Predicting excavation performance via inverse analysis

Prédiction du comportement d'une excavation par analyse inverse

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ABSTRACT

Predicting excavation performance in dense populated urban areas is critically important. Inverse analyses are powerful tools that are used to learn from local experience and predict soil response in new excavations with similar soil stratigraphy. This paper demonstrates the performance of a recently developed inverse analysis approach, SelfSim, with a special focus on its ability to provide soil models based on field measurements that can predict excavation performance in similar ground conditions for a case study in Shanghai. In Shanghai metro station excavation, the soil behavior is extracted by learning from a set of measured wall deflections and surface settlements at a selected section. The extracted soil models provide a reasonable prediction of wall deflections and surface settlements elsewhere.

RÉSUMÉ

La prédiction du comportement d'une excavation dans des zones urbaines densément peuplées est cruciale. Les méthodes inverses sont des outils puissants qui permettent de prédire le comportement d'une excavation, à partir d'informations obtenues sur un ouvrage réalisé dans des couches stratigraphiques similaires. Ce papier présente ainsi les performances d'une approche inverse appelée SelfSim sur l'excavation d'une station de métro à Shanghai. Il montre les capacités de cette nouvelle méthode à fournir des modèles de sol pour prédire le comportement futur de l'excavation. A partir des mesures des déformations horizontales et des tassements autour de l'excavation, le comportement du sol est extrait et un modèle de comportement est créé. Appliqué en différentes sections de l'excavation, ce modèle prédit alors avec précision les déplacements et tassements à venir du sol.

Keywords : Excavations, soil behavior, inverse analysis, case study

1 INTRODUCTION

There is continuing and increased demand for underground space in urban area. The construction in this space could influence surrounding structures. Therefore instruments are commonly set up at excavation sites to evaluate the design assumptions, determine causes of movements, improve the construction procedure, determine the need for immediate repair, and evaluate the stability of the excavation.

In many major urban areas, there are a number of well documented excavation case histories that are used by engineers as the precedent to estimate performance of new excavations in similar soil stratigraphy. Learning from precedent represents a classic inverse analysis problem aimed in part at interpreting the soil behavior implied by field observations.

In addition to local empirical experience, there are semi-empirical methods (Clough and O'Rourke, 1990; Kung et al., 2007; Peck, 1969) and numerical simulations (Finno and Calvello, 2005; Finno and Roboski, 2005; Hashash and Whittle, 1996; Kung et al., 2007; Mana and Clough, 1981; Ou et al., 2000; Ou and Lai, 1994; Whittle and Hashash, 1994) available to estimate excavation induced ground deformations.

Hashash et al. (2006) introduced a robust and efficient approach to extract soil behavior using SelfSim framework by integrating field observations and numerical modeling. SelfSim is an inverse analysis framework that implements and extends the autoprogressive algorithm proposed by Ghaboussi et al. (1998). It extracts soil behavior through the use of continuously evolving Neural Network (NN) material models. Therefore, SelfSim is different from common inverse analysis approaches whereby soil parameters of conventional constitutive models are adjusted to match the observed behavior.

2 SELFSIM INVERSE ANALYSIS APPROACH

In SelfSim, at a given excavation stage two complementary effective stress analyses are performed. First, the force boundary (construction sequence) condition is applied to extract stresses. Second, the measured field deformations (displacement boundary) are imposed on the model to extract strains. The extracted stress-strain pairs are used to re-train the NN material model until the two analyses give similar results (Hashash et al., 2006; Marulanda and Hashash, 2007). The extracted NN material model, which is an effective stress model can be used in a forward analysis to predict excavation response of a new excavation. This framework is depicted in Fig. 1. The numerical analyses assume the soil to be dry above the water table and do not deal with partially saturated soils.

The SelfSim analyses presented by Hashash et al. (2006) use lateral wall deflections and surface settlement measurements to capture excavation response and extract soil behavior. However, Song et al. (2007) demonstrated that SelfSim framework is not limited to these two types of measurements and can benefit from other instrument measurements such as inclinometers at further distances from the wall, strut loads, extensometers, and piezometers. Hashash et al. (2006) demonstrated SelfSim learning capacity and the ability to predict performance of a new excavation using numerically simulated excavation case histories.

In this paper, we demonstrate the performance of SelfSim learning using 15.5 m excavation case history in Shanghai. Shanghai Yishan Road metro station (Liu et al., 2005) is extensively instrumented along the length of the station with inclinometers and surface settlement points. The instrumented excavation in one section of the station is used in learning of the relevant underlying soil behavior. The learned soil behavior is

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then used in a numerical analysis to predict the performance of other sections which were not used in the learning process.

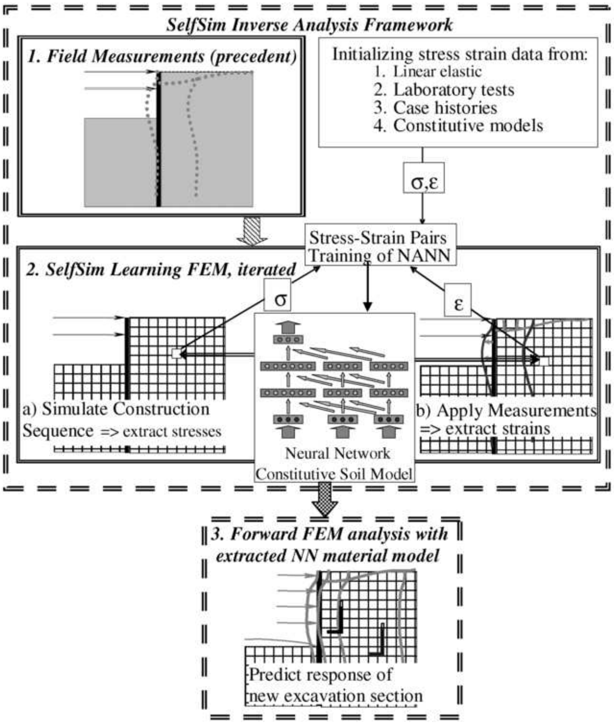


Fig. 1. Application of SelfSim inverse analysis framework to predict ground response at a new excavation section or site

3 METRO STATION IN SHANGHAI

The Yishan Road metro station, located in southwest Shanghai, is a 15.5 m deep excavation with 17.4 m width and 335 m length in Shanghai soft clays at Pearl II metro line (Liu et al., 2005). The site is instrumented to monitor wall deflections, total earth pressures at the wall, pore-water pressures, and vertical ground movements.

Fig. 2 shows the part of a plan view of Yishan Road metro station and instrument locations used in the current analyses. Fig. 3 shows the soil profile and typical cross section of the excavation site. The site is underlain by thick, relatively soft to medium soil deposits. The uppermost clay layer is desiccated and has lower water content but higher shear strength than those of the underlying marine deposits (i.e., soft silty medium clays).

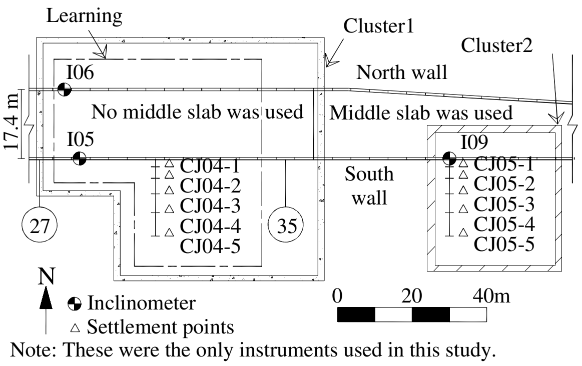


Fig. 2. Plan view of Yishan road metro station and instrument locations, Shanghai excavation, modified after Liu et al. (2005)

The shear strength and compressive modulus profiles were obtained from in situ vane shear tests and oedometer tests at stress ranges from 100 to 200 kPa, respectively. The permeability of shallow sedimentary marine soft silty and marine medium clays was 10^{-8} and 10^{-9} m/s, respectively. Generally the water content of each soil lies close to the liquid limit and the soils have a relatively high void ratio and hence high compressibility (Liu et al., 2005). The ground water table is at about 1 m below the ground level. The Yishan Road metro station excavation was supported by a 0.6 m thick concrete diaphragm wall. The wall length between Panels 27 and 35 was 28 m and in the remaining panels were 28 and 34 m at the north and south sides of the station, respectively. In order to minimize the effect of the station excavation on adjacent light-rail line existing parallel to the wall about in 20-30 m away, deeper wall in the south was designed and constructed. Prior to the main excavation, the soil at depths between 8.6 and 10.6 m and between 16.6 and 19.6 m below the ground surface was treated by compaction grouting at the passive zone of the excavation with 3 m spacing after the construction of the diaphragm wall.

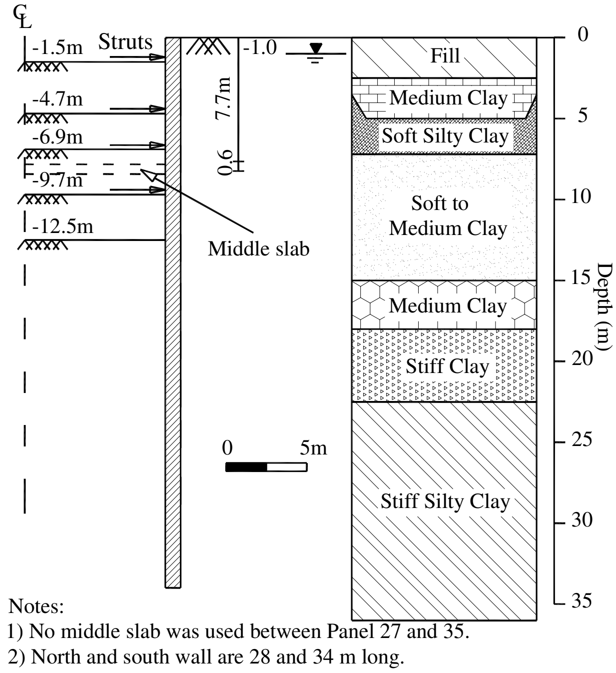


Fig. 3. Typical cross section of the Yishan road metro station, modified after Liu et al. (2005)

Since the compaction grouting was discontinuous, the interpreted inclinometer deflections showed that the grouting was ineffective. The excavation was conducted from two ends towards the center of the station.

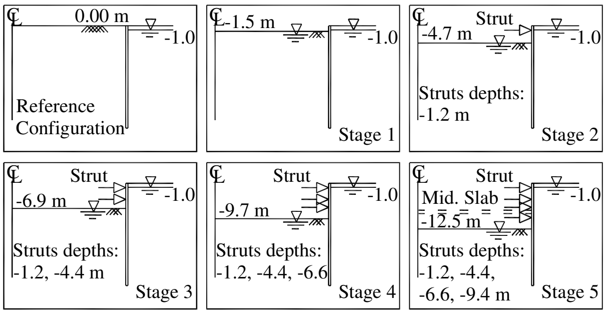
Reinforced concrete struts of 800 mm width and 1200 mm depth were installed at 6 m horizontal spacing at -1.2 m depth. Pre-stressed steel pipes of 609 mm in diameter (external) and 16 mm in thickness were used at 3 m horizontal spacing at other levels to support the diaphragm wall. Each pre-stressed strut was periodically adjusted to maintain the pre-stress to not less than 0.7 times the estimated total vertical stress (Liu et al., 2005). Prior to excavation to -12.5m, a 0.6 m thick reinforced concrete middle slab was constructed except for the section between Panels 27 and 35. 60 days were allowed for curing the concrete. Based on Liu et al. (2005) no significant creep effect could be identified over the 60 days curing of the middle slab.

The inclinometer measurements at the wall showed large lateral deflections from excavation depth of 12.5 to 15.5 m, which was not consistent with reported construction activities. One possible reason might be the insufficient application of pre-stress of struts (Liu et al., 2005). Therefore, the metro station excavation in this study is simulated down to 12.5 m excavation depth.

Two clusters are identified based on the support system configuration, and construction activities to perform the analyses, Fig. 2. In cluster 1 the wall length for both north and south walls of the excavation is 28 m and no middle slab was used in the analyses of this cluster. In cluster 2 the middle slab and wall length of 34 m are used to simulate excavation.

The idealized construction sequence for clusters 1 and 2 is illustrated in

Fig. 4. The instruments and wall length used for each cluster analysis is also shown in this figure. SelfSim learning is conducted using measurements of inclinometer I05, inclinometer I06, and settlements CJ04 in cluster 1 to extract the underlying soil behavior, Fig. 1 (Osouli, 2009).



Cluster	Instruments	Mid. Slab	Wall length North	Wall length South
1	I05, I06, CJ04	No	28m	28m
2	I09, CJ05	Yes	----	34m

Fig. 4. Construction sequence for different clusters

The measured deflections of inclinometers in the first stage were not reported. Therefore SelfSim learning was conducted using the measurements of stages two to five. Thereafter the extracted soil models are used to predict the instrument measurements in clusters 2, shown in Fig. 2. Since inclinometer data of I05 and I06 are similar, one set of measured wall deflections is proposed to represent both inclinometers measurements and it is labeled as "proposed measurements". A continuous surface settlement profile is also developed from the discrete settlement point measurements for CJ04 (Osouli, 2009).

4 LEARNING SOIL BEHAVIOR FROM MEASUREMENTS IN CLUSTER 1

The support wall for the deep excavation is simulated using solid elements with a bending stiffness equivalent to that of 0.6 m thick concrete diaphragm wall. The soil profile in the analyses is represented with five NN material models to represent soil layers: (1) for top fill layer, (2) for medium clay, soft silty clay, and soft to medium clay between depths of 2 m and 15 m, (3) for medium clays between depths of 15 m and 18 m, (4) for stiff clays between depths of 18 m and 23 m, and (5) for stiff silty clays at depths lower than 23 m.

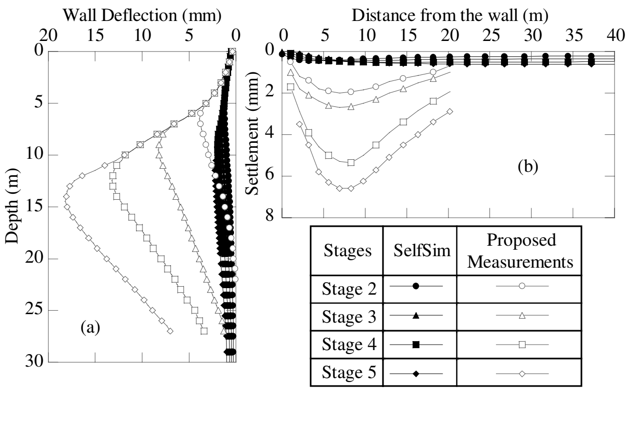


Fig. 5. Computed deformations in Cluster 1 prior to SelfSim learning; a) wall deformations, and b) surface settlements

Shanghai deep excavation is modeled as 2D symmetric excavation with half width of 8.7m. The model dimensions are 130 m and 70m in horizontal and vertical directions, respectively. Prior to SelfSim learning all soil constitutive models are pre-trained to represent linear elastic response within a very small strain range. Computed deformations prior to SelfSim learning are shown in Fig. 5. As it is expected the computed deformations significantly underestimate the proposed measurements.

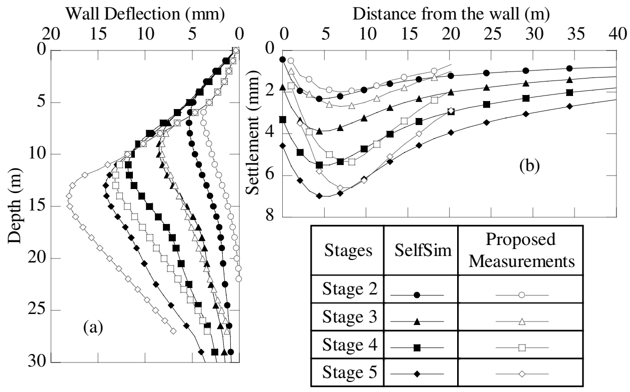


Fig. 6. Computed deformations in Cluster 1 after six passes of SelfSim learning with Cluster 1 measured deformations; a) wall deformations, and b) surface settlements

In SelfSim learning it is necessary that the soil stratigraphy be well known as the approach is limited to learning of soil behavior within well defined strata. SelfSim learning is then conducted using proposed measured wall deformations of inclinometer I05 & I06 and surface settlement points CJ04 (for locations see cluster 1 in Fig. 2). Computed and proposed measured deformations of the excavation after six passes of SelfSim learning are shown in Fig. 6. In comparison to Fig. 5, the computed deformations improved significantly. The difference between measured and computed deformations except for wall movements in the fifth stage of excavation is generally less than 2 mm. Therefore the computed measurements match the measured values. The lateral deformations in the fifth stage are underestimated.

5 PREDICTING EXCAVATION RESPONSE IN CLUSTER2

The developed soil models after SelfSim learning with measured wall deformations and surface settlements in Cluster 1, are used to predict excavation behavior in Clusters 2 shown in Fig. 2.

Prediction for Cluster 2

The predicted wall deformations of I09, and surface settlements CJ05 in cluster 2 are shown in Fig. 7. Since the middle slab was used in cluster 2, the inclinometer deflections of I09 are less than the measured deflections of I05 and I06.

The predicted deformations of the wall for inclinometers I09 in stages 3 and 4 are in reasonable agreement with the measured deflections. The predicted lateral deflections of stage 2 overpredict the measured values. The wall deflections and surface settlement for stage 5 are underestimated. Similar observation made for settlements CJ04. The predicted settlements in stage 2 and 3 match the measurements. The predicted settlements of stage 2 and 5 overpredict and underpredict the measurements, respectively.

However the sudden increase in measured settlements occurred between Stage 4 & 5 cannot be explained by reported construction activity. It is possible that an unrecorded deviation from the construction sequence caused this sudden increase.

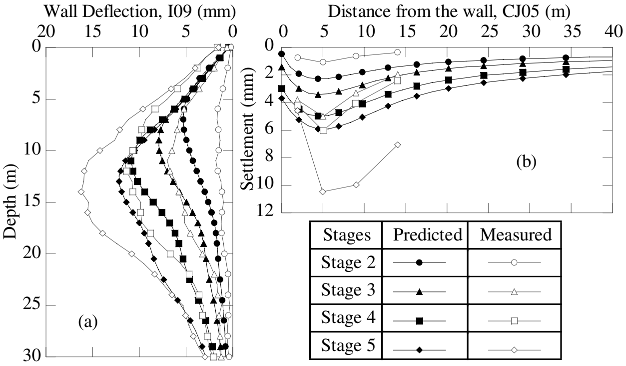


Fig. 7. Predicted deformations in cluster 2 after six passes of SelfSim learning with Cluster 1 deformations; a) wall deformations (I09) and b) surface settlement CJ05, (middle slab was used)

6 CONCLUSIONS

This paper demonstrated that it is possible to learn from precedent case histories or local experience and predict the excavation performance through SelfSim inverse analysis framework. The study described in this paper is part of a larger study reported in Osouli (2009).

The extracted soil models from learning instrument measurements in cluster 1 of Yishan Road metro station case study provide a reasonable prediction of wall deformations and surface settlements in clusters 2 of Yishan Road metro station.

This finding can lead to enhancement of current engineering practice whereby the proposed inverse analysis approach, SelfSim, can be used to learn from previous instrumented excavations and gain “local experience”. The database of performance of excavations can provide area-specific soil models (e.g. San Francisco Bay Mud, Boston Blue Clay). Then, the developed soil models can be used to predict excavation performance for new excavations constructed in these areas.

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