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Application of Micro-Tunneling Technique to Rectify Tilted Structures Constructed on Cohesive Soil

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***Abstract*—**Foundation differential settlement and supported structure tilting are an occasionally occurred engineering problem. This may be caused by overloading, changes in ground soil properties or unsupported nearby excavations. Engineering thinking points directly toward the logic solution for such problem by uplifting the settled side. This can be achieved with deep foundation elements such as micro-piles and macro-piles™, jacked piers, and helical piers, jet grouted mortar columns, compaction grout columns, cement grouting or with chemical grouting, or traditional pit underpinning with concrete and mortar. Although, some of these techniques offer economic, fast and low noise solutions, many of them are quite the contrary.

For tilted structures, with the limited inclination, it may be much easier to cause a balancing settlement on the less-settlement side which shall be done carefully in a proper rate. This principal has been applied in Leaning Tower of Pisa stabilization with soil extraction from the ground surface. In this research, the authors attempt to introduce a new solution with a different point of view. So, the micro-tunneling technique is presented in here as an intended ground deformation cause. In general, micro-tunneling is expected to induce limited ground deformations. Thus, the researchers propose to apply the technique to form small size ground unsupported holes to produce the target deformations. This shall be done in four phases: 1. Application of one or more micro-tunnels, regarding the existing differential settlement value, under the raised side of the tilted structure. 2. For each individual tunnel, the lining shall be pulled out from both sides (from jacking and receiving shafts) in the slow rate. 3. If required, according to calculations and site records, an additional surface load can be applied on the raised foundation side. 4. Finally, a strengthening soil grouting shall be applied for stabilization after adjustment.

A finite element based numerical model is presented to simulate the proposed construction phases for different tunneling positions and tunnels group. For each case, the surface settlements are calculated and induced plasticity points are checked. These results show the impact of the suggested procedure on the tilted structure and its feasibility. Comparing results also show the importance of the position selection and tunnels group gradual effect. Thus, a new engineering solution is presented to one of the structural and geotechnical engineering challenges.

***Keywords*—**Differential settlement, micro-tunnel, soil-structure interaction, tilted structures.

I. Introduction

TILTING is one of the most critical problems that threat the stability and safety of buildings. Tilting of structures causes soil overstressing beneath foundation. If the soil settlement and building inclination have been controlled and stopped, the structure may reach a new stable state. Otherwise, structures may face continuous slow-rate soil settlement resulting in unstable condition or even a complete failure for the whole building.

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Residents usually do not feel safe to live in tilted buildings. However, demolishing and reconstruction of tilted structures is waste of money, unless no other solution exists. Moreover, the demolishing of valuable historical buildings is out of choice. Thus, restoration processes for tilted structures should be considered and developed. Various methods are used to rectify tilted structures including compaction grouting, underpinning of the foundation, chemical grouting, jacking technique, and soil extraction technique [1]-[3].

Rectifying using soil-extracting technique, tilting building should go through a short unstable, but controlled, stage that is required to reduce the soil differential settlements. There are limited reports and researches investigate the possibility and the efficiency of using soil extraction process to rectify tilted structures. In 1832, James Trubshaw used soil extraction method to rectify the Wybunbury tower (England). It has square cross section with 9.8 m side length, 29.3 m height and weighs 1,500 tons. The tower was leaning over 1.56 m from its vertical axis and it had large crack with few centimeters width. After reaching the bottom level of the foundation, Trubshaw drilled rows of extraction auger-holes under the higher side of the foundation. The tower gradually began to sink and the fracture kept gradually closing up. This process was continued until the tower became perfectly straight [4].

Pisa tower (most famous leaned structure) has a hollow cylinder shape with 4.5 m inner diameter, 58 m height and 19.6 m foundation diameter. The angle of inclination of the Pisa tower reached 5.5°. In 1962, Terracina suggested a soil extraction technique by drilling holes and extracting soil from beneath the less settled side of the foundations [5]. Under-excavation was performed in two stages from year 1999 to 2001. The first excavation stage was completed by the extrusion of 7 m^3 of soil (29% of the soil was extracted from beneath the foundation). The second stage was completed by extracting 38 m^3 of soil (40%of the extracted soil was taken from the beneath of the tower foundation). The method of under-excavation is thought to have majorly contributed to the current apparently stable situation for the Pisa tower. The excavation process stopped the leaning instability and reduced the angle of inclination of the tower by about 10% [5].

This research suggests a micro-tunneling based technique as an alternative delicacy technique for the process of soil excavation under tilted structures. Micro-tunneling is defined as remotely controlled, steerable, continuous pipe jacking [6].

Micro-tunneling can help to extract soil from underneath the foundation with precise and accurate dimensions and locations. Furthermore, it can reduce the risk and increase the factor of safety against leaning instability. The construction phases for the proposed technique are simulated with a finite element program to check the technique's feasibility, safety and the impact of associated variables; tunnels position and number.

II. Methodology

The proposed procedure uses the micro-tunneling to form unsupported small holes in soil under the less settled side of the tilted structure's foundation. These holes shall collapse, under the structural and additional surface loads, causing a local failure at certain points in the ground soil in order to form a sliding surface leading the foundation to rotate counter to the tilting direction.

Although it sounds like a soil extrusion technique, it is supposed to cause lower disturbance for the ground and it works from the front and back sides when tilted side is not accessible. Fig. 1 shows a general layout for the proposed solution and Fig. 2 demonstrates the different procedure phases.

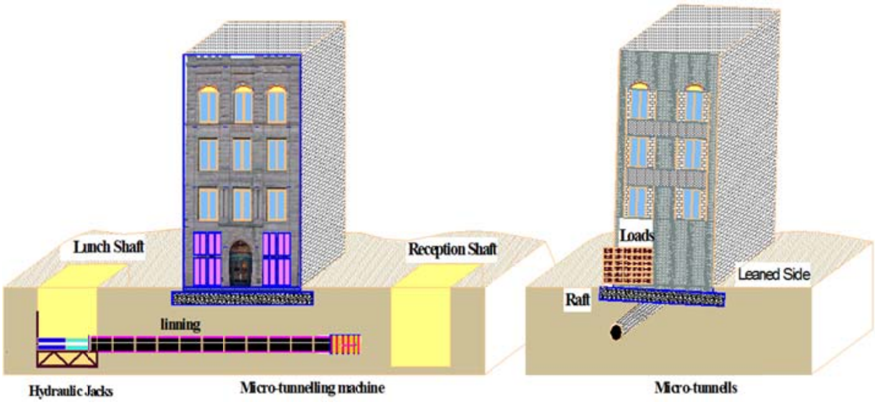
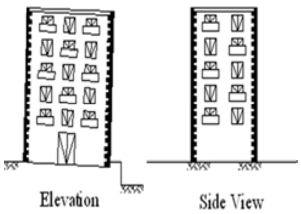
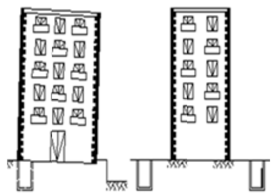


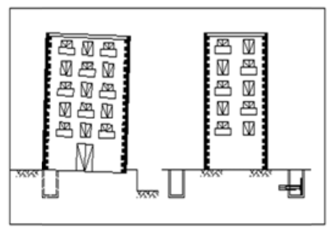
Fig. 1 Micro-tunneling technique to rectify tilted structures



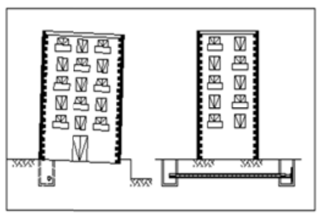
(a) Different views for studied problem



(b) Construction of jacking and receiving shafts



(c) Tunneling machine break through



(d) Complete lining (pipe) installation

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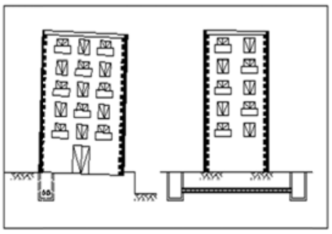
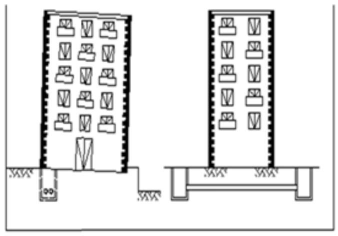
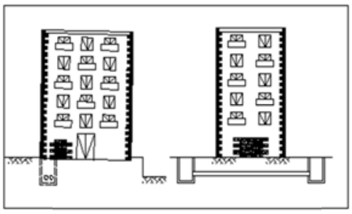


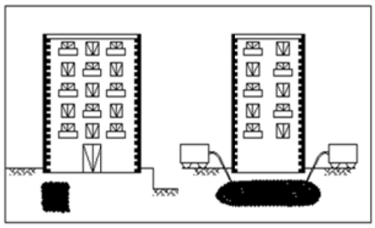
(e) Tunnels group construction (if needed)



(f) Lining removal one by one



(g) Additional surface load gradual application (if needed)



(h) Strengthen grouting for soil stabilization

Fig. 2 Construction phases for proposed procedure

The procedure starts with jacking and receiving shafts construction in front and back to the less settled side. The shafts should have minimum dimensions and depth and should be constructed as far as possible from the structure with an adequate construction technique to minimize ground disturbance. After that, tunneling process starts and lining rings are jacked in slow rate [7]. One or more tunnels may be needed, according to numerical calculations, to reach the balancing differential settlement value. Generally, the pipe-jacking tunneling does not induce significant surface settlements. Thus, the target value is expected to be reached through the next two synchronous steps. In these steps, the lining rings are pulled out from both shafts in very slow rate and additional surface load is applied gradually and simultaneously with lining removal process. Accurate dial gage records, that read the differential settlement value, shall determine the stopping point and the final step start, after restoring the structure vertical status. The final step is to apply strengthening soil grouting to stabilize the ground after structure rectification.

III. Numerical Analysis

A. Problem Definition

It is required to rectify a tilted building, which is constructed using a RC Skelton and has a 16 m length rigid raft foundation, Fig. 3. The foundation was constructed 2.5 m below the normal ground surface level. An unsupported excavation was performed beside the foundation, which is responsible for the building tilting.

Micro-tunneling technique is suggested to give a well-controlled and safe solution to rectify a tilted building. Extra surface load could be applied on the less settled side of the foundation to produce higher values of soil deformations. However, the formation of micro-tunnels should be properly designed to produce limited and proportional values of differential settlement in order to protect the structural elements from excessive stresses. Fig. 4 shows the alternative locations for the micro-tunnels beneath the structure foundation. The suggested locations for the tunnels are divided into five rows and five columns with 1m step in both vertical and horizontal directions.

Rectifying a tilting building, the forces and stresses subjected to a raft foundation are the own weight of the building (F_b), the surface loads (F_s), and the soil stresses (σ_s). The soil deformations, resulted from the formation of micro-tunnels, highly reduce the soil bearing capacity [8]. Thus, non-uniform soil stress distribution is expected due to the building rotation and the soil deformations, as shown in Fig. 3. The resultant force (F_r) acting on the raft foundation is required to remedy the situation of the building into a vertical position. The value of the resultant force varies with time due to the soil deformations and as a result to the changes of the soil bearing capacity. The values of the resultant force and moment could be calculated using (1) and (2), respectively. These values are highly affected by the number and locations of the micro-tunnels as well as the presence of the surface loads.

$$F_r = [F_b + F_s] - \int_{x1}^{x2} \sigma s(x) dx \quad (1)$$

$$M = F_r l_a \quad (2)$$

where: l_a (lever arm) is the distance between the resultant force and the point of rotation.

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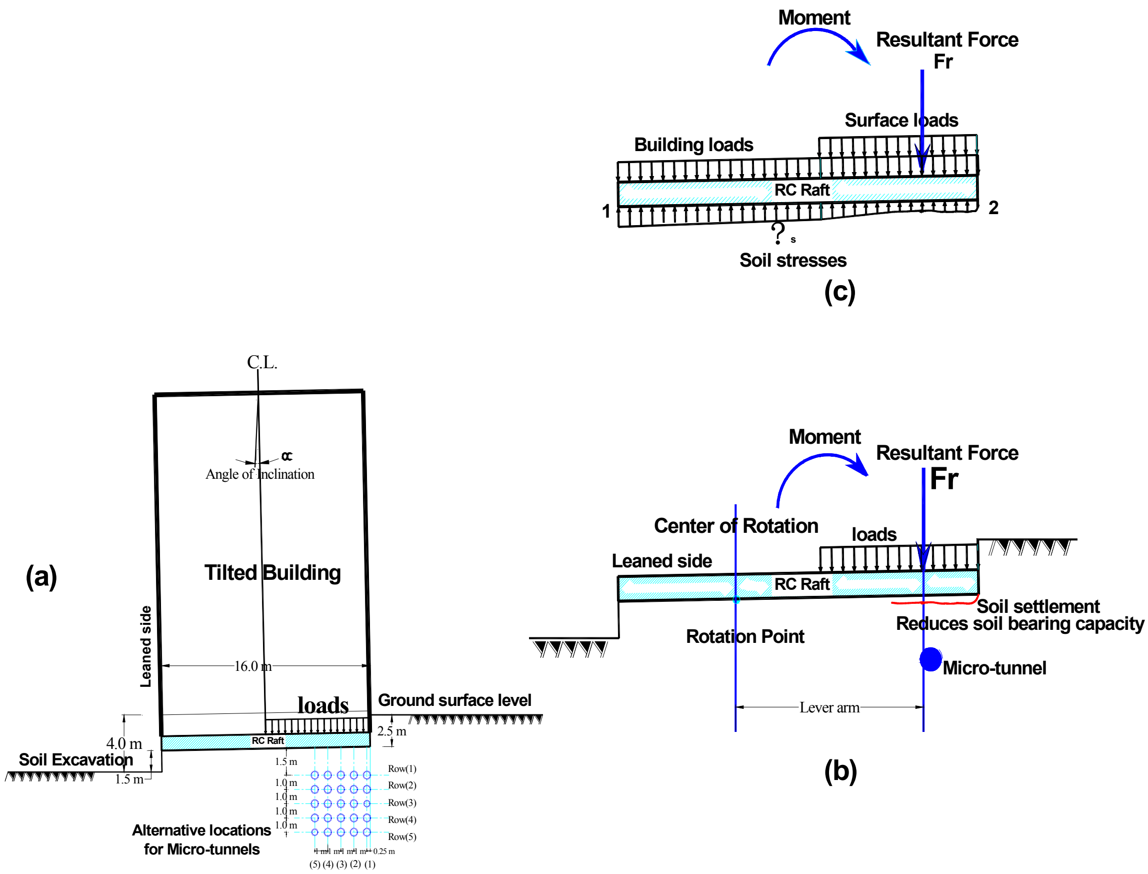


Fig. 3 Details of tilted building (case study) and the forces and stresses applied on its raft foundation

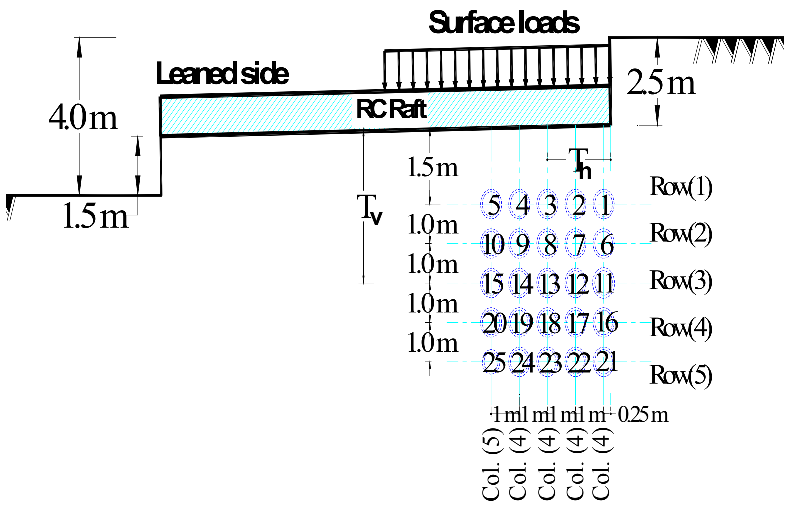
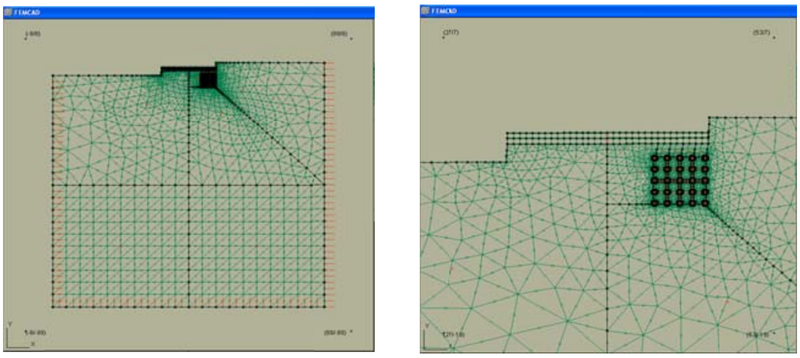


Fig. 4 Alternative suggested locations of the micro-tunnels



(a) (b)

Fig. 5 (a) Finite Element mesh layout, (b) Raft foundation and alternative tunnels positions

B. Parameters and Assumptions

The structure is assumed to be constructed on a rigid raft foundation rested on a cohesive soil with mechanical properties shown in Table I. The average contact pressure between raft and soil, resulted from structural loads, is assumed to be 100 kN/m^2 and the additional surface load on the less settled side is limited to 20 kN/m^2.The proposed tunneling zone is located at the less settlement raft edge with 1.5 m clear depth from foundation bottom. The applied tunnels are standard precast concrete pipes with 500 mm outer diameter and 60 mm thickness [9].

TABLE I
SOIL MECHANICAL PROPERTIES

Density	18 kN/m^3
Elastic Modulus	50 MPa
Poisson Ratio	0.3
Angle of Internal Friction	20 ^{o}
Cohesive Strength	50 kPa

C. Finite Element Simulation

A conventional 2-D numerical model with plane-strain analysis is used to simulate the proposed construction phases. Fig. 5 (a) shows the finite element mesh layout and the applied boundary condition while Fig. 5 (b) presents a close view for the structure raft foundation and alternative tunnels positions

For the modeling process in the Finite Element program, FINAL package [10], the soil media is modeled using a six node linearly varying strain triangular finite elements (L.S.T) and both raft and tunnel lining are represented by a six node beam elements (Beam6). Sufficient mesh depth and width, to model soil infinite body, are used. For boundary condition, vertical and horizontal movements are prevented at the bottom of the model while only the horizontal movements are prevented at both sides. The excavation sequences and lining installation are modeled in successive loading cases. The initial loading case is the geostatic stat of stresses and the existing raft and structure load. Excavation step is simulated in two steps using stiffness reduction method. In the first step, the stiffness of the soil in the excavated part is reduced by a factor accompanied with stress redistribution at the tunnel zone. In the second step, the excavated part is removed and lining elements are activated accompanied with a stress elimination of the excavated soil. Then, lining elements are deleted and stress is redistributed to represent the lining removal. Finally, the raft load is increased at the less settlement side with the additional surface load value, if applied.

IV. RESULTS AND DISCUSSION

A. Soil Differential Settlement

Rectifying a tilted building, the existed soil differential settlement should be reduced or faded by creating a reverse soil differential settlement. The formation of micro-tunneling was found to create a soil differential settlement that is found to be highly dependent on the number and location of the micro-tunnels as well as the application of surface loads. Fig. 6 shows the values of differential settlement due to the formation of one micro-tunnel through different locations (different values of T_v and T_H). The values of differential settlement due to the formation of one micro-tunnel were ranged from 0.5 to 2 cm. For all rows, almost the general trend was detected for the effect of the horizontal distance (Foundation edge-tunnel center (T_H)) on the value of the soil differential settlement. The tunnels located on column 2 (1.25 m far from the raft edge) showed the highest values of soil differential settlement; Figs. 6-8. The increase of the horizontal distance (T_H) reduces the values of the induced soil differential settlement.

The formation of two micro-tunnels at locations (21 and 22) or locations (24 and 25) resulted in differential settlement equal 3.71 and 4.46 cm, respectively. Compared with one micro-tunnel, the formation of two micro-tunnels under the less settled side of the foundation resulted in up to 135% increase for the values of soil differential settlement. The formation of three micro-tunnels at locations (21,22and 23) or locations (23, 24and 25) resulted in differential settlement equal 8.38 and 9.03 cm, respectively. The formation of three micro-tunnels instead of one micro-tunnel resulted in 375% increase in differential settlement value, Fig. 9.

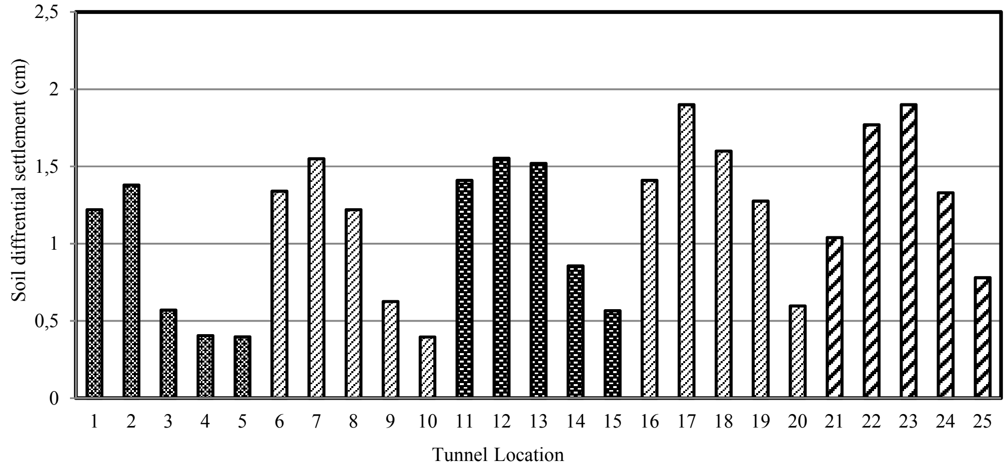


Fig. 6 Effect of tunnel location on soil deferential settlement under tilted building

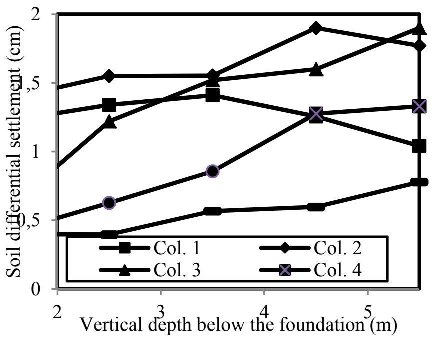


Fig. 7 Effect of tunnel location (T_v) on soil differential settlement

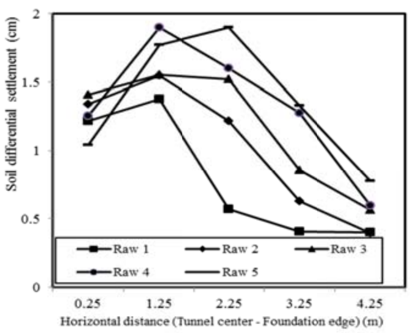


Fig. 8 Effect of tunnel location (T_H) on soil differential settlement

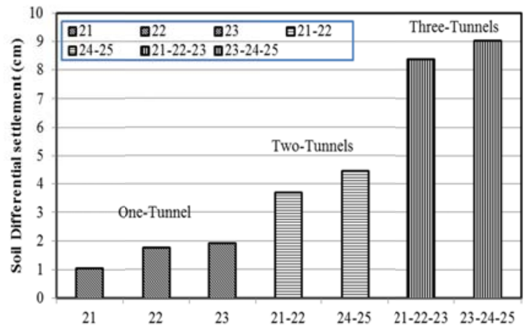


Fig. 9 Effect of micro-tunnels number on soil differentialsettlement

B. Soil Plastic Points and Landslide Surfaces

Soil excavation using micro-tunneling technique forms an unsupported hollow cylindrical space under the less settled side of the foundation. Because of the applied loads and pressure, these holes begin to deform and finally collapse forming a sliding surface. The sliding surface shape clearly depends on the number and locations of the micro-tunnels. Increasing the number of the micro tunnels resulted in an increase in plasticized zones. Figs. 10 (a)-(d) show plastic points distribution due to application of the proposed technique at locations 7, 8, 24-25 and 23-24-25 respectively. The plastic point are localized and well distributed, so that, a safe smooth sliding surface is formed.

In other cases, plastic points are localized forming U-shape with vertical sliding surface at the edge. This shall cause a fast or sudden ground movement that may affect the structure integrity, even after rectification. This shape is formed clearly with deep tunneling near the less settled edge. Figs. 11 (a) and (b) show plastic points distribution, giving examples for this case, due to application of the proposed technique at locations 16 and 21-22-23 respectively.

V. CONCLUSIONS

1- The results show that the proposed micro-tunneling based technique can represent a safe and a good solution to

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rectify tilted structures. Applying this technique causes an intended limited settlement that reduces or eliminates the existing differential settlement under tilted structures.

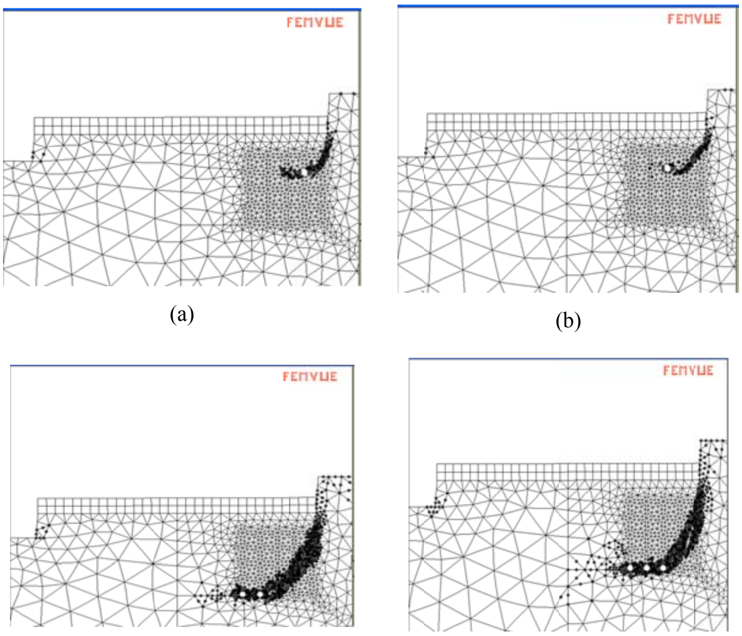
2- Tunneling numbers and locations have a high impact on the induced values of soil differential settlement, plastic point's distributions and sliding surface shape. Implementation of the proposed technique with groups of tunnels induces significantly high differential settlement values that can totally balance or overcome the existing settlement. Thus, an accurate selection for the applied tunnels number and locations should be considered to insure numerically, at least, reaching the safe and exact balancing value.

VI. Recommendations for Future Work

The authors highly recommend that further research should include the following points:

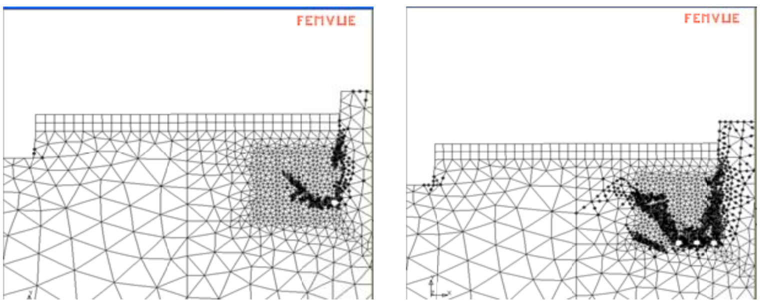
1- An optimization process, to the applied tunnels number and locations should be performed to induce a precise and safe soil differential settlement.

2- The numerical analysis for micro-tunnels soil excavation technique should be verified experimentally using physical modeling.



(a) (b) (c) (d)

Fig. 10 Plastic point distribution for smooth sliding surfaces



(a) (b)

Fig. 11 Plastic point distribution for U-shape sliding surfaces

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