Settlement of Shallow Foundations on Sand Overlaying Compressible Clay, Part- I

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ABSTRACT
A group of (29) residential Buildings were built in New Demmiat City, which locates on the north of Delta of River Nile at the coast of the Mediterranean Sea, Egypt. Soil stratification was very complicated due to existence of fat compressible silty clay layers which have very low shear strength and high compressibility. The buildings consist of five stories with very rigid reinforcement concrete raft foundations. Subsurface soil consists of sand layers in medium dense state of relative density from ground surface down to an average depth of 10.0 m overlaying silty clay layers extended down to depth more than 30m. After determining soil properties the settlements could be estimated under several points of the building. The maximum calculated settlements ranged between 10cm and 33cm according to shape and dimensions of the building. These settlements will occur through tens of years according to the calculated rate of consolidation. Hence, it was recommended that construction works should be slow and all the buildings should be put under observation to measure the settlement behaviors during and after construction. The measurements, mentioned here, belong to 29 buildings covering the duration of construction stage, about 24 months and one year later. These measurements have shown that settlements of the chosen buildings mostly uniform. The rate of settlement was much more than the estimated. It was believed that these settlements were referred to the total settlement included immediate and consolidated because of the slow rate of construction. The shape of average settlements for the buildings group was very interesting similar to a huge raft. Therefore, this study was carried out to investigate the suitable method for determining rate of consolidation in the light of the lab test results and field measurements. The validity of the method mentioned by Polous (2000) for estimating the equivalent coefficient of consolidation was discussed in the light of field measurements.

RESUME
Un groupe de (29) Bâtiments résidentiels ont été construits à New Demmiat City, qui se trouve au nord du Delta du Nil à la côte du Méditerranée, en Egypte. La stratification du sol était très compliqué à cause de l'existence de couches compressibles d'argile limoneuse qui ont une très faible résistance au cisaillement et de grande compressibilité. Les bâtiments se composent de cinq étages avec des foundations de radiers très rigides en béton armé. Le sol est constitué de couches de sable de densité relative moyenne de la surface du sol jusqu'à une profondeur moyenne de 10,0 metres suivits par des couches d'argile limoneuse prolongée jusqu'à une profondeur de plus de 30m. Les propriétés du sol ont été determinées et le tassement a été estimé pour plusieurs points sous les bâtiments. Le tassement maximum calculé varie entre 10cm et 33cm suivant la forme et les dimensions des bâtiments. Ces tassements se feront pendant des dizaines d'années selon le taux calculé de consolidation. Par conséquent, il a été recommandé que les travaux de construction doit être lente et tous les bâtiments devraient être mis sous observation afin de mesurer les comportements du tassement pendant et après la construction. Les mesures, mentionnées ici, appartiennent à 29 bâtiments couvrant la durée de la construction, environ 24 mois et un an plus tard. Ces mesures ont montré que le tassement des bâtiments choisis était presque uniforme. Le taux du tassement a été beaucoup plus que les estimations. On croyait que le tassement total été a cause du tassement immédiate et consolidés à cause de la lenteur de la construction. Le tassement moyen pour le groupe de bâtiments a été très semblable à un vaste radier. Par conséquent, cette étude a été réalisée pour examiner la méthode convenable pour déterminer le taux de consolidation à la lumière des résultats des essais de laboratoire et de mesures sur le terrain. La validité de la méthode mentionnée par Polous (2000) pour estimer le coefficient équivalent de consolidation a été examinee à la lumière des mesures sur le terrain.

1 INTRODUCTION

Consolidation is defined as the reduction of bulk soil volume under loading due to flow of pore water. When saturated clay is loaded externally, the water is squeezed out of the clay over a long time due to its very low permeability. Granular soils are freely drained, and thus the settlement is instantaneous or immediately. The traditional approach for estimating settlement, first developed by Terzaghi, employs the one-dimensional method, 1-D in which the settlement is assumed to arise from consolidation due to increase in effective stress caused by the dissipation of excess pore pressure. 1-D method suggests that all the settlement arises from consolidation and hence it may give a misleading prediction of settlement. Although 1-D method has several limitations when compared with the two or three-dimensional method, it is still widespread used and can not be ignored. The immediate settlement has been also considered and discussed by several researchers. For over consolidated clay, immediate settlement can be a significant proportion of the total settlement. On the other hand, for soft clay the ratio of immediate to total settlement is considerably small so 1-D theory may provide an adequate prediction of the final settlement. It is also often that the field un-drained Young`s modulus is significantly greater than the theoretical value which would be included for an ideal elastic two-phase soil. Thus the immediate settlement may, in reality, be smaller proportion of the final settlement.

For most soil foundations we have two problems: how much settlement will occur and how long it will take. The latter problem could be represented by the rate of consolidation or coefficient of consolidation, c_v which could be determined through 1-D method or conventional consolidometer. According to the assumptions of 1-D theory, the experimental evidences indicated that the degree of consolidation U% that depends on c_v, thickness of consolidated strata H and time factor T_v, is much smaller than the reality and several researchers alluded to this phenomenon (Bowles 79). For example, Janbu (1965) proposed using soil strain at various depths to obtain nonlinear strain profiles and hence it could drew relationships between time factor T and degree of consolidation U to simulate the field conditions. From another viewpoint, several researchers used 2-D and 3-D conditions (Davis & Poulos, 1972, Small et al., 1976, Small, 1998) for estimating the rate of settlement. It is well known that 3-D effects may significantly accelerate the rate of settlement of foundations because of the ability of excess pore pressures to dissipate horizontally as well as vertically. Poulos (2000) stated that it may not always be feasible to employ a full 2-D or 3-D consolidation analysis. However, it is possible to adapt 1-D analysis to take account of this effect by using an equivalent coefficient of consolidation, C_{ve}, which is obtained by multiplying the conventional c_v by a geometrical rate factor R_f. R_f values can be derived from 3-D rate of settlement solutions, such as those derived by Davis and Poulos (1972).

2 GEOTECHNICAL PROPERTIES

In 1996, a client demanded from the second author of this paper to carry out geotechnical investigations for a site with area of about 9 hectares, in New Demmiat city to build a group of (29) residential buildings which included about 1080 housing units, Fig (1). This area is located on north of the Delta of River Nile at the coast of Mediterranean sea. For this project, nine borings were drilled to depths ranged between 20m and 30m below ground surface level. In cohesion-less soils disturbed samples were obtained by standard split spoon and its density was determined by carrying out the standard penetration tests, SPT. In cohesive soils undisturbed samples were extracted using thin wall Shelby tubes and SPT was also carried out. The results of the borings showed that the soil strata comprise in succession: sandy layers consisting of brown to dark grey calcareous sand with traces of shells, silt and mica in medium dense state of relative density as indicated by SPT (its standard penetration N values were generally in the range from 11 to 19). These strata were encountered from ground surface and extended to a depth ranged between 9.0m and 11.0m. The following strata are dark grey high plastic soft to very soft silty clay mixed with traces or some fine sand extended to the maximum explored depth of 30m. According to some researches on the Delta of Egypt, these strata extend to a depth of 50m below ground surface underlain by the base deposits that consist of very dense sand and hard clay. Table (1) shows some of the geotechnical properties.

Table (1): Geotechnical properties of soil

Boring No.	4	5	7	8
Depth (m)	23.0	12.0	12.0	25.0
Natural Water Content %	48.0	47.0	42.0	52.5
Liquid Limit %	108	101	94	117
Plasticity Index %	83	74	70.5	89.5
Initial Void Ratio, e_i	1.19	1.29	1.11	1.38
Compression Index, c_c	0.39	0.54	0.48	0.45
Over Consolidation Ratio	0.47	1.04	0.90	0.47
Coefficient of Consolidation, c_v (cm^2/min)	0.006	0.006	0.006	0.006

Of the ground water conditions, there are two water regimes in the site, according to the geology of the area. One is perched, which was experienced during performance the borings, on top of the impervious fat clayey layers and reflects the sea level. The other originates under pressure at depth in the granular basal deposits beneath the clay. The upper water level is found at a depth ranged between 0.4m and 0.50m below ground surface and it has very high sulfate and chloride contents.

3 FIELD PROBLEM AND DESIGN CRITERIA

In order to accommodate the field conditions with the constructions which involved five stories, it was decided to choose rigid reinforced concrete raft having up-stand beams in two directions to increase the stiffness of the foundations. Furthermore, it was suggested that the applied stresses at the foundation level, which lay at a depth of 0.75m below the natural ground surface, must not increase $50kN/m^2$. The dwellings consisted of two models (H and Z) as shown in figure (1). The model Z (with outside dimensions 11m x 42m) has no structural joint but the model H (with outside dimensions 25m x 46m) has four joints throughout the superstructure. As a result of the geotechnical properties of the soil, settlements could be estimated. The ultimate settlement values for raft center were about 33cm and 19cm for the models H and Z respectively. While the settlement values for edges and corners were about 20cm and 10cm for the models H and Z respectively. The maximum differential settlement for buildings model Z gives distortion angle less than 0.005. But for buildings model H it gives distortion angle more than that limit. The time settlement calculations approved that these settlements will happen through a period of time extends to more than 50 years and about 25% of the consolidation settlements will finish within 10 years.

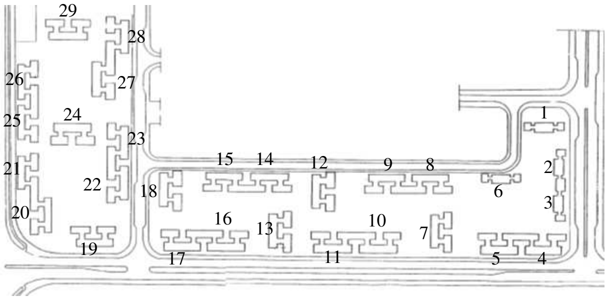

Fig. 1: Layout of the buildings (Building 1,2,3 & 6 model Z , the other buildings model H)

4 SETTLEMENT MEASUREMENTS

Due to the above challenges it was decided to choose very rigid raft foundations to uniform the total settlements and decrease the differential settlements between the different elements of the building. It was recommended that the construction period should be slow enough to cancel the rapid effect of settlements. Also an elaborated program of settlement measurements was desired in order to check the predicted settlements and to follow up the behavior of the buildings. Therefore, the author recommended measuring the settlement of all buildings during and after the construction. The client undertook the responsibility of this observation. Seven and six positions on the periphery of buildings H and Z were chosen for settlement measurements respectively. The erection of buildings started in Nov. 1997 then the measurements works commenced after ten months, exactly in Sep. 1998. Through this period the first and sometimes the second floor were mostly completed. The measurements, mentioned here, covered the duration of construction about 24 months and one year just after the end of construction stage. This observation has shown that the uniform settlement predominated on the behavior of each building, except building No. 21 which suffered an excessive differential settlement. Figures (2 to 5) show examples for settlement measurements of some buildings.

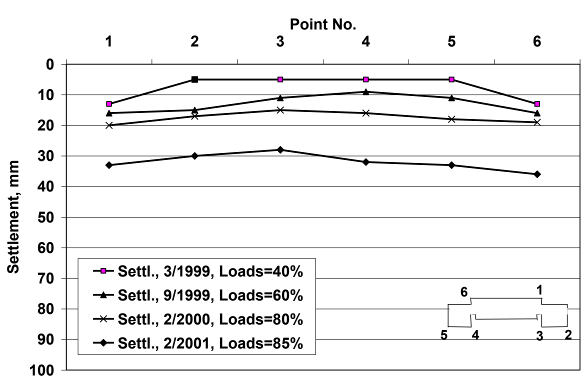

Figure 2: Settlement Measurements of Building # 6

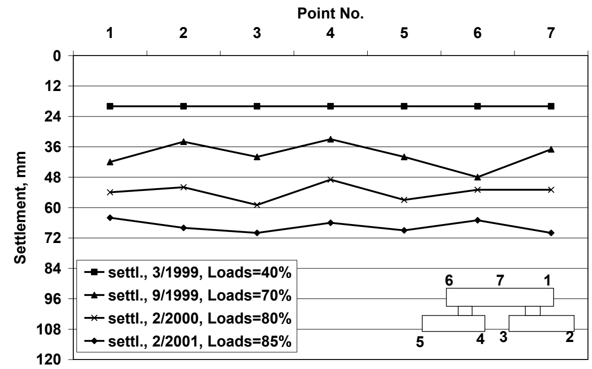

Figure 3: Settlement Measurements of Building # 8

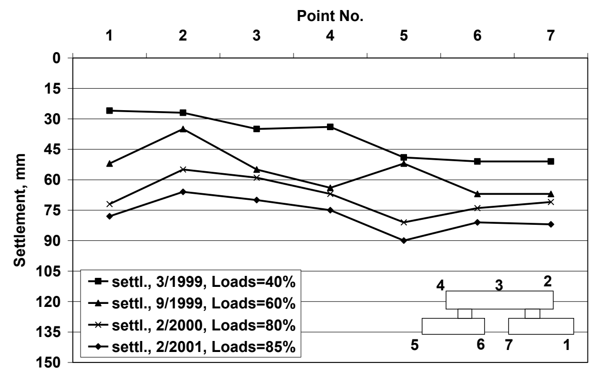

Figure 4: Settlement Measurements of Building # 16

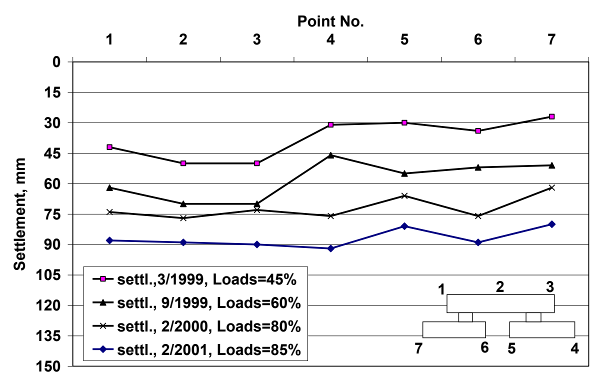

Figure 5: Settlement Measurements of Building # 22

5 RESULTS AND DISCUSSIONS

The discussion concentrated on three points included degree of consolidation, suitability of building shape to the geotechnical properties of the site and group shape effect on the settlement behavior of each building inside the group.

5.1 Degree of consolidation, U%

Estimating the degree of consolidation, U% depends mainly on coefficient of consolidation, c_v which could be determined during the consolidation test, see table (1).

Several factors affect c_v value such as coefficient of permeability, change in void ratio, viscosity of pore water and homogeneity of soil strata. These factors can be controlled for soil specimen during the test while in the field can not. Hence, some researchers have suggested that c_v can be practically used for thin layers with thickness not more than 5.0m. Refer to the results of lab tests the maximum estimated settlements S_e during construction and just after one year later have been in the range of 58mm. This value includes the immediate settlement and about 8% of consolidation settlement for model H buildings. Three buildings were chosen represented the measured settlements S_m depending on its location in the group. The average values of S_m were 67mm, 87mm and 87mm for buildings no 8, 16 and 22 respectively as shown in figure (3, 4 and 5). Because of the rigidity of raft foundation, S_m was considered the average values for edge, corner and center of the raft. Accordingly the field U% could be determined to be 12%, 20% and 20% for the three buildings respectively. Hence, the field or actual c_{ve} could be determined to be 0.015, 0.052 and 0.052 cm^2/min which indicated that the ratio c_{ve}/c_v is ranged between 2.3 and 8.0.

To check this observation, Janbu (1965) proposal was used in which consolidation of clay layers based on non-liner stress-strain had been discussed. Bowles (1979) reported and explained how one can estimate degree of consolidation according to U% - T relationship of Janbu. As soon as U% could be determined the traditional time factor T_v and the field c_{ve} could be also determined, tables (2 & 3) show in details these calculations. It can be noticed that the field c_{ve} values are higher 7.6 to 9.1 times than that of c_v within the first three years. Moreover, the ratio c_{ve}/c_v increased at the beginning of consolidation and still decreased with time.

In the light of field measurements Polous (2000) suggested curves for using equivalent coefficient of consolidation c_{ve}. Accordingly, for our case study the ratio c_{ve}/c_v is equal to 3.0 for double drainage conditions of consolidated layers, see figure (6).

The above discussion can be concluded as follows. Although Janbu proposal is complicated and includes difficult calculations it is considered a theoretical approach for estimating an equivalent coefficient of consolidation c_{ve} in good agreement with the field measurements. It also enables the engineer to predict the degree of consolidation at any time after construction stage. The method of Polous gave low value for c_{ve}/c_v which could be referred to certain assumptions such as shape of foundation, uniformity of soil and drained conditions, hence it needs to adjust. Moreover, the ratio c_{ve}/c_v is considered an average value expressing the whole period of consolidation. But with some skills and pivoting one can benefit too much from this method.

5.2 Suitability of Building Shape to Geotechnical Properties of the Site

As mentioned before the project consisted of group of buildings includes 25 buildings with model H shape (25mx46m) and 4 buildings with model Z shape (11mx42), as shown in figure (1). Buildings no 8, 16 and

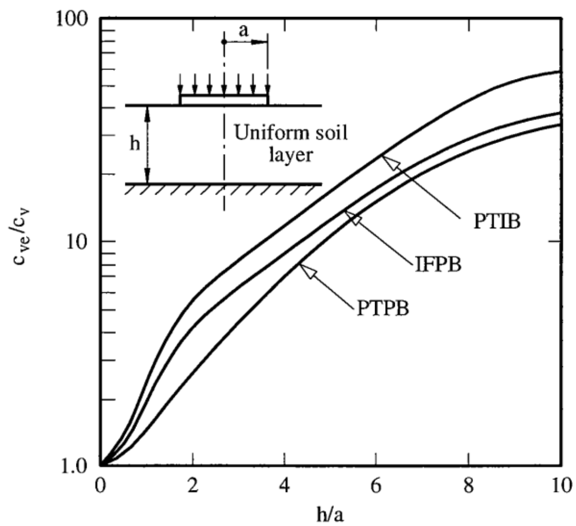

Figure 6: Equivalent coefficient of consolidation for 1-D analysis of rate of settlement – circular footing (after Polous 2000)

22 were selected to represent the model H shape while building no 6 was selected to represent the model Z shape. Settlement measurements for theses buildings have been presented in figures (2, 3, 4 and 5). It can be noticed that the values of S_m for model Z are much less than that for model H which can be attributed to the shape of the building. It can be concluded that the long rectangular shape similar to Z model is considered the most suitable shape for the geotechnical properties of this site. Refer to soil stratification that consisted of 10m sand overlaying more than 30m soft clayey layers, the bearing capacity for the raft foundation of model Z shape has completely arisen from the sand layer. While for model H shape the bearing capacity has arisen from both sand and clayey layers. So it was very important to adjust the shape and width of building to match with the thickness of top sand layers in New Demmiat City and similar sites.

5.3 Shape of Buildings Group Effect on the Settlement Behavior

It is known that the shape of settlement under raft foundation depends mainly on rigidity of the raft and type of soil while the amount of settlements depends mainly on soil properties and dimensions of the building. The uniform the settlement is related to the increase of raft rigidity. Rarely the researchers and the engineers have concerned with the group shape effect on the settlement behavior of an individual building inside the group in view of geotechnical properties of the site. Figure (7) shows relationship between the average measured settlements and number of buildings which reversed the group shape effect on the settlement of the individual building. It can be seen that the settlement obviously increased for the buildings near the middle of the group while decreased for the buildings near the edge. Refer to soil stratification the majority of settlement has happened due to the clayey layers compressibility which encountered at a depth of 10m below foundation. The stresses distribution from the group overlapped at certain depths through the clayey layers depending on the clearance between the buildings and hence the soil strained with the group as one building with huge raft. Generally this group action can not be avoided but it should be taken in consideration.

6 Conclusions

This paper presented settlement measurements of 29 residential buildings which have been measured during construction and one year later. These measurements were carried out to confirm the estimated settlements and to follow up the behavior of the buildings. The most important observations could be summarized as follows:

- The field or equivalent coefficient of consolidation c_{ve} was ranged between 2.3 and 8.0 higher than that of lab consolidation test c_v.
- Although Janbu proposal is complicated and includes difficult calculations, but it is considered a theoretical approach for estimating an equivalent coefficient of consolidation c_{ve} in good agreement with the field measurements.
- The method of Polous gave low value for c_{ve}/c_v which could be referred to certain assumptions such as shape of foundation, uniformity of soil and drained conditions, hence it needs to adjust.
- It was very important to adjust the shape and dimensions of a building to match with the thickness of top sand layers in New Demmiat City and similar sites.
- For estimating settlement of any individual building the group action should be taken in consideration.

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Table 2: Strain and settlement calculations according to Janbu (1965)

Point	Depth, H (m)	Hi (m)	ε_2			Sc (cm)			Y (m)	Y/ H	$\varepsilon_2 / \varepsilon_1$		
			C	e & r (aver)	Total (aver)	C	e & d (aver)	Total (aver)			C	e & d (aver)	Total (aver)
Top	10.0	----	0.032	0.017	0.0245	----	------	------	----	----	1.0	1.0	1.0
1	12.5	5.0	0.025	0.0123	0.0187	12.5	6.15	9.33	2.5	0.1	0.78	0.72	0.76
2	17.5	5.0	0.0135	0.009	0.0113	6.75	4.50	5.63	7.5	0.3	0.42	0.53	0.47
3	22.5	5.0	0.0079	0.006	0.0070	4.00	3.00	3.50	12.5	0.5	0.25	0.35	0.30
4	27.5	5.0	0.0057	0.004	0.0049	2.90	2.00	2.45	17.5	0.7	0.18	0.23	0.20
5	32.5	5.0	0.0037	0.003	0.0034	1.90	1.50	1.70	22.5	0.9	0.12	0.17	0.14
Bottom	35.0	----	------	------	------	-----		----	---	1.0	----	-----	-----

Notes: Top = top surface of clay layer. ε_2= strain of each layer with thickness of Hi. ε_1= strain at the top of clay layer. C = center, e & r = edge & corner of the raft. Sc= consolidation settlement. Y=depth of mid-high of each layer from top surface of clay layer. Bottom = bottom surface of clay layer. Total= average of C, e & r.

Table 3: Expected settlement and field coefficient of consolidation calculations according to Janbu (1965)

Time (year)	T	U %	Scf (cm)			Tv	Cve cm^2/min	Cve/Cv
			C	e & r (aver)	Total (aver)			
0.5	0.001	12	3.37	2.06	2.71	0.010	0.060	9.1
1.0	0.002	15	4.21	2.57	3.39	0.020	0.060	9.1
2.0	0.004	20	5.62	3.43	4.52	0.035	0.052	8.0
3.0	0.007	25	7.02	4.29	5.65	0.050	0.050	7.6
6.0	0.013	32	9.00	6.00	7.92	0.090	0.045	6.9
10.0	0.022	40	11.24	7.03	9.28	0.130	0.039	5.9
15.0	0.033	45	12.65	7.72	10.19	0.180	0.036	5.5
20.0	0.044	50	14.04	8.58	11.31	0.200	0.030	4.6

Notes: T & U= time factor & degree of consolidation (after Janbu, 1965). Scf= expected field consolidation settlement.

Tv= traditional time factor. Cve= field coefficient of consolidation. Cv= lab coefficient of consolidation = 0.0065 cm^2/min.

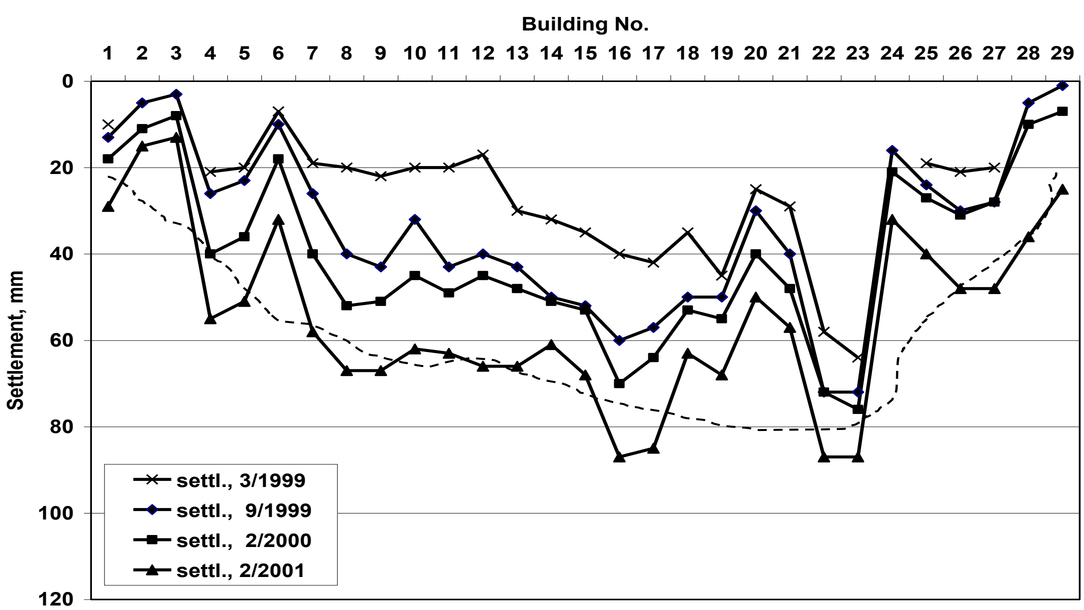

Figure 7: The Average Settlement Measurements of (29) Buildings