that took place after construction of the infill walls (i.e., the difference of this step to the previous one) that is associated to their deformation, and thus may have lead to damage.

- **Step 3: Construction of the RC frame of Building B.** Since this structure has been designed according to modern seismic codes, most of its structural elements are of substantially increased size, and therefore increased weight (compared to Building A). Therefore, on each floor of Building B a distributed load of 8 kN/m^2 is applied, corresponding to the dead load of the RC slabs (having a thickness of 20 to 25 cm), the columns, and the beams. An additional load is applied to simulate the dead load of the 70 cm thick raft foundation. The aim of this step is to estimate the absolute and differential settlement that took place during the erection of the RC frame of Building B, corresponding to the present situation.

NUMERICAL ANALYSIS RESULTS

The results of the numerical analyses are summarized as follows:

Step 1: Construction of the RC frame of Building A and the corresponding idealized building in place of the Hotel

The results are presented in **Fig. 7** in terms of absolute (marked in red) and differential (marked in black) settlements at characteristic locations of the two buildings (corresponding to the locations of the measurements). Evidently, only with the dead loads of its RC frame, Building A experiences maximum absolute settlement of -2.2 cm (right footing). At the same time, the maximum absolute settlement of the idealized building at the location of the hotel is almost 50% lower: -1.2 cm. Since the two buildings are identical, this difference can only be attributed to the construction defects of Building A, due to which its foundation and superstructure are indeed extremely flexible in the transverse direction.

However, at this stage the differences between the two structures are not that important in terms of differential settlements. Taking as a reference the middle of the building (as for the precision leveling measurements), the left span of the 1st floor experiences differential settlement d = -0.8 cm and the right one -1.2 cm. In the fourth floor, the left span has a relative elevation d = +1.0 cm while the right one +0.6 cm. This strange distribution is due to the elimination of the middle-right column from the first floor and above. Since the infill walls (and the door frames, etc.) have not yet been constructed at this stage, these differential settlements (or elevations) could not have caused any damage.

Step 2: Completion of Building A and of the corresponding idealized building in place of the adjacent Hotel

The results are presented in **Fig. 8** in terms of absolute (in red) and differential (in black) settlements at characteristic locations of the two buildings. Even considering a lower bound estimate for the additional permanent loads (infill walls, floors, etc.), and assuming that only 50% of the design live loads is imposed, Building A is subjected to a maximum absolute settlement of -6.0 cm (left footing) – purely due to its own weight. Correspondingly, the maximum absolute settlement of the idealized building in place of the neighboring Hotel does not exceed -2.4 cm. Evidently, since the two buildings are identical, this major difference is solely

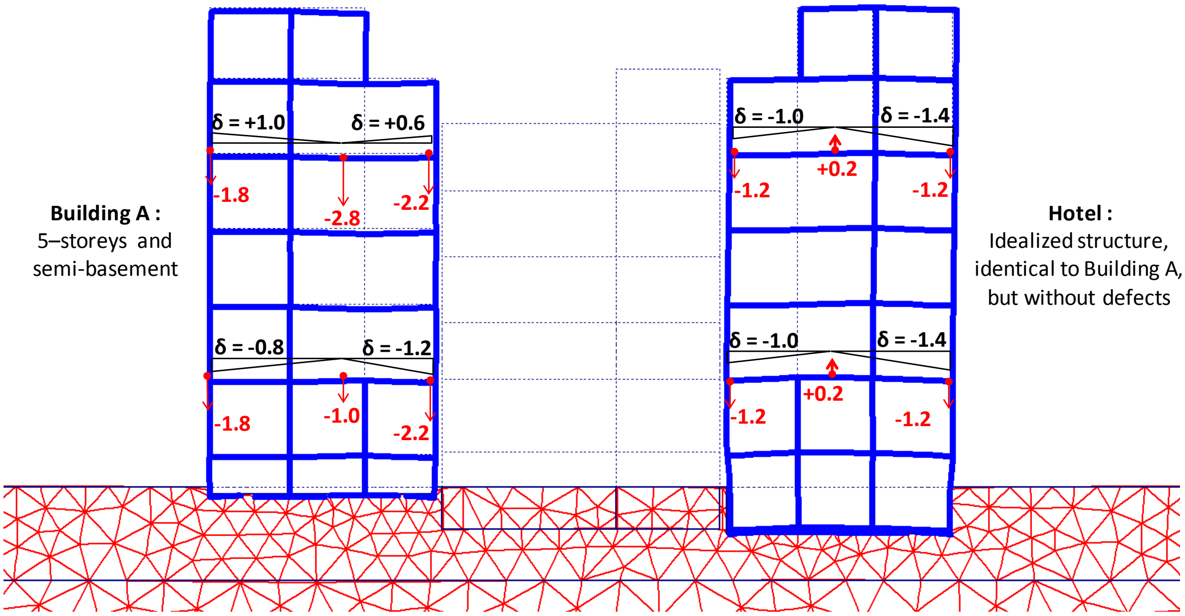

Fig. 7. Numerical analysis results for Step 1 – Construction of the RC frame of Building A and the corresponding idealized building in place of the adjacent Hotel: absolute (in red) and differential (in black) settlements at characteristic locations of the two buildings.

due to the previously discussed construction defects of Building A (completely superficial foundation, lack of tie beams), and the absence of RC beams (and therefore frames) in the transverse direction of its superstructure. As a result, the entire foundation–structure system is excessively flexible, being susceptible to differential settlements.

In contrast to the previous analysis step, the differences between the two structures in terms of differential settlements are quite noticeable. Always taking as a reference the middle of the building, the left span of the 1st floor is subjected to differential settlement *d* = -1.8 cm, and the right one to *d* = -3.5 cm. In the 4th floor, the left span experiences differential elevation *d* = +1.5 cm, while the right one *d* = -0.4 cm. As mentioned above, this peculiar distribution is due to the elimination of the middle-right column from the 1st floor and above. Such differential settlements could have caused noticeable damage to infill walls and door panels. However, since the differential settlements took place gradually during construction, the infill walls were actually subjected to the differential settlements that took place after their construction: i.e., the difference between this step and the previous one. Under this prism, the differential settlements that were actually "felt" by the infill walls of Building A did not exceed -2.3 cm (on its right side, close to the boundary with Building B). Hence, it is quite reasonable that no damage had been observed for almost 30 years.

At this stage, the differential settlements of the idealized building in place of the neighboring Hotel are considerably smaller. Considering as a reference the middle of the building, the left span of the 1st floor experiences differential settlement *d* = -2.0 cm, and the right one *d* = -2.1 cm. In the 4th floor, the left span is subjected to differential settlement *d* = -1.0 cm and the right one to *d* = -1.1 cm. The differential settlements actually suffered by the infill walls (i.e., the difference of this step to the previous one) are substantially lower, not exceeding -0.7 cm – no damage should be expected. Again, since the two buildings are identical, the differences can only be attributed to the construction defects of Building A.

Step 3: Construction of the RC frame of Building B

This final analysis step is of particular importance as it corresponds to the current situation. Moreover, as discussed below, through comparison with the precision leveling measurements, this step also serves as validation of the numerical analysis conducted herein. The results are presented in **Fig. 9** in terms of absolute (in red) and differential (in black) settlements at characteristic locations of the two buildings. Considering a conservative upper bound for the dead loads of the RC frame of Building B, the maximum settlement due to its erection reaches -2.9 cm – totally reasonable for such soft soil. This inevitable (at least with a raft foundation) settlement led to an increase of the settlement of the two neighboring buildings. More specifically, the maximum absolute settlement of Building A is increased to -7.5 cm (as expected, at the boundary with Building B). Note that the increase of the absolute settlement of Building A due to erection of the RC frame of Building B is only -1.5 cm, as Building A had already settled by -6.0 cm due to its own weight (see **Fig. 8**). At the same time, the maximum absolute

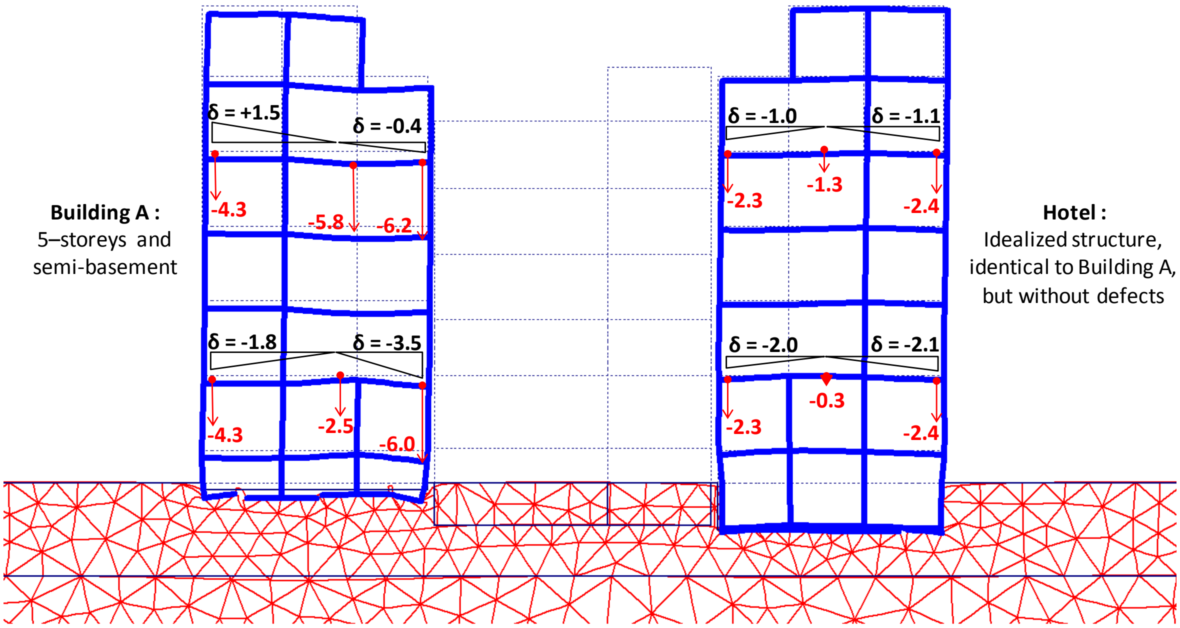

Fig. 8. Numerical analysis results for Step 2 – Completion of Building A and the corresponding idealized building in place of the adjacent Hotel: absolute (in red) and differential (in black) settlements at characteristic locations of the two buildings.

settlement of the idealized building in place of the Hotel does not exceed -3.4 cm, of which only -1.1 cm are due to the additional loading due to the construction of the RC frame of Building B; the remaining -2.3 cm are due to its own eight (see **Fig. 8**). As previously mentioned, since the two buildings are identical, this very substantial difference is due to the construction defects of Building A.

Taking as a reference the middle of the building, the computed differential settlements (or elevations) are directly comparable to the precision leveling measurements. In **Fig. 9**, the measured values are shown in yellow circles to facilitate direct comparison with the numerical analysis results. On the left span of the 1st floor of Building A, a differential settlement *d* = -1.2 cm is computed (compared to -2.3 cm of the measurements); the right span of the same floor experiences much larger differential settlement *d* =-4.9 cm (as opposed to -5 cm of the measurements). Note that this is exactly at the location where the most severe shear cracking is observed (see the photo of **Fig. 4a**). Moreover, notice that the differential settlement of the left span is to the opposite direction, being totally consistent with the observed damage of the outer infill walls (see the photo of **Fig. 4b**). In the 4th floor, the left span experiences differential elevation *d* = +1.5 cm (compared to +3.0 cm of the he measurements), and the right one differential settlement *d* = -2.1 cm (as opposed to -3.0 cm of the measurements). The numerical prediction can be seen to compare adequately well with the measurements qualitatively and quantitatively, confirming the validity of the analysis method and the adopted soil parameters.

As previously discussed, the deformation of the infill walls of Building A can only be associated with the differential settlements that occurred after their construction (i.e., the difference between Step 3 and Step 1). Hence, the differential settlement actually suffered by the infill walls of Building A currently stands at -3.7 cm (close to the border with Building B), and is quite reasonable to have led to the observed damage (shear cracking of infill walls and distortion of inner door panels). Note that from the -3.7 cm of differential settlement, -2.3 cm are due to the dead loads of Building A, and only the remaining -1.4 cm took place during construction of the RC frame of Building B.

As expected, the differential settlements of the idealized building in place of the neighboring Hotel are substantially lower (**Fig. 9**). Taking as a reference the middle of the building, the right span of the 1st floor experiences differential settlement d = -1.5 cm, while the left one reaches -2.9 cm. As for Building A, the stressing of the infill walls is associated with the differential settlement that took place after their construction (i.e., the difference between this Step and Step 1). Thus, the differential settlement that has actually stressed the infill walls of the idealized building currently stands at -1.5 cm (on the left, close to Building B), and hence, it is quite reasonable that no damage has been observed in the neighboring Hotel. Most importantly, since the two buildings are identical (with the only difference lying in the construction defects), this substantial difference in their performance actually suggests that no damage would have been inflicted to Building A had it been properly constructed (i.e., if the previously discussed construction defects had been avoided).

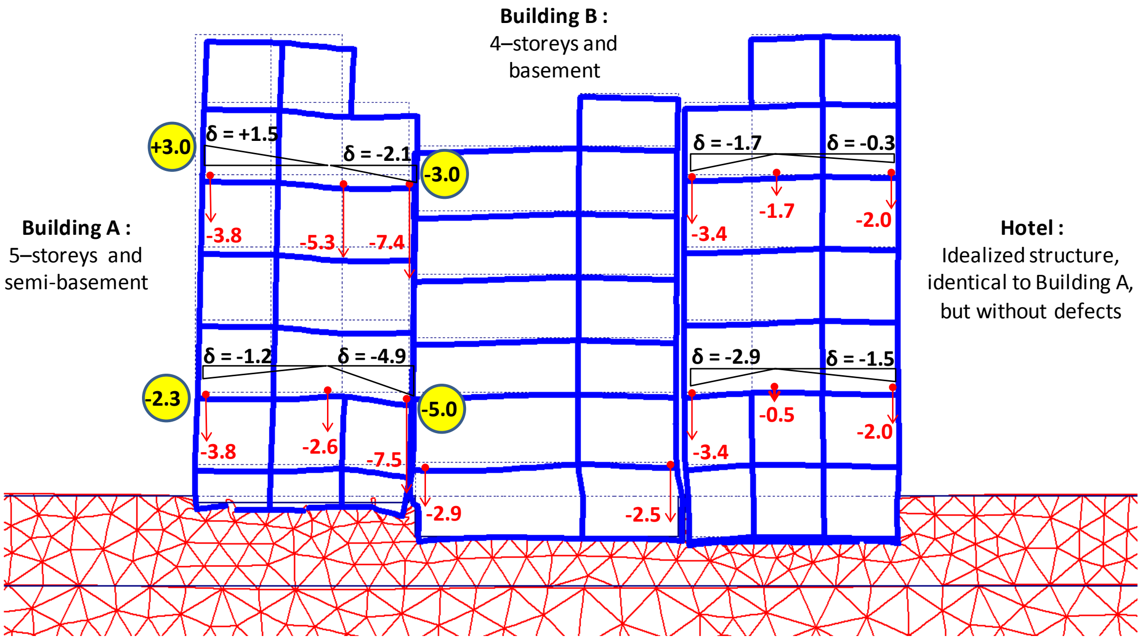

Fig. 9. Numerical analysis results for Step 3 – Construction of the RC frame of Building B: absolute (in red) and differential (in black) settlements at characteristic locations of the two buildings. The values in yellow circles correspond to the measurements.

CONCLUSIONS

Based on the forensic investigation and the numerical analyses, the validity of which is verified through comparison with the measurements (**Fig. 9**), the damage to Building A is primarily due to its construction defects, with the erection of Building B playing a secondary role. More specifically:

- Before the erection of the RC frame of Building B (**Fig. 8**), the maximum settlement of Building A (due to its own weight) reached -6.0 cm, leading to maximum differential settlement of -3.5 cm. Since the latter took place gradually during construction, the infill walls were subjected to the differential settlements that took place after their construction, namely -2.3 cm. Therefore, it is reasonable that no damage had been observed for 30 years.

- The additional loads due to construction of the RC frame of Building B (**Fig. 9**) led to maximum absolute settlement of -2.9 cm – reasonable for such soft soil. This led to an increase of the maximum absolute settlement of Building A from -6.0 cm to -7.5 cm, and to an increase of the maximum differential settlement from -3.5 cm to -4.9 cm. The differential settlement actually suffered by the infill walls of Building A rose from -2.3 cm to -3.7 cm, leading to the observed shear cracking of infill walls.

- If Building A had been constructed properly–without construction defects, no damage would have been observed. The maximum absolute settlement due to its own weight would not exceed -2.3 cm (**Fig. 8**), accompanied by maximum differential settlement of -2 cm.

- After the erection of the RC frame of Building B, the maximum absolute settlement would increase to -3.4 cm (**Fig. 9**), accompanied by maximum differential settlement of -2.9 cm (almost 50% lower). The differential settlement actually suffered by the infill walls of Building A would rise to -2.2 cm, not leading to observable damage.

- This is confirmed by the observed performance of the adjacent Hotel, which is of similar age and construction typlogy with Building A, but hasn't any construction defects (it is founded at about 2 m depth instead of 0.3 m, and its footings are connected with tie beams), and hasn't suffered any damage.

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